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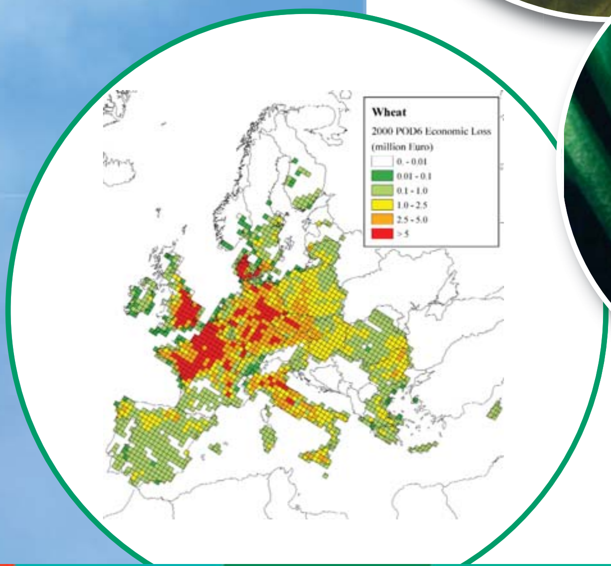
OZONE POLLUTION:
A hidden threat to food security







Report prepared by the ICP Vegetation September, 2011

Editors:
Gina Mills
and
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Working Group on Effects of the Convention on Long-range Transboundary Air Pollution

September, 2011

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[1] International Cooperative Programme on Effects of Air Pollution on Natural Vegetation and Crops.

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Executive summary

With the world population predicted to increase to 9 billion by 2050, security of food supplies is one of the most important challenges for this century. The key components of the food system that ozone pollution interferes with are the productivity of crops, the nutritional value and the stability of food supplies, and it is these effects that feature in this report. We concentrate here on impacts within the countries covered by the United Nations Convention on Long-Range Transboundary Air Pollution (LRTAP Convention) and have also included a review of potential impacts on crop production in South Asia as a case study. This report has been prepared by the ICP Vegetation (http://icpvegetation.ceh.ac.uk), an International Cooperative Programme that reports to the Working Group on Effects of the LRTAP Convention. Current knowledge of ozone impacts on crops and consequences for food security is reviewed, and new information is included on spatial and economic impacts in Europe, ranking of crop sensitivity to ozone, and local and national risk assessments.

Ozone pollution

Ozone is a naturally occurring chemical that can be found in both the stratosphere (the so-called "ozone layer", 10 - 40 km above the Earth) and the troposphere (the “ground level layer”, 0 - 10 km above the Earth). Within the troposphere where crops are growing, there is always a background concentration of ozone resulting from natural sources of the precursors. Of concern for food security (as well as for human health and carbon sequestration etc.) is the additional tropospheric ozone which is formed from complex photochemical reactions involving oxides of nitrogen (NO_x), carbon monoxide and non-methane volatile organic compounds (NMVOCs) released from industrial and vehicle sources. As a result of these emissions, there has been a steady rise in the background ozone concentration in Europe since the 1950s to the current 30 – 40 ppb. Also of concern for crop production, are ozone episodes where concentrations rise above 60 ppb for several days at a time, usually during periods of hot dry weather and stable pressure. For example, during July 2006, ozone concentrations in excess of 90 ppb were experienced on 10 days in the UK, Belgium, the Netherlands, France, Germany, Switzerland and Italy with the highest one hour value being recorded in Italy at over 180 ppb.

Ozone damage to crops

Ozone is absorbed into plants via the thousands of microscopic stomatal pores on the leaf which normally open during the day to allow CO_2 absorption for photosynthesis and evaporation of water. The more open the stomata are, the more ozone will enter the plant. Once inside the plant, cell walls and membranes are damaged by the reactive oxygen species that are formed leading to cell death and/or reductions in key processes such as photosynthesis. The results of these damaging effects depend on both the concentration and duration of ozone exposure. Plants are able to detoxify low concentrations of ozone but only to a certain threshold level. Above the detoxification level, ozone pollution damages crop plants by, for example, causing a yellowing of leaves and premature leaf loss, decreased seed production and reduced root growth, resulting in reduced yield quantity and/or quality and reduced resilience to other stress such as drought.

Two of the world’s most important staple food crops, wheat and soybean are sensitive to ozone with yield being reduced by 18% at a 7h mean ozone concentration of 60 ppb compared to 30 ppb (**Table 1**). Rice, maize and potato are moderately sensitive, having a ca. 10% yield reduction at 60 ppb ozone. In terms of economic value, eight of the nine crops with the highest production in Europe are sensitive or moderately sensitive to ozone. Sensitivity to ozone varies between cultivars, which means that there is scope for exploiting ozone resistance within breeding programmes. In general, modern cultivars of crops such as wheat seem to be more ozone sensitive than older, traditional cultivars,

suggesting that breeding for high crop productivity might have resulted unintentionally in breeding more ozone-sensitive cultivars. Compared to the impact on yield quantity, considerably less information exists on the impacts of ozone on food and feed quality and few dose-response relationships have been derived. So far, impacts have been found on important parameters for food security such as the protein yield of wheat, sugar content of potato, and oil quality in oilseed rape.

Table 1 Grouping of crops by sensitivity of yield to ozone. Values in brackets represent the percentage decrease in yield at a 7h mean ozone concentration of 60 ppb compared to that at 30 ppb.

Sensitive	**Moderately sensitive**	**Tolerant**
Peas and beans (including peanut) (30)	Alfalfa (14)	Strawberry (1)
Sweet potato (28)	Water melon (14)	Oat (-3)
Orange (27)	Tomato (13)	Broccoli (-5)
Onion (23)	Olive (13)	
Turnip (22)	Field mustard (12)	
Plum (22)	Sugar beet (11)	
Lettuce (19)	Oilseed rape (11)	
Wheat (18)	Maize (10)	
Soybean (18)	Rice (9)	
	Potato (9)	
	Barley (6)	
	Grape (5)	

Impacts of ozone on global crop production

The quantification of global impacts of ozone pollution on food security currently relies on the use of concentration-based ozone metrics such as AOT40[2] and 7h mean ozone concentration. All such studies have highlighted the potential for ozone to impact on yield by between ca. 3 and 20% depending on crop. Current global yield losses are estimated to be between 4 - 15% for wheat, 6 - 16% for soybean, 3 - 4% for rice and 2.2 - 5.5% for maize, with global economic losses estimated to be in the range $11 - $26 billion. Under the IPCC SRES[3] A2 Scenario, global yield losses for the year 2030 due to ozone are predicted to range from 5.4 - 26% for wheat, 15 - 19% of soybean, and 4.4 - 8.7% for maize, with total global agricultural losses in the range $17 - $35 billion annually. Even under the lower emission scenario B1, less severe impacts will nevertheless be in the range $12 - $21 billion annually. In areas of the world where demand already outweighs supply, the “hidden” threat from ozone impacts on crop production will add to the many threats to food security in areas of rapidly increasing population. So far no global evaluation is available on the impacts of ozone on food and feed quality, thus the total impacts of ozone on food security might be even higher than those described here.

Impacts of ozone on crop production in Europe

The current study has, for the first time, quantified ozone impacts on wheat yield in Europe using the flux-based methodology which incorporates the effects of climate, soil moisture, ozone concentration and plant growth stage on the hourly uptake of ozone through the stomatal pores in the leaf surface

[2] The accumulated hourly mean ozone concentration above 40 ppb, during daylight hours
[3] The Intergovernmental Panel on Climate Change Special Report on Emissions Scenarios

(ozone flux or stomatal flux). This method is biologically more relevant than the AOT40-based method which only takes into the account the amount of ozone in the air above the plant. We have shown that using the national emissions projections scenario for 2000, ozone pollution in EU27 (+ Norway and Switzerland) was predicted to be causing an average of 13 % yield loss for wheat, with an economic loss of €3.2 billion predicted if soil moisture is not limiting (**Table 2**). Economic losses per grid square in 2000 were greatest for wheat in the highest producing areas in France, Germany, Belgium, Denmark and the UK, indicating that ozone flux was high enough in these central and northern areas to have an impact on wheat production. Effects were also predicted for more southern countries such as Italy and Bulgaria. Impacts on tomato, a moderately ozone sensitive crop were investigated as a representative horticultural crop for southern Europe. Using the flux-based method, economic losses of €1.02 billion representing 9.4% of production value were estimated for 2000, with the highest total losses predicted for Italy, Spain, Greece and the Netherlands. Predicted effects for 2020 were generally lower than those in 2000. For both wheat and tomato, economic impacts were predicted to decrease by 38% to €1.96 billion and €0.63 billion respectively. However, for wheat, critical level exceedance remained high at 82.2% for the wheat growing areas. Critical level exceedance reduced from 77.8% of tomato growing areas in 2000 to 51.3% in 2020.

Other crops investigated using the AOT40 approach were less sensitive to ozone. Percentage losses in 2000 were predicted to be mainly between 0.5 and 10% for barley and maize over most of Europe. Effects of 10 – 15% losses were predicted for sugar beet in northern Italy, oilseed rape for parts of Italy and southern France, Germany, Austria and Slovenia, and for potato in northern Italy.

Table 2 Predicted impacts of ozone pollution on wheat and tomato yield and economic value, together with critical level exceedance in EU27+Switzerland+Norway in 2000 and 2020 under the current legislation scenario (NAT scenario). Analysis was conducted on a 50 x 50 km EMEP grid square using crop values in 2000 and an ozone stomatal flux-based risk assessment.

	Wheat		**Tomato**	
	2000	**2020**	**2000**	**2020**
Total production, million t	133.53		17.68	
Total economic value of wheat in 2000, billion Euro	15.87		6.85	
Mean % yield loss per grid square	13.7[1]	9.07[1]	9.4[2]	5.7[2]
Total production loss, million t	26.89	16.45	2.64	1.62
Total economic value loss, billion Euro	3.20	1.96	1.02	0.63
Percentage of EMEP grid squares exceeding critical level	84.8[1]	82.2[1]	77.8[2]	51.3[2]

[1]based on all grid squares with wheat production, [2] based on grid squares with > 1 tonne of production

This study has highlighted the contrasting concerns in northern and southern Europe. Despite experiencing lower atmospheric ozone concentrations, yield losses for crops such as wheat are predicted to be as high in northern Europe as in central areas due to favourable climatic conditions for ozone uptake. There is concern that the risk of crop losses might increase for northern Europe in a future, warmer climate when spring peak ozone concentrations might start to overlap with earlier growing seasons. In contrast in Mediterranean areas, climatic conditions (such as drought, low air humidity) do not necessarily result in high ozone uptake in rain-fed crops despite generally high atmospheric ozone concentrations. However, significant effects of ozone are likely where the crops are irrigated inducing stomatal opening, increasing ozone uptake and increasing impact. Prediction of ozone effects on crops in the Mediterranean part of Europe are more uncertain than those for central and northern Europe as flux models and dose-response functions are still being developed.

Two European case studies are included in the report describing impacts at the national scale in the UK and application of risk methodology at the local scale for the Federal State of Saxony in Germany. In the UK, ozone effects on crop yield were almost as high in a cooler wetter year with lower ozone concentrations (2008) when conditions were highly conducive to ozone uptake as in a relatively hot, dry year (2006) when higher ozone concentrations coincided with climatic conditions that were less conducive to ozone uptake. Ozone fluxes and thus predicted effects were greatest in the main crop growing areas in central and eastern UK, with several crops including wheat, barley, oilseed rape, sugar beet, peas and beans, maize and potato being impacted. There has been a steady increase in AOT40 over the period 1975 to 2010 at the Radebeul-Wahnsdorf monitoring station in Saxony, Germany, with values exceeding the critical level for effects on wheat yield of 3 ppm h from the mid-1990s onwards. The flux-based critical level of 1 mmol m^{-2} was exceeded from the mid 1980s onwards (no soil water limitation was assumed). This case study showed how the flux-based methodology can be used to provide a target value for local application in combination with a traffic light system showing the potential risk of wheat yield loss.

Impacts in South Asia

Food security of many countries of South Asia is under threat due to the rapidly increasing population, industrialisation and economic growth. This has resulted in an increase in the emission of ozone precursors and hence atmospheric ozone concentrations. Asia is now the world's biggest emitter of NO_x, a major ozone precursor, and its NO_x emissions are predicted to further increase over the coming decades. Studies with a chemical protectant against ozone damage, and ozone filtration experiments using open-top chambers, have shown that current ambient ozone levels in South Asia are reducing crop yield and quality for a range of important crops in the region, commonly within the range of 10 to 20%, but sometimes considerably more. Comparison of the Asian data with European and North American dose-response relationships show that, almost without exception, Asian crops appear to have a higher sensitivity to equivalent ozone concentrations. Hence, Asian crop yield and economic loss assessments made using North American or similar European based dose-response relationships may underestimate the damage caused by ozone. As such, there is an urgent need for co-ordinated experimental field campaigns to assess the effects of ozone across Asia to allow the development of dose-response relationships for Asian cultivars and growing conditions leading to improved quantification of current and future impacts.

Ozone impacts on crops in a changing climate

Very few field-based experiments have been conducted on the combined impacts of ozone and climate change on crops. In general, chamber-based studies have shown that elevated CO_2 tends to reduce stomatal conductance and stimulate crop yield, hence there may be some mitigation of the impacts of ozone by reduced uptake as CO_2 concentrations continue to rise. However, recent field-based studies have indicated that the positive effect of CO_2 identified in chamber studies might have been overestimated. Although drought might protect crops from ozone damage due to a reduction in stomatal conductance and hence ozone uptake, recent research indicates that several species can become more sensitive to drought after prolonged ozone exposure. When considered as a single factor, increased temperature is likely to increase stomatal uptake of ozone providing the optimum for stomatal conductance has not been reached. However, the response to warming will also be affected by the following indirect effects of increased warming: added stimulation of tropospheric ozone formation, an increase in vapour pressure deficit (humidity) and decrease in soil water potential (soils will dry out faster due to enhanced soil evaporation and enhanced canopy evapotranspiration); and earlier and enhanced plant development, resulting in a forward shift of the period within the year when plants are absorbing ozone.

Recommendations

Policy-related More stringent reductions of the emissions of precursors of ozone are required across the globe to further reduce both peak levels and background concentrations of ozone and hence reduce the growing threat from ozone pollution to food security. It would be of benefit to better integrate policies and abatement measures aimed at reducing air pollution and climate change as both combine together to affect food security. Improved quantification of impacts of ozone within the context of climate change is urgently required to facilitate improved future planning of availability of food at a range of scales (national, regional, global). There is an urgent need to raise political awareness of the adverse impacts of ozone on food security in regions such as South Asia where some of the most important staple foods of wheat, rice, maize and bean are ozone sensitive and productivity is likely to be adversely affected by ozone. Crop breeding programmes should test cultivars for ozone sensitivity to develop more resistant cultivars aiming to ensure that ozone does not diminish the yield gain of the higher yielding cultivars being developed. Future crop management strategies should consider ways of reducing ozone fluxes into crops, including for example withholding irrigation during episodes of peak ozone concentrations and consideration of use of chemical protectants.

Further research Further development of the ozone flux-based method and establishment of additional flux-effect relationships is required. This would include additional ozone exposure experiments for current and newly developing cultivars, with effort focussed on regionally-important staple food crops and derivation of dose-response for impacts of ozone on nutritionally-important aspects of yield quality as well as on quantity. Experiments on the interacting effects of climate change and ozone should be conducted including quantifying impacts of reduced soil moisture availability, rising temperature and incidences of heat stress, and impacts of rising CO_2 concentration. Climate region-specific parameterisations for flux models need to be developed to improve the accuracy of predictions.

For Europe, it would be beneficial to quantify impacts for a range of future ozone scenarios incorporating predicted changes in climate and crop price, and quantification of the range of uncertainty. Improved regional modelling of the input factors for flux calculations is required, including modelling of soil moisture content, establishment of thresholds for irrigation application and updated mapping of the locations where irrigation facilities exist. For South Asia (and other developing areas), a network of ozone monitors is urgently required to facilitate improved ozone mapping and prediction of impacts.

Whilst technical methodologies for ozone precursor emission reductions are being developed and international negotiations are taking place to reduce national and transboundary ozone, the development of crop management practices that will reduce or alleviate ozone stress is required, including: testing of current varieties for ozone sensitivity to provide farmers with a list of ozone-resistant cultivars for use in regions where negative impacts of ozone are likely; improved recognition of ozone sensitivity within crop breeding programmes, facilitating the selection of ozone-resistant cultivars; and development of locally-applicable crop management practices that provide farmers with methods of reducing impacts, including, for example, appropriate cultivar selection, withholding irrigation during the highest ozone episodes and possible use of chemical protectants.

Contents

1. Introduction

Gina Mills, Harry Harmens, Karine Vandermeiren and Jürgen Bender

1.1 Background

With the world population predicted to increase to 9 billion people by 2050, security of food supplies is one of the most important challenges for this century. Food security may be usefully conceptually divided into three major components: Food availability (production, distribution, and exchange), food access (affordability, allocation, and preference), and food utilization (nutritional value, social value, and food safety). The FAO (and others) also explicitly include stability as a fourth component, to acknowledge that food security varies seasonally and inter-annually in many places. The key components of the food system that ozone pollution interferes with are the productivity of crops, the nutritional value and the stability of food supplies, and it is these effects that feature in this report. This report addresses an urgent need to bring together available knowledge on ozone impacts on food security as highlighted by three recent global studies (Royal Society, 2008, 2009, Foresight, 2011). We concentrate here on impacts within the countries covered by the United Nations Convention on Long-Range Transboundary Air Pollution (LRTAP Convention) and have also included a review of potential impacts on crop production in south-east Asia as a case study. This report has been prepared by the ICP Vegetation (http://icpvegetation.ceh.ac.uk), an International Cooperative Programme that reports to the Working Group on Effects of the LRTAP Convention.

Current global yield losses are estimated to be between 4 - 15% for wheat, 6 - 16% for soybean, 3 - 4% for rice and 2.2 - 5.5% for maize (Van Dingenen et al., 2009, Avnery et al., 2011a), with global economic losses estimated to be in the range $11 - $26 billion. Under the IPCC SRES[4] A2 Scenario, global yield losses for the year 2030 due to ozone are predicted to range from 5.4 - 26% for wheat, 15 - 19% of soybean, and 4.4 - 8.7% for maize, with total global agricultural losses in the range $17 - $35 billion annually (Avnery et al., 2011b). Even under the lower emission scenario B1, less severe impacts will nevertheless be in the range $12 - $21 billion annually. In terms of economic value, eight of the nine crops with the highest production in Europe (FAOSTAT, http://faostat.fao.org) are sensitive or moderately sensitive to ozone, including wheat, potato, sugar beet, oilseed rape and tomato (Mills et al., 2007; see chapter 4). Typical effects include premature senescence and reduced yield quantity and quality (see later).

All European assessments made so far have been based on either the 24h mean ozone concentration or AOT40[5]. These ozone metrics only take into account the ozone concentration in the air above the leaves of crops. In the last decade, a new method of quantifying ozone impacts has been developed that incorporates the effects of climate, soil moisture, ozone concentration and plant growth stage on the hourly uptake of ozone through the pores in the leaf surface known as stomata (ozone flux or stomatal flux). The latter method includes a model of the opening and closing of the stomata as climate etc. changes and is biologically more relevant than concentration-based methods. Procedures for assessment of risk of damage to crops have been reviewed recently, and are included in the LRTAP Convention's Modelling and Mapping Manual (LRTAP Convention, 2010) and summarised in Mills et al. (2011c). As well as describing the scientific background to risk assessment methods for ozone, details are provided in the manual on the methodology for applying concentration-based and flux-based critical levels, above which effects of ozone on crops can be expected. In this report, we have used the concentration-based and flux-based methodology to quantify impacts of

[4] The Intergovernmental Panel on Climate Change Special Report on Emissions Scenarios
[5] The accumulated hourly mean ozone concentration above 40 ppb, accumulated during daylight hours

ozone on wheat and tomato yields in Europe for the years 2000 and 2020. We have also mapped impacts for other crops using the AOT40-based method.

1.2 The role of the ICP Vegetation

The ICP Vegetation comprises over 200 scientists representing 33 countries of Europe and the USA and Canada and has its Programme Coordination Centre at the Centre for Ecology and Hydrology, Bangor, UK. The programme conducts experiments, analyses vegetation samples, synthesises current knowledge and develops models on current and future impacts of ozone, heavy metals and nitrogen pollutants on crops and (semi-)natural vegetation (Harmens et al., 2011). These outputs contribute to the development of internationally-agreed protocols on pollution control by the LRTAP Convention by providing scientific evidence and risk assessment methodology. This report covers one aspect of the work of the ozone group within the ICP Vegetation and contains reviews and data synthesis from participants in Belgium, Germany, Spain, Sweden and the UK. In addition to this report, the ICP Vegetation Programme Coordination Centre is putting together a similar report on impacts of ozone on carbon sequestration and ozone absorption of vegetation and the implications for climate change, due for publication in December 2011 together with reports on heavy metal contamination and nitrogen enrichment of mosses in Europe (March, 2013). Other contributions to the Convention include predictions of ozone impacts on crops, (semi-)natural vegetation and trees in Europe for inclusion in the negotiations related to the revision of the Gothenburg Protocol to abate effects of acidification, eutrophication and ground level ozone, biomonitoring studies of ozone impacts using sensitive indicator species, and a review of the potential use of mosses as biomonitors of persistent organic pollutants.

1.3 Ozone pollution

Ozone is a naturally occurring chemical that can be found in both the stratosphere (the so-called "ozone layer", 10 - 40 km above the Earth) and the troposphere (the “ground level layer”, 0 - 10 km above the Earth). Within the troposphere where crops are growing, there is always a background concentration of ozone resulting from natural sources of the precursors such as oxides of nitrogen (NO_x) and non-methane volatile organic compounds (NMVOCs) released from, for example soil and vegetation, as well as incursions of ozone from the stratosphere which occurs under certain meteorological conditions.

Of concern for food security (as well as for human health and carbon sequestration etc.) is the additional tropospheric ozone which is formed from complex photochemical reactions involving NO_x, carbon monoxide and NMVOCs released from industrial and vehicle sources. As a result of these emissions, there has been a steady rise in the background ozone concentration in Europe since the 1950s to the current 30 – 40 ppb (Royal Society, 2008). Models predict that the background ozone concentration will continue to rise in Europe, reaching at least 45 ppb over most areas by the end of this century (Sitch et al., 2007). Also of concern for crop production, are ozone episodes where concentrations rise above 60 ppb for several days at a time. Episodes usually develop during periods of hot dry weather and stable pressure which are particularly conducive to ozone formation and can result in potentially damaging ozone concentrations over large areas of Europe. For example, during July 2006, ozone concentrations in excess of 90 ppb were experienced on 10 days in the UK, Belgium, the Netherlands, France, Germany, Switzerland and Italy with the highest one hour value being recorded in Italy at over 180 ppb (EEA, 2007).

Due to the implementation of ozone precursor emission abatement policies, peak level ozone concentrations are gradually declining in Europe, North America and Japan. However, background ozone concentrations in Europe are still rising and predicted to rise until at least 2050 due in part to hemispheric transport of the precursors of ozone from developing areas of the world (Royal Society, 2008). Indeed, the background concentrations in Europe have now reached levels where they could be damaging to crop production.

Ozone concentrations are usually highest in rural areas that are downwind of major conurbations where there are few other pollutants to react with ozone to reduce the concentration. They are also usually highest in spring and summer when temperature and light conditions are more conducive for ozone formation. These spring and summer peaks coincide with the growing season of most crops increasing their vulnerability to ozone impacts.

An illustration of the spatial variation in ozone concentration within Europe is presented in **Figure 1.1**. using the AOT40 metric for the year 2000. Ozone concentrations were highest in southern Europe resulting in AOT40s above 7.5 ppm h in most of the wheat growing areas of Italy, southern Spain, southern France, Switzerland, southern Germany, Austria, Hungary, Slovenia and Slovakia. Later in this report, we show how the areas with mid-low ozone concentrations of ozone are not necessarily free from risk of damaging effects of the pollutant. In areas such as northern France, Belgium, the Netherlands, southern UK and parts of Scandinavia, climatic conditions are highly conducive to ozone uptake (flux) and even modest ozone concentrations can be expected to have an impact as stomatal fluxes match those found further south where concentrations are higher but ozone flux is restricted by partial stomatal closure.

1.4 Why are we concerned about ozone effects on crops?

Ozone is absorbed into plants via the thousands of microscopic stomatal pores on the leaf which normally open during the day to allow CO_2 absorption for photosynthesis and evaporation of water. The more open the stomata are, the more ozone will enter the plant. Once inside the plant, cell walls and membranes are damaged by the reactive oxygen species that are formed leading to cell death and/or reductions in key processes such as photosynthesis. The results of these damaging effects depend on both the concentration and duration of ozone exposure. Plants are able to detoxify low concentrations of ozone to a certain level, but above this level damage to crop occurs in two ways:

Acute injury due to exposure to the "high" ozone concentrations that usually occur during ozone episodes. Visible leaf damage develops that appears first on the lower leaf surface as pin-head sized pale yellow, brown or bronze spots. If the ozone episode lasts for several days the spots join together to form large areas of dead leaf tissue. Visible ozone injury on the leaves of foliage crops such as alfalfa, lettuce, spinach and cabbage reduces the economic value of the crop by reducing the quality or grade. It may also impact on profit if the farmer employs staff to remove the damaged leaves resulting in a lower weight but visibly unblemished crop. Overall, over 250 incidences of leaf injury attributed to ozone pollution have been reported on 27 crop species growing in 15 countries over the period 1990 to 2006 (see **Figure 1.4** and Mills et al., 2011b). Examples of ambient ozone pollution causing visible damage to horticultural crops in Greece are provided in **Figure 1.2.**

Chronic damage due to exposure to elevated background ozone with/without ozone episodes.This type of damage is more subtle and, depending on plant species, may include symptoms such as chlorosis and premature senescence, resulting in earlier leaf abscission and flowering (Pell et al., 1997). Often though no visible injury is observed, but lower rates of photosynthesis do indicate adverse effects on plant vitality. In crops, ozone induced decreases in photosynthetic capacity and accelerated loss of leaf area lead to smaller and fewer grains/pods/tubers being produced and retained, reducing quantity and quality (e.g. protein content) of yield leading to reduced economic value.

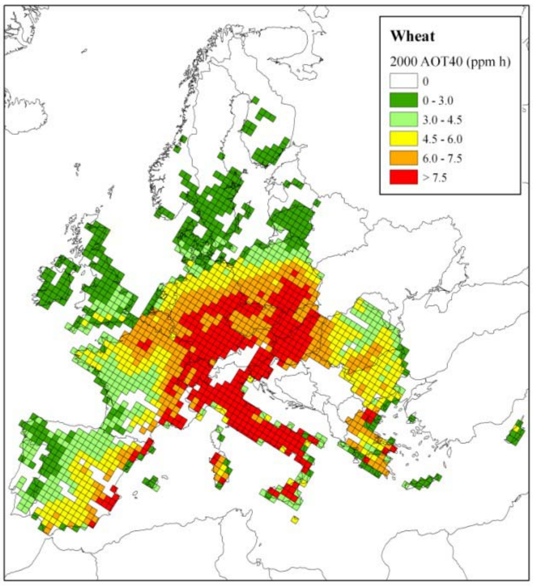


Figure 1.1 AOT40 in the wheat growing areas of Europe in 2000. Squares are included where wheat production exceeded 6t per 50 x 50 km grid square.

Figure 1.2 Ozone damage to lettuce on a commercial farm in Greece (a) hydroponically-grown indoor crop and (b) outdoor crop. Source: D. Velissariou, Greece.

Figure 1.3 Exposure of wheat to ozone in open-top chambers placed over the crop as it emerged. Source: H Pleijel, Sweden.

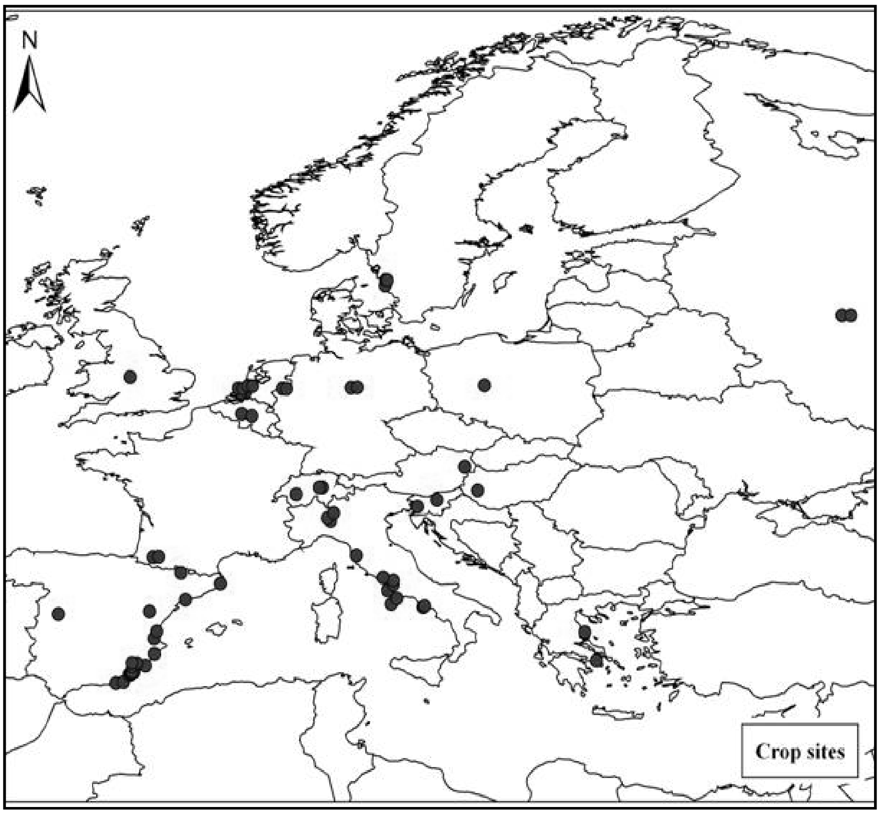


Figure 1.4 Locations where there have been a total of over 250 incidences of visible injury attributed to ozone pollution on crops (1990 – 2006, Mills et al., 2011b).

1.5 Quantifying the damaging effects of ozone on crops

Many crops are sensitive to ozone within the range of concentrations experienced in Europe. Effects have been quantified by exposing crops growing in the field in open-top chambers (**Figure 1.3**) which are placed over the crop as it emerges. The ozone concentration within the chamber is controlled by either filtration to remove ozone present in the air or by computer-controlled addition of ozone to either filtered or unfiltered ambient air. Microclimate within the open-top chamber is modified to a certain extent, but does fluctuate naturally with the climate. These types of experiments were conducted extensively in Europe and the USA in the 1980s and early 1990s, with fewer experiments with crops conducted since then.

Data from the open top chamber experiments were collated and analysed for crop sensitivity to ozone (Mills et al., 2007), with an update presented in Chapter 4 of this report. Wheat, peas and beans, and soybean were found to be amongst the most sensitive group of crops, with maize, barley potato, oilseed rape and sugar beet being moderately sensitive. Although this analysis was based on effects on seed or marketable yield, experiments have also shown that ozone impacts on yield quality such as the protein (wheat) and sugar content (sugar beet).

Under the auspices of the ICP Vegetation, critical levels have been derived for agricultural and horticultural crops, above which effects on yield are expected. The critical levels used for the LRTAP Convention's Gothenburg Protocol to abate the effects of acidification, eutrophication and ground-level ozone were based on AOT40. Ozone exposures below 40 ppb were believed to be being detoxified by the plant's natural defence mechanisms and thus were not contributing to the damaging effects of ozone. Scientific research has developed further in the last decade, and currently the accumulated ozone flux via the stomatal pores on the leaf surface is considered to provide a more biologically sound method for describing observed effects. This new parameter is the Phytotoxic Ozone Dose above a threshold of Y, POD_Y (previously described as $AF_{st}Y$). It is calculated from modelling the effects of climate (temperature, humidity, light), ozone, soil (moisture availability) and plant development (growth stage) on the extent of opening of the stomatal pores, and like AOT40 is accumulated over a threshold, in this case a flux of Y nmol m^{-2} s^{-1}. Five flux-based critical levels for crops were agreed by the ICP Vegetation Task Force in February 2010 and were subsequently approved by the LRTAP Convention as targets for protection against adverse effects on yield quality and quantity (**Table 1.1**). It should be noted that the critical levels and response functions for wheat and potato have been mainly derived from data from central and Northern Europe. The risk of adverse ozone impacts on vegetation in the Mediterranean area is more uncertain as Mediterranean data are still scarce and flux models and/or dose-response functions are still being developed for some crops.

Table 1.1 Critical levels for agricultural and horticultural crops (from LRTAP Convention, 2010).

(a) Flux-based critical levels			
Receptor	**Effect (per cent reduction)**	**Parameter**	**Critical level (mmol m^{-2} PLA)***
Wheat	Grain yield (5%)	POD_6	1
Wheat	1000 grain weight (5%)	POD_6	2
Wheat	Protein yield (5%)	POD_6	2
Potato	Tuber yield (5%)	POD_6	5
Tomato	Fruit yield (5%)	POD_6	2
(b) Concentration-based critical levels			
Receptor	**Effect**	**Parameter**	**Critical level (ppm h)****
Agricultural crops (based on wheat)	Yield reduction	AOT40	3
Horticultural crops (based on tomato)	Yield reduction	AOT40	6
(c) VPD-modified concentration-based critical level***			
Receptor	**Effect**	**Parameter**	**Critical level (ppm h)****
Vegetation (derived for clover species)	Visible injury on leaves	$AOT30_{VPD}$	0.16

* PLA = projected leaf area; ** ppm h = parts per million hour; *** VPD = vapour pressure deficit

1.6 Content of this report

Firstly, we summarise current knowledge of the physiological basis of ozone damage to crop yield and quality (Chapter 2), followed by maps of the stomatal ozone flux to wheat and tomato within Europe and yield and monetary losses quantified for the years 2000 and 2020 (Chapter 3). An assessment of the relative sensitivity of different crops based on an analysis of published data is provided in Chapter 4 and a review of ozone impacts on food and feed quality in Chapter 5. Future concerns are considered further in a review of ozone impacts in a changing climate, focussing on ozone and drought interactions (Chapter 6). Regional variations in current and future concerns about ozone impacts on the security of food supplies are covered by assessments of effects in northern and southern Europe (Chapter 7) together with examples of risk assessment at the national scale for the UK, and the local scale for the Federal State of Saxony in Germany (Chapter 8). We also describe the evidence for ozone impacts in south Asia where rapid industrialisation and economic growth has resulted in increased emissions of ozone precursors and hence elevated ozone concentrations (Chapter 9). In this region, there is evidence to show that current ambient ozone concentrations are impacting on staple food crops, with effects likely to worsen in future years. In the final chapter, we summarise the evidence provided in this report together with that from global assessments of ozone impacts on the security of food supplies, and consider the policy implications of the findings from this study.

2. How does ozone decrease the availability of food?

Sally Wilkinson, Karine Vandermeiren, Felicity Hayes, Bill Davies and Gina Mills

2.1 Transfer of ozone into crop plants

The first stage in impacting on crop production is the transfer of ozone through the atmosphere and into the plant via the thousands of microscopic stomatal pores on the leaf surface. Firstly, atmospheric processes above the plant canopy such as wind turbulence and the roughness of the terrestrial landscape control the transfer of ambient ozone towards the vicinity of the leaf surface. At the leaf surface the thickness and resistance of the boundary air layer around the leaf to ozone transfer depends primarily on wind speed and leaf characteristics such as orientation, size, shape and hairiness. Once through the boundary layer, ozone entry into the plant is dependent upon how open the stomatal pores are. The stomata normally open or close to control CO_2 exchange with the outside air during photosynthesis and respiration, and/or to control water loss from the plant, depending on environmental conditions. Thus, the more open the stomata are, the more ozone will enter the plant. Stomatal flux of ozone is not only determined by the ozone concentration in ambient air but also by other factors such as light, air temperature and humidity (vapour pressure deficit: VPD), soil water potential (SWP) or plant available water (PAW), and plant developmental stage (phenology). It is modelled using the algorithm contained in Box 2.1 incorporating species-specific parameterisations for the effects of the various climatic, soil water and growth stage factors on the maximum stomatal conductance (LRTAP Convention, 2010).

2.2 Ozone damage to plant cells leading to visible injury and early leaf die-back

Inside the plant, ozone interacts with the aqueous contents of the sub-stomatal pore and with adjoining cell membranes and walls, to form reactive oxygen species (ROS) such as hydrogen peroxide, superoxide, and hydroxyl radicals (reviewed in Fiscus et al., 2005). This induces a chain reaction whereby further ROS are formed within adjoining cells. Plants have a limited ability to detoxify ROS by “mopping up” or scavenging them via antioxidants such as superoxide dismutase. The ROS that remain unscavenged can cause a variety of leaf injury symptoms such as interveinal necrosis, and markings on the upper surfaces of leaves known as stipple, flecking, mottling, yellowing, bronzing, bleaching or tip-burn (e.g. **Figure 1.2**). Affected leaves commonly senesce, wither and fall off the crop plant early. These visible injuries are caused by free-radical induction of unregulated and/or programmed cell death and accelerated senescence and abscission, and evidence is growing that these processes are in part mediated by the plant hormones ethylene, jasmonic acid and salicylic acid (see Fiscus et al., 2005 and Kangasjärvi et al., 2005, for reviews).

2.3 Ozone reduces photosynthesis leading to less seed production and smaller roots

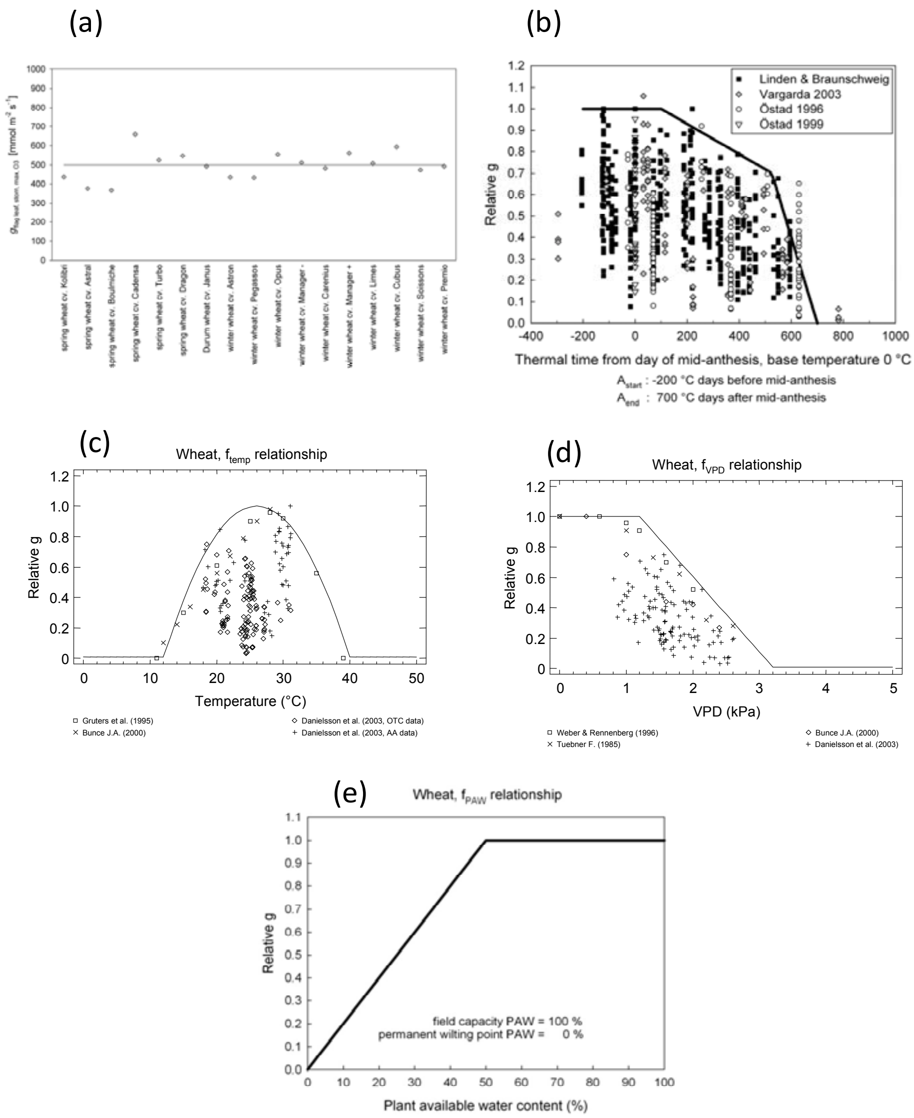
In grain, pod, or tuber crops, visible leaf damage can also contribute to reduced yield by reducing the amount of leaf area available for carbon fixation for further biomass growth and grain filling. However, effects on leaf functioning may not always be visible. Loss of photosynthetic capacity is an early effect of ozone exposure and is sometimes the only physiological symptom of damage during prolonged exposure to modest ozone concentrations (e.g. Fiscus et al., 2005). In part, this is due to a decrease in the amount and activity of the CO_2 fixating enzyme ribulosebiphosphate carboxylase (Rubisco) (Lehnherr et al., 1988; McKee et al., 1995) and in part it is due to accelerated senescence, with a down-regulation of photosynthetic genes and an up- regulation of genes involved in programmed cell

Box 2.1: Calculating the stomatal flux of ozone

Stomatal flux of ozone for an upper canopy sun-lit leaf is modelled using a multiplicative algorithm adapted from Emberson et al. (2000a) that incorporates the effects of air temperature (f_{temp}), vapour pressure deficit of the air surrounding the leaves (f_{VPD}), light (f_{light}), soil water potential (f_{SWP}) or plant available water content (f_{PAW}), plant phenology (f_{phen}) and ozone concentration (f_{ozone}) on the maximum stomatal conductance (g_{max}, mmol O_3 m^{-2} projected leaf area (PLA) s^{-1}), i.e. the stomatal conductance under optimal conditions (see figures). The algorithm has the following formulation:

$$g_{sto} = g_{max} * [\min(f_{phen}, f_{O3})] * f_{light} * \max\{f_{min}, (f_{temp} * f_{VPD} * f_{SWP})\}$$

where g_{sto} is the actual stomatal conductance of ozone (mmol O_3 m^{-2} PLA s^{-1}). The parameters f_{phen}, f_{O3}, f_{light}, f_{temp}, f_{VPD} and f_{SWP} or f_{PAW} are all expressed in relative terms (i.e. they take values between 0 and 1 as a proportion of g_{max}), with f_{PAW} replacing f_{SWP} for wheat only, see figures below. Stomatal flux of ozone is estimated at the leaf level using the DO_3SE model (Deposition of Ozone for Stomatal Exchange) which is available in downloadable form at http://sei-international.org/do3se. The DO_3SE model estimates stomatal ozone flux as a function of the ozone concentration at the leaf boundary layer, the transfer of ozone across this boundary layer, stomatal conductance to ozone (g_{sto}) and ozone deposition to the leaf cuticle. Further details of the algorithms used in this calculation can be found in LRTAP Convention (2010).



The flux parameterisation for wheat: (a) derivation of g_{max}, the maximum stomatal conductance; (b) f_{phen}, the effect of phenology on relative stomatal conductance (g); (c) f_{temp}, the effect of temperature on relative g; (d) f_{VPD}, the effect of vapour pressure deficit on relative g; (e) f_{PAW}, the effect of plant available water in the soil on relative g (LRTAP Convention, 2010).

death and/or tissue senescence. Inhibition of CO_2 assimilation can also result from direct or indirect inhibition of stomatal opening (Saurer et al., 1991; Torsethaugen et al., 1999; Evans et al., 2005; Overmyer et al., 2008). On the other hand, recent studies have indicated that ozone might actually cause stomata to close less sensitively under certain environmental conditions, in particular during periods of drought (e.g. Mills et al., 2009), which reduces plant stress tolerance, and which might be regulated by ozone effects on the concentration of plant hormones such as ethylene and abscisic acid (ABA; Wilkinson and Davies, 2009, 2010, also see Chapter 6).

Reductions in carbon acquisition are likely to result in a reduction of whole plant biomass, inducing yield reductions in crops by reducing the availability of leaf surface area to fix and provide carbon for reproductive parts. **Figure 2.1** shows the various contributions to the reduced availability of carbon for grain or pod production, stemming from reduced photosynthetic efficiencies, foliar biomasses, root biomasses and/or stomatal conductances, and from reduced partitioning of available carbon to grains in favour of synthesis of protective chemicals (Betzelberger et al., 2010). Within the context of reduced carbon provision, it is also important to note that ozone accelerates phenological development (e.g. Gelang et al., 2000). For example, maturity can be advanced by days or weeks in rice (cultivar dependent), with early flowering being a well-known ozone response, but this does not always correlate to effects on final plant biomass or yield (Shi et al., 2009).

The often observed ozone-induced reduction in root biomass (Grantz et al., 2006) is understood to arise either from a reduction in carbon translocation from the shoot to the root via the phloem (either due to reduced availability of carbon at the source or as a result of the blockage of phloem sieve plates with callose tissue (Asensi-Fabado et al., 2010)), or from an effect of ozone on the concentrations of plant hormones such as ethylene that control root growth (hypothesized in Wilkinson and Davies, 2010). Ozone-induced reductions in root biomass indirectly affect shoot biomass and therefore seed (grain/pod) production via a reduction in the ability of the plant to take up the nutrients and water required to sustain growth and yield. Reductions in root biomass directly affect the yield of root crops such as potato, carrot, turnip and sugar beet.

Many experiments have been conducted to quantify impacts of ozone on yield quantity (see Chapter 4), the direct consequence of ozone-induced reductions in photosynthesis and photosynthate allocation to the reproductive structures. Ozone also impacts on the quality of feed and food crops by reducing, for example, the protein yield or sugar content of seeds and tubers (see Chapter 5).

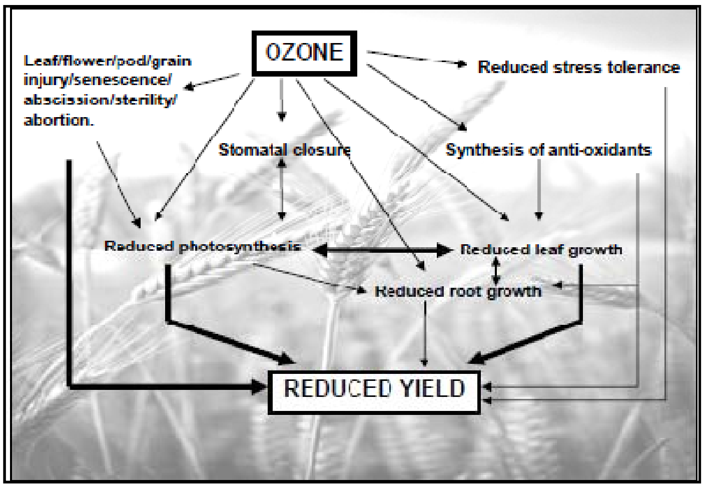


Figure 2.1 The processes involved in ozone-induced reductions in crop yield (reproduced from Wilkinson et al., 2011).

2.4 Ozone interferes with plant hormonal control of growth and stomatal functioning

It has long been known that ozone increases the generation of the gaseous stress hormone ethylene from the leaves of sensitive plants, and there is much data demonstrating that sensitivity to ozone is linked to the extent of ethylene generation by leaf tissue, usually with respect to foliar injury or senescence responses (Diara et al., 2005; Nunn et al., 2005; Overmyer et al., 2003; Sinn et al., 2004; Tamaoki et al., 2003). Ethylene can directly reduce shoot growth, root growth and yield components, and speed up senescence, abscission and phenological development (Abeles et al., 1992; Morgan and Drew, 1997; Pierik et al., 2007; Wilkinson and Davies, 2010). Ethylene has been implicated in stomatal opening, inhibition of abscisic acid (ABA)-induced closure, and in closure (Wilkinson and Davies, 2009, 2010).

Root-sourced signals of soil drying, such as increased ABA concentrations, interact with signals that arise in shoots in response to conditions within the aerial environment: VPD, light, CO_2, temperature, and air-borne pollutants such as ozone (Wilkinson and Davies 2002, 2009, 2010). Signals from the aerial environment directly affect concentrations of chemical signalling molecules such as ABA and ethylene, but also affect the sensitivity of guard cells, leaf cells and/or cells of reproductive organs to a given concentration of ABA or ethylene. Recently, Wilkinson and Davies (2009) hypothesized that an ozone-induced up-regulation of ethylene could be responsible for the observed reduction in stomatal sensitivity to ABA, drought and other closing stimuli observed in plants exposed to ozone. They suggested that some of the crops in which ozone is known to up-regulate ethylene production are more susceptible to ozone damage via disruption of the stomatal signalling mechanism. These crop species include varieties of pea and pinto bean (Mehlhorn et al., 1991), potato (Sinn et al., 2004), tomato (Bae et al., 1996), snap bean (Elagoz and Manning, 2005) and some wheat and rice cultivars (Tiwari et al., 2005). Variable ethylene production may explain some of the genetic variability in ozone susceptibility of crops (see Chapter 4).

2.5 Are crops more sensitive to ozone at certain growth stages?

The timing of ozone exposure in relation to the developmental stage of the crop may influence the size and nature of the response. Some studies suggest that ozone exposure in either the vegetative or the reproductive stages can cause the deleterious effects of ozone on plant productivity and yield (e.g. Heagle, 1989; Mulholland et al., 1998; Pleijel et al., 1998), whilst others show that the sensitivity of seed crop yield to ozone is greatest during the period between flowering and seed maturity (e.g. Lee et al., 1988; Soja and Soja, 1995). Singh and Agrawal (2010) showed that the presence of ethylene diurea (EDU – a compound that can be used to protect plants against ozone damage that is used as an experimental tool rather than a yield enhancer for practical reasons) was necessary at all stages of wheat crop production, in order to prevent ozone-induced yield reduction, implying that ozone effects on yield were cumulative throughout plant development. This is likely to vary genotypically, however, and there is still much evidence to suggest that ozone episodes that coincide with flowering and seed set are particularly deleterious. For several species including bean and wheat it has been demonstrated that ozone exposure around the time of anthesis can have a larger effect than exposure of the same magnitude at an earlier or later developmental stage (e.g. Soja et al., 2000), although ozone exposure during pod development or grain filling can also have a large influence, possibly due to reduced assimilate available for repair during this time (Tingey et al., 2002). Yield reductions in wheat due to ozone exposure have been demonstrated to be related to a reduced duration of grain filling (Gelang et al., 2000).

2.6 Why are some crops more sensitive to ozone than others?

The range of ozone sensitivity of crops is described in detail in Chapter 4, an update of Mills et al. (2007). In summary, some of our most important staple food crops are sensitive to ozone pollution, including wheat, rice and soybean, whilst other crops such as barley are relatively resistant. In this section, we provide a brief overview of the physiological basis of this range in sensitivity.

Crops can be sensitive to ozone regarding the visible injury symptoms seen on foliage at early growth stages, but apart from in foliage crops (such as leafy salad crops and alfalfa) this does not necessarily give rise to an equivalent negative impact on grain/pod/fruit yield in fully developed crops. In fact Sawada and Kohno (2009) have shown in rice, and Picchi et al. (2010) in wheat, that cultivars in which grain yields are most impacted by ozone are those which showed the least visible injury symptoms to foliage. Picchi et al. (2010) proposed that this may be related to genotypic variation in the extent of the stomatal closure response to ozone. Cultivars where ozone closes stomata could be said to be relatively ozone insensitive in reference to visible injury, as the ozone flux will be reduced subsequent to this closure, preventing further foliar injury. However prolonged stomatal closure reduces C fixation (see **Figure 2.1**), and thereby the amount of assimilate available for grains/pods/leaves, thus these cultivars may be more sensitive to ozone in terms of grain yield.

Some of the variability in ozone tolerance has been attributed to the levels of detoxifying antioxidants and free radical scavengers present in and/or generated by certain genotypes in response to ozone stress, since ROS produced in ozone-polluted plants mediate many of the damaging effects of ozone (e.g. Frei et al., 2008, 2010). Plants possess a wide range of ROS detoxification mechanisms. These include production or reduced catabolism of low molecular weight antioxidants such as ascorbic acid (AsA), glutathione, tocopherol, carotenoids, flavonoids, and phenolics that can detoxify ROS directly. Alternatively, ROS can be detoxified through scavenging enzymes such as superoxide dismutase (SOD), catalase, or peroxidases (Blokhina et al*.*, 2003). The level of AsA and its redox state have been shown to be important for efficient ozone detoxification (Conklin and Barth, 2004), and high activities of some antioxidant enzymes can protect leaves from visible ozone damage, including monodehydroascorbate reductase (MDHAR) (Eltayeb et al*.*, 2007) and SOD (Van Camp et al*.*, 1994). Naturally occurring genetic variation in ozone tolerance of visible leaf injury in rice was dissected into two distinct quantitative trait loci (QTLs; Frei et al., 2008). These were developed into two chromosome segment substitution lines (Frei et al., 2010). Possible tolerance mechanisms of the tolerant line, SL41, were found to be related to lower expression of genes encoding ascorbate oxidase, and AsA catabolism was proposed to be reduced in tolerant lines, which had higher concentrations of apoplastic AsA when exposed to ozone. Genes related to ethylene and jasmonic acid metabolism were also differentially regulated between the tolerant and sensitive lines.

Alternatively, or in addition, some of the variability in the susceptibility of wheat and rice varieties to ozone has been linked to the inherent rate of stomatal conductance in each. In general, modern cultivars released in the last two decades are the most vulnerable to ozone, and these also display the greatest stomatal conductances (Biswas et al., 2008a,b), perhaps as breeding for high yield has a functional link to increased stomatal CO_2 influx. Studies have also shown that the ozone-sensitive biotype of white clover used in the ICP Vegetation biomonitoring surveys has a higher stomatal conductance than the resistant biotype (Wilkinson et al., 2011).

Flowers et al. (2007 – snap bean), Betzelberger et al. (2010 – soybean) and Pang et al. (2009 – rice) amongst others, have determined that genetic variability in ozone susceptibility in terms of yield is related to direct ozone effects on photosynthetic processes. However it is important to note that genetic variability in photosynthetic capacity will, to some extent, depend on genetic variability in both stomatal conductance-related parameters, and on genetic variability in the efficiency of ozone detoxification, as the amount of ROS that arrives at the photosynthetic apparatus is a function of both stomatal conductance and detoxification.

As described above, many crop species have been shown to respond to ozone by emitting more gaseous ethylene from shoot tissues. A role for ethylene in genetic variability in ozone sensitivity in terms of visible injury has previously been demonstrated in *Arabidopsis* and poplar (Overmyer et al., 2003, and see Wilkinson and Davies, 2009). Several of the mutants and *Arabidopsis* accessions originally described as being ozone-sensitive regarding leaf injury have now been shown to be ethylene over-producers (see Kangasjärvi et al., 2005), and ethylene-insensitive *Arabidopsis* mutants are ozone tolerant.

2.7 Are modern varieties more tolerant of ozone?

Most people assume that modern varieties are likely to be relatively resistant to ozone because they have been selected in an ozone rich environment during breeding programmes. However, several studies have shown that this is not likely to be the case as the modern varieties tend to have higher stomatal conductances to maximize CO_2 uptake for growth which also means that they have greater ozone uptake.

In Sweden the modern wheat cultivar ‘Dragon’ was more sensitive to ozone than the 100-year old cultivar ‘Lantvete’ (Pleijel et al., 2006) and ozone exposure to approximately 50 ppb resulted in a decrease in yield of approximately 20% for `Lantvete’ and 40% for ‘Dragon’. Although not included in the database for the current study of crop sensitivity to ozone due to the short, high ozone exposure used, it has been shown that elevated ozone had a larger impact on the high-yielding modern wheat variety ‘Yannong 19’, released in the 1990’s, compared to ‘Nongda 311’ released in the 1960’s (Xu et al., 2009). In the study of Xu et al. (2009) a few days of high ozone exposure resulted in decreased stomatal conductance and maximum photochemical efficiency in both varieties, with a larger decline for ‘Yannong 19’. Similarly a study of the response to ozone of 10 cultivars of wheat bred and introduced in Greece between 1932 and 1980 showed that the modern varieties were more sensitive (in terms of relative growth rate) (Barnes et al., 1990). The authors suggest that there may have been inadvertent selection of more sensitive varieties by breeders, and although the trait that may have correlated with increased sensitivity was not identified they hypothesise that new varieties may have increased stomatal conductance to increase yield. This was also suggested in a study using 20 wheat cultivars released over a 60-year time-span in China, where there was increased sensitivity to ozone with the more modern varieties (Biswas et al., 2008b). This corresponded with increased stomatal conductance and alterations in antioxidant capacity of the newer varieties.

Overall, there are no indications that modern crop cultivars, bred under higher ozone concentrations than decades ago, are more tolerant to ozone. This suggests that in wheat, for example, selection for higher yield has also led to selection for characteristics associated with greater ozone sensitivity.

2.8 Is it possible to prevent or reduce ozone damage to crops?

Strategic irrigation management. In some cases deficit irrigation (or shifting crop growth calendars to somewhat drier ends of the growing season) can close stomata and reduce ozone flux into plants, thereby reducing impact. For example, farmers in Cuba have been successful in reducing ozone damage by withholding irrigation from leaf crops such as salad lettuce and tobacco for a day or two prior to the onset of a forecasted ozone episode, in order to reduce the ozone dose that the plants receive. However this approach is only sometimes successful as a yield protectant as some genotypes exhibit uncoupling between drought signals and adaptive plant responses (stomatal closure and reduced leaf surface area). It should also be considered that prolonged stomatal closure will compromise carbon gain reducing yield and/or that maintaining soil water deficits may increase crop vulnerability to co-occurring stresses such as wind, biotic attack or high VPD.

Selection of ozone tolerant traits and genotypes. As described above, many of the modern cultivars of crops have been selected because of increased carbon assimilation and yield which has inadvertently led to selection for ozone susceptibility. Nevertheless, the scatter within dose-response relationships (see Chapters 3 and 4) for a given ozone flux/AOT40 provides evidence that there is scope for improving ozone tolerance by careful genotype selection. Within the horticultural industry, some farmers in southern Europe are already selecting cultivars that are less susceptible to visible injury. However, care must be taken not to directly link tolerance to foliar injury with tolerance to yield reductions in agricultural crops as the two are not usually linked. More effort is needed to screen local cultivars and those being developed for use for ozone sensitivity, in areas of high ozone pollution in order to identify the most resistant varieties whilst keeping in mind that resistant varieties may not be the ones giving the highest yields.

Chemical protection. Over recent decades several possible protectants have been used as research tools and in biomonitoring programmes. The most commonly used chemical is the antioxidant EDU ((*N*-[2-(2-oxo-1-imidazolidinyl) ethyl]-*N*-phenylurea)), a chemical that provides protection against ozone when applied in appropriate quantities (dependent upon species and cultivar) as a soil drench, foliar spray, stem injection or gravitational infusion at frequent intervals over the crop growth period (Feng et al., 2010). This chemical was used extensively by the ICP Vegetation in the 1990s to indicate the areas in Europe where ambient ozone was damaging to crops (Benton et al., 2000) and has since been used by the APCEN network in Asia (see Chapter 9). There is limited scope, however, for this chemical to be used commercially within an agricultural environment due to problems with EDU uptake and high and repeated rates of application. Several fungicides, especially those within the benzimidazole group have also been shown to reduce ozone impacts (Sanders et al., 1993). The most promising of these was benomyl which is now banned from use in most countries due to health concerns. In addition, chemicals that prevent ethylene from binding are showing promise as protectants. Given the current and projected increased likelihood of ozone impacts on crop production described in this report, there is clearly scope for the development of chemical protectants against ozone effects.

3. Quantification of economic losses due to ozone impacts on crop yield in Europe

Gina Mills, David Norris, David Simpson, Harry Harmens, Steve Cinderby and Howard Cambridge

3.1 Introduction

A recent ICP Vegetation study indicated that in Europe over 30 crop species growing in commercial fields in 16 countries showed visible ozone injury symptoms and other negative effects of ozone such as biomass/yield reduction during the period 1990 to 2006 (Hayes et al., 2007, Mills et al., 2011b). As well as the effects on crops expected from the higher ozone concentrations in southern and parts of central Europe (**Figure 1.1**), effects of ozone were found in northern Europe where concentrations were comparatively low but climatic conditions were conducive to high ozone uptake (flux). Data from surveys, ozone exposure experiments and epidemiological studies were recently critically evaluated leading to agreement on revised critical levels for crops (described in Section 1.5). The ICP Vegetation Task Force recommended to the LRTAP Convention that risk assessments for ozone effects on vegetation, including crops, should be conducted using the flux-based methodology whereby ozone uptake by the stomatal pores is modelled using ozone concentration, climatic conditions (temperature, humidity, light), soil moisture and plant growth stage. In this chapter, we present a first economic impact analysis for crops in Europe using the flux-based methodology.

All previous European assessments have been based on either the 24h or 7h mean ozone concentration or AOT40. These ozone metrics only take into account the ozone concentration in the air above the leaves of crops and not the uptake or flux of ozone. In a study conducted using the AOT40 metric for the ICP Vegetation, Holland et al. (2006) predicted that total crop losses across 47 LRTAP Convention countries were €6.4 billion (90% confidence interval of 4.5 to 9.3) in 2000 falling to 4.5 and 1.7 billion Euro for the 2020 baseline scenario and the RAINS model maximum feasible reduction scenario respectively. Yield losses for wheat and tomato were predicted to be 23.5% and 15.2% in 2000 respectively. Ozone impacts on crops in Europe have also been predicted using AOT40 as part of global impact studies, for example, Avnery et al.(2011a) predicted that for EU-25 wheat yield losses were 12.1% rising to 16.9% in 2030 using the IPCC A2 scenario (Avnery et al., 2011b). Van Dingenen et al. (2009) indicated that ozone effects on maize, wheat, rice and soybean in EU-25 resulted in losses of $US 0.86 to 1.05 million. A meta-analysis of published data on ozone effects on crops compared effects of current (31 – 50 ppb) and future (51 – 75 ppb) ozone against a baseline ozone concentration of <26 ppb (Feng et al., 2009). Losses in current ozone were indicated to be for potato 5.3%, barley 8.9%, wheat 9.7%, rice 17.5%, bean 19.0%, soybean 7.7%, and 10% higher for soybean, wheat and rice and 20% higher for bean in the concentration range predicted for 2030. These studies all indicate that current and future ozone concentrations are detrimental to crops in Europe, with substantial economic losses likely.

In this study, we used the flux-based approach to quantify impacts of ozone on the economic value of wheat and tomato for 2000 and 2020 using the current legislation scenario (NAT scenario) developed as part of the negotiations for the review of the Gothenburg Protocol. Thus, for the first time, economic impacts have been quantified using the flux approach recommended within the Modelling and Mapping Manual (LRTAP Convention, 2010). We consider here only the impacts on yield quantity, but effects on yield quality as described in Chapter 5 will also have economic implications. Maps of percentage crop losses are also provided for potato, oilseed rape, sugar beet, maize and barley determined using AOT40 but, in accordance with the Modelling and Mapping Manual's recommendations, no economic losses were calculated. The study was conducted for the Parties to the LRTAP Convention that represent EU27 plus Switzerland (CH) and Norway (NO).

3.2 Quantification methods

To calculate the impacts of ozone on wheat and tomato production in Europe, several sources of information were drawn together:

Land cover and yield data: The LRTAP Convention's harmonised land cover map (formerly the SEI European Land Cover Map, 2006 Revision; Cinderby et al., 2007) was used to define agricultural land (EUNIS code - I1: Arable land and market gardens). The data within the land cover map was compiled from a mixture of existing digital and paper sources including the European Environment Agency (EEA) Corine Land Cover 2000, SEI European Land Cover Map (2002 Revision), FAO Soil Map of the World and the EEA European Biogeographical regions (2005). The IGBP Global Land Cover agricultural data was used to differentiate types of agricultural land. Firstly, the agricultural classification information was extracted from the full GLC classification. From this subset a thiessen polygon map was generated of the dominant agricultural classes across Europe. This was overlaid with the original agricultural polygon boundaries to identify the most likely agricultural class for all locations in Europe. The LRTAP Convention map identified where agricultural land existed with the IGBP classification identifying the most likely types of crop existing within these locations (for example, “Cropland (Winter Wheat, Small Grains)". For mixed land use IGBP polygons it was assumed the agricultural component occupied the entire LRTAP Convention polygon. For example, "Cropland (Rice, Wheat) with Woodland" was reclassified to indicate “Rice, Wheat” production. Crop types and areas were summed for each NUTS3 region and converted to the EMEP 50 x 50 km grid square. Yield data collected in this exercise was mainly for 2007, with data from the nearest other year available used where 2007 data was missing. Yield data was then converted to that for 2000 using a country-specific conversion factor, with the 2000 yield data also being used to quantify impacts in 2020.

Ozone flux modelling: The EMEP Eulerian model maps ozone concentrations and fluxes on a grid of ca. 50 km x 50 km grid. Described by Simpson et al. (2003, 2007) and references therein, the EMEP model simulates the emissions, transport, transformation and removal of pollutants, and includes the calculation of ozone fluxes using a version of the Deposition of Ozone for Stomatal Exchange (DO_3SE model, described in Emberson et al. (2000b), available at http://sei-international.org/do3se). Ozone flux and AOT40 maps were supplied by EMEP on a 50 km x 50 km grid for the years 2000 and 2020 using the national projections (NAT) scenario. The latter are based on either national energy and agricultural projections, updated in 2009 (12 EU member states, plus Switzerland and Norway) or 2008 PRIMES model energy projections with the EU climate and energy package and the 2009 CAPRI agricultural projections (15 EU member states) (Minutes of 37th TFIAM meeting, February, 2010).

As far as currently possible, the flux parameterisation matched that described within the Modelling and Mapping Manual (LRTAP Convention, 2010), with the exception that soil moisture was assumed to be non-limiting for both wheat and tomato. This assumption is appropriate for tomato as the crop is usually irrigated, but may lead to unquantifiable uncertainty for wheat as soil moisture availability may be limiting to ozone uptake in some areas, especially in southern Europe. A soil moisture module for the EMEP model is currently under development. AOT40 maps for the wheat time interval were used to give an indication of effects on yield for the other crops.

Yield response functions: For wheat and tomato, the flux-based yield response functions used were those from the Modelling and Mapping Manual and reproduced in **Figure 3.1**. For other crops, updated functions from Mills et al. (2007) were used incorporating new data published since then (**Figure 3.2**). For all of these functions, for each individual study and variety within a study, regression analysis of yield versus ozone exposure (POD_6 or AOT40) was used to calculate the absolute yield at zero ozone exposure. The relative yield for each ozone treatment used was then calculated in relation to this absolute yield with a value of less than one indicating that there was a reduction in yield. For each crop, relative yield was plotted against POD_6 or AOT40 using data from all relevant experiments, to determine a dose-response relationship; a linear dose-response relationship was assumed.

Economic valuation: For wheat and tomato, the mean value in Euro per tonne for EU27+CH+NO in the year 2000 was used (http://epp.eurostat.ec.europa.eu). For wheat, the producer price for soft wheat of €11.89 per 100 kg was used, which was ca. 10% lower than the mean price in the period 2000 - 2009 of €12.78 per 100 kg (range €10.12 to €18.41). For tomato, the producer price for tomatoes grown in the open was used, with the value in 2000 of €45.52 per 100 kg being very close to the mean for the period 2000 – 2009 of €44.90 per 100 kg (range €36.15 to €58.92).

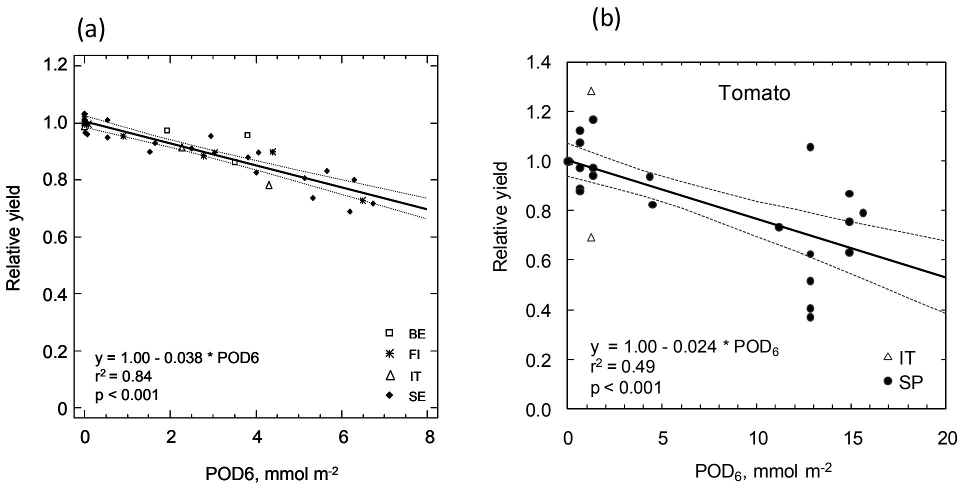


Figure 3.1 The relationship between the relative (a) seed yield of wheat and (b) fruit yield of tomato and POD_6 for sunlit leaves based on data from BE: Belgium, FI: Finland, IT: Italy, SP: Spain and SE: Sweden. The dashed lines are the 95% confidence intervals.

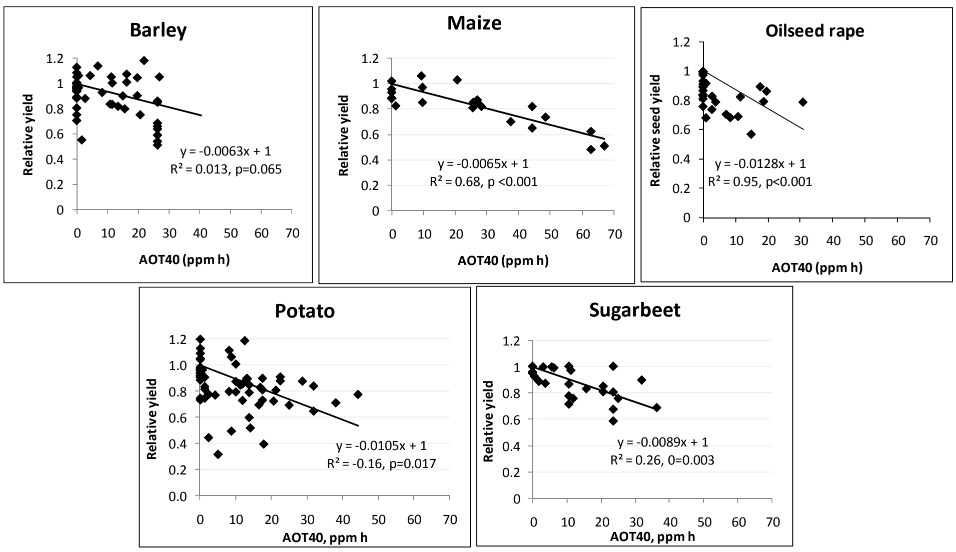


Figure 3.2 AOT40 – response functions for barley, maize, oilseed rape, potato and sugar beet. Functions are updated from Mills et al. (2007) using more recently published data where available (see Chapter 4 for further details).

For each crop, the following maps were generated:

1. Crop distribution. The 50 x 50 km grid squares for which there is production for the particular crop is shown in all of the maps. Different cut-off values (e.g. >1 tonne for tomato) were used for each crop dependant on the intensity of production across Europe.

2. Crop production data as tonne/grid square.

3. Ozone flux (POD_6) or AOT40.

4. Percentage yield loss, calculated for each square using the response function. The same scale is used on all maps to allow comparison across crops.

5. Crop loss in tonnes per grid square. This was calculated by assuming that the yield recorded in a grid square had been affected by ozone.

6. Economic loss in € per grid square (calculated as value in €/tonne in 2000 multiplied by crop loss in tonnes). The maps show losses per grid square for those squares the crop is present in (as defined in step 1). Summed values for Europe include crop losses for all squares, including those with the area of production is below the relevant cut-off value whereas mean % crop loss figures are for those squares where the crop is mainly grown (as defined at step 1).

3.3 Economic losses for wheat

The year 2000 AOT40 map for wheat shows a clear north-south gradient of ozone (**Figure 3.3a**), with the highest values (AOT40 > 7.5 ppm h) in Italy and southern parts of several countries including France, Spain and Austria. The area of highest POD_6 (> 5 mmol m^{-2}) spreads much further north covering large areas of Germany, eastern France and areas of southern UK, Denmark and Sweden (**Figure 3.3c**). Assuming full implementation of current legislation by the year 2020, ozone concentrations above 40 ppb are predicted to fall (Van Aardenne and Streets, 2011) as reflected in the lower AOT40 values across Europe shown in the EMEP map (**Figure 3.3b**). In contrast, POD_6 values are predicted to remain within the mid-range (3 - 5 mmol m^{-2}) in areas such as Germany, Belgium, north-eastern France and sourthern UK, and in the highest range (> 5 mmol m^{-2}) in parts of Italy, Greece and southern Spain and France (**Figure 3.3d**).

As the regions of medium-high flux coincided with the areas of highest wheat production in France, Germany, Bulgaria and the UK, the economic impacts were predicted to be greatest in these areas (**Figures 3.4 and 3.5**) with total economic losses predicted to be over €800 million in France in 2000 and > €600 million in Germany. Overall, over 26 million tonnes of wheat production were predicted to be lost due to ozone pollution in EU27+CH+NO in 2000 representing €3.2 billion of lost value (**Table 3.1**). Using the NAT scenario, losses for 2020 were predicted to fall to 16.5 million tonnes, representing €1.96 billion. Between 2000 and 2020 there was only a small fall in the percentage of squares exceeding the critical level of a POD_6 of 1 mmol m^{-2} (from 84.8% to 82.2%). Percentage exceedance for individual countries can be found in **Table 3.2**.

Table 3.1 Predicted impacts of ozone pollution on wheat yield and economic value, together with critical level exceedance in EU27+Switzerland+Norway in 2000 and 2020 under the current legislation scenario (NAT scenario). Analysis was conducted on a 50 x 50 km EMEP grid square using crop values in 2000 and an ozone stomatal flux-based (POD_6) risk assessment.

Wheat	**2000**	**2020**
Total production, million tonnes	133.53	
Total economic value of wheat in 2000, billion Euro	15.87	
Mean % yield loss per grid square	13.66	9.07
Total production loss, million t	26.89	16.45
Total economic value loss, billion Euro	3.20	1.96
Percentage of EMEP grid squares exceeding critical level[2]	84.8	82.2

Table 3.2 Number and proportion of 50 x 50 km grid squares exceeding the POD_6-based critical levels (CL) for wheat (1 mmol m^{-2}) and tomato (2 mmol m^{-2}) yield per country in 2000 and 2020.

	Wheat					Tomato				
		2000		2020			2000		2020	
	no. of grid squares	no. of sq exceeding CL	% exceedance	no. of sq exceeding CL	% exceedance	no. of grid squares	no. of sq exceeding CL	% exceedance	no. of sq exceeding CL	% exceedance
Austria	39	37	94.9	32	82.1	19	14	73.7	11	57.9
Belgium	15	15	100.0	15	100.0	15	15	100.0	13	86.7
Bulgaria	58	58	100.0	58	100.0	50	40	80.0	23	46.0
Cyprus	12	12	100.0	12	100.0	11	11	100.0	11	100.0
Czech R.	37	37	100.0	37	100.0	19	19	100.0	18	94.7
Denmark	37	20	54.1	16	43.2	2	2	100.0	0	0.0
Estonia	4	4	100.0	4	100.0	0	0	0.0	0	0.0
Finland	139	109	78.4	93	66.9	9	0	0.0	0	0.0
France	289	266	92.0	261	90.3	250	220	88.0	105	42.0
Germany	160	151	94.4	151	94.4	82	82	100.0	78	95.1
Greece	113	111	98.2	108	95.6	112	90	80.4	71	63.4
Hungary	53	53	100.0	53	100.0	36	36	100.0	36	100.0
Ireland	49	29	59.2	27	55.1	3	0	0.0	0	0.0
Italy	200	196	98.0	190	95.0	191	162	84.8	132	69.1
Latvia	8	7	87.5	7	87.5	1	0	0.0	0	0.0
Lithuania	35	33	94.3	33	94.3	15	4	26.7	0	0.0
Luxembourg	2	2	100.0	2	100.0	2	2	100.0	2	100.0
Malta	2	2	100.0	2	100.0	2	2	100.0	0	0.0
Netherlands	25	15	60.0	15	60.0	15	15	100.0	14	93.3
Norway	113	10	8.8	4	3.5	4	0	0.0	0	0.0
Poland	149	143	96.0	143	96.0	106	106	100.0	100	94.3
Portugal	60	58	96.7	58	96.7	15	13	86.7	3	20.0
Romania	123	123	100.0	123	100.0	109	102	93.6	73	67.0
Slovakia	20	20	100.0	20	100.0	11	11	100.0	6	54.5
Slovenia	8	8	100.0	8	100.0	8	8	100.0	8	100.0
Spain	290	281	96.9	280	96.6	278	177	63.7	66	23.7
Sweden	108	68	63.0	59	54.6	53	16	30.2	0	0.0
Switzerland	19	12	63.2	10	52.6	11	6	54.5	3	27.3
UK	143	79	55.2	78	54.5	77	19	24.7	0	0.0
TOTAL/mean	**2310**	**1959**	**84.8**	**1899**	**82.2**	**1506**	**1172**	**77.8**	**773**	**51.3**

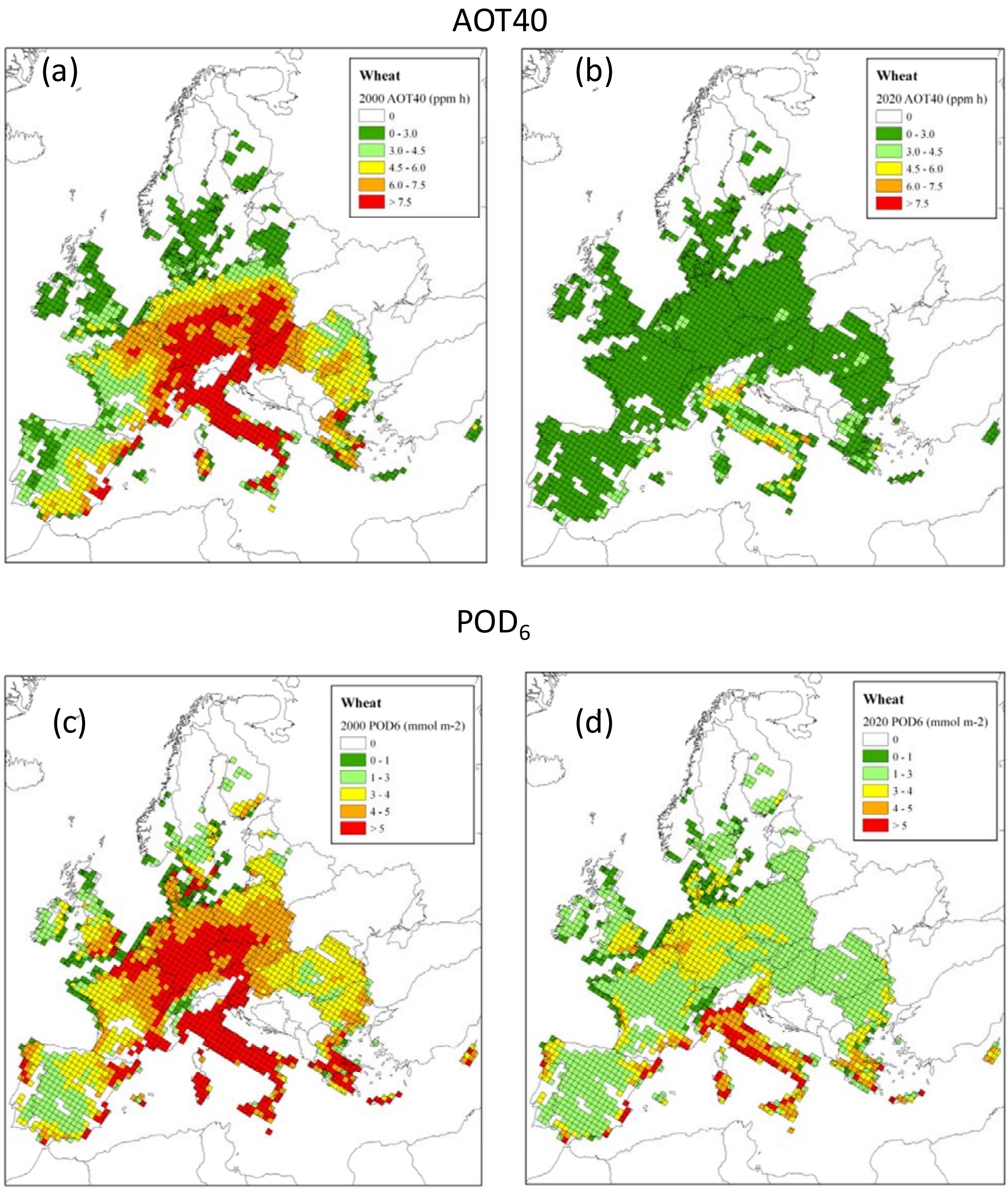


Figure 3.3 AOT40 (ppm h) for (a) 2000 and (b) 2020 and POD_6 (mmol m^{-2}) in (c) 2000 and (d) 2020 for the wheat growing areas of EU27+CH+NO as indicated by the NAT scenario.

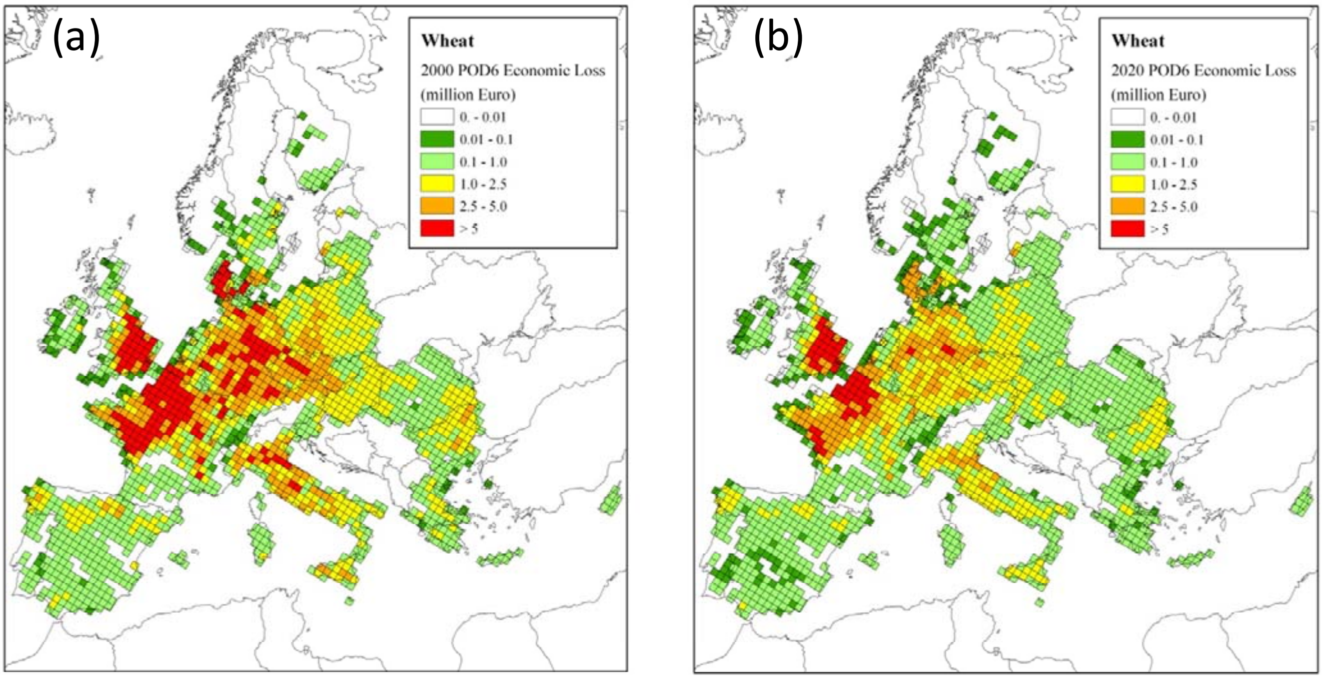


Figure 3.4 Predicted economic losses for ozone effects on wheat in million Euro per 50 x 50 km grid square in (a) 2000 and (b) 2020 for the wheat growing areas of EU27+CH+NO as indicated by the NAT scenario and flux-based methodology.

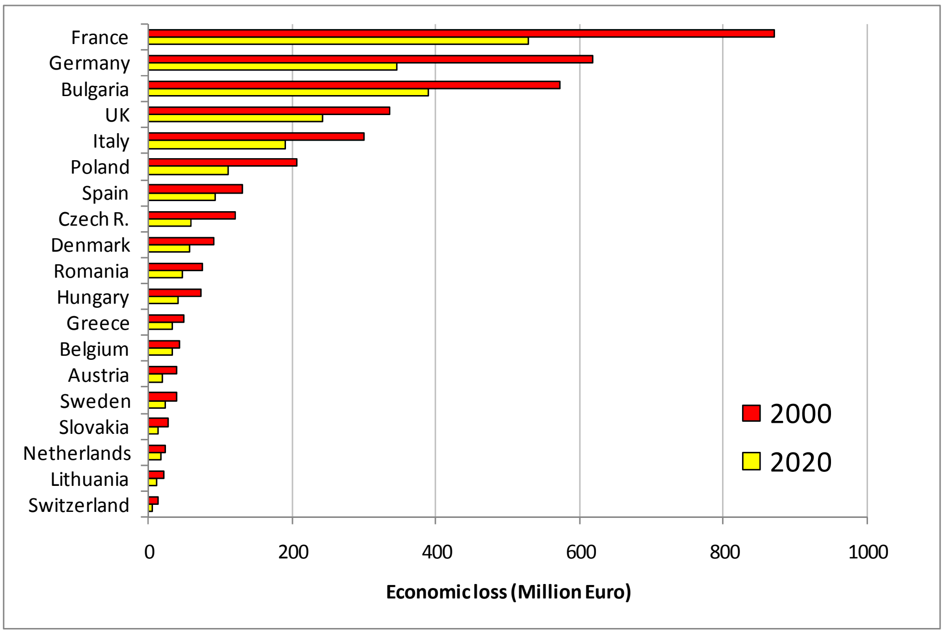


Figure 3.5 Predicted economic losses resulting from effects of ozone on wheat yield in million Euro for countries where losses exceeded €10 million as indicated by the NAT scenario and flux-based methodology.

3.4 Economic losses for tomato

AOT40 values were highest in the tomato growing areas in 2000 in Italy and Slovenia, where values of > 12 ppm h were predicted for approximately two thirds of the tomato-growing grid squares (**Figure 3.6a**). In southern Spain, Greece and parts of France, Hungary, Slovakia, Belgium, Czech Republic and Poland, the AOT40 values exceeded 12 ppm h in a few grid squares and were > 9 ppm h in many other squares. In almost all of these areas, the NAT scenario predicted that AOT40 values would fall significantly to < 9 ppm h, with exceptions being grid squares in northern Italy and some coastal grid squares in Italy (**Figure 3.6b**). For tomato, the areas with the highest AOT40 values in 2000 were approximately the same as the areas with the highest POD_6 values (**Figure 3.6c**). However, by 2020, reductions in POD_6 (**Figure 3.6d**) were less dramatic than predicted reductions in AOT40 (**Figure 3.6b**), with POD_6 values in excess of 6 mmol m^{-2} predicted for parts of Italy, southern Spain, southern France and Greece.

The highest production of tomato in Europe (>100,000 t in some grid squares) is found in Italy, Spain, The Netherlands and Greece. Predicted total economic losses in 2000 due to ozone effects on tomato were highest in Italy where > €700 million of lost income was predicted (**Figure 3.7 and 3.8**). Predicted total losses for Spain and Greece were similar at €110 – 160 million representing 9.6 and 7.0% losses. Due to the lower fluxes predicted for the Netherlands (2 – 6 mmol m^{-2} per grid square) and the lower number of grid squares, economic impacts were lower at €23 million but nevertheless representing 10.6% losses in 2000. Losses were predicted to be <€1 million in 12 countries. Predicted losses remained at >€5 million for several grid squares in Italy in 2020, but generally were <€2.5 million per EMEP grid square in most of the tomato growing areas.

Overall, this analysis predicted that ozone pollution caused €1.02 billion economic losses for tomato in 2000 representing an average of 9.4% loss per tomato-growing grid square (**Table 3.3**). By 2020, these losses were predicted to fall to €0.63 billion representing 5.7% loss in crop value. Exceedance of the POD_6-based critical level of 2 mmol m^{-2} for tomato was predicted to decrease from 77.8% in 2000 to 51.3% in 2020. Percentage exceedance for individual countries can be found in **Table 3.2**.

Table 3.3 Predicted impacts of ozone pollution on tomato yield and economic value, together with critical level exceedance in EU27+Switzerland+Norway in 2000 and 2020 under the current legislation scenario (NAT scenario). Analysis was conducted on a 50 x 50km EMEP grid square using crop values in 2000 and an ozone stomatal flux-based (POD_6) risk assessment.

Tomato	**2000**	**2020**
Total production, million tonnes	17.68	
Total economic value of tomato in 2000, billion Euro	6.85	
Mean % yield loss per grid square[1]	9.4	5.7
Total production loss, million t	2.64	1.62
Total economic value loss, billion Euro	1.02	0.63
Percentage of EMEP grid squares exceeding critical level[1]	77.8	51.3

[1] based on grid squares with > 1 tonne of production

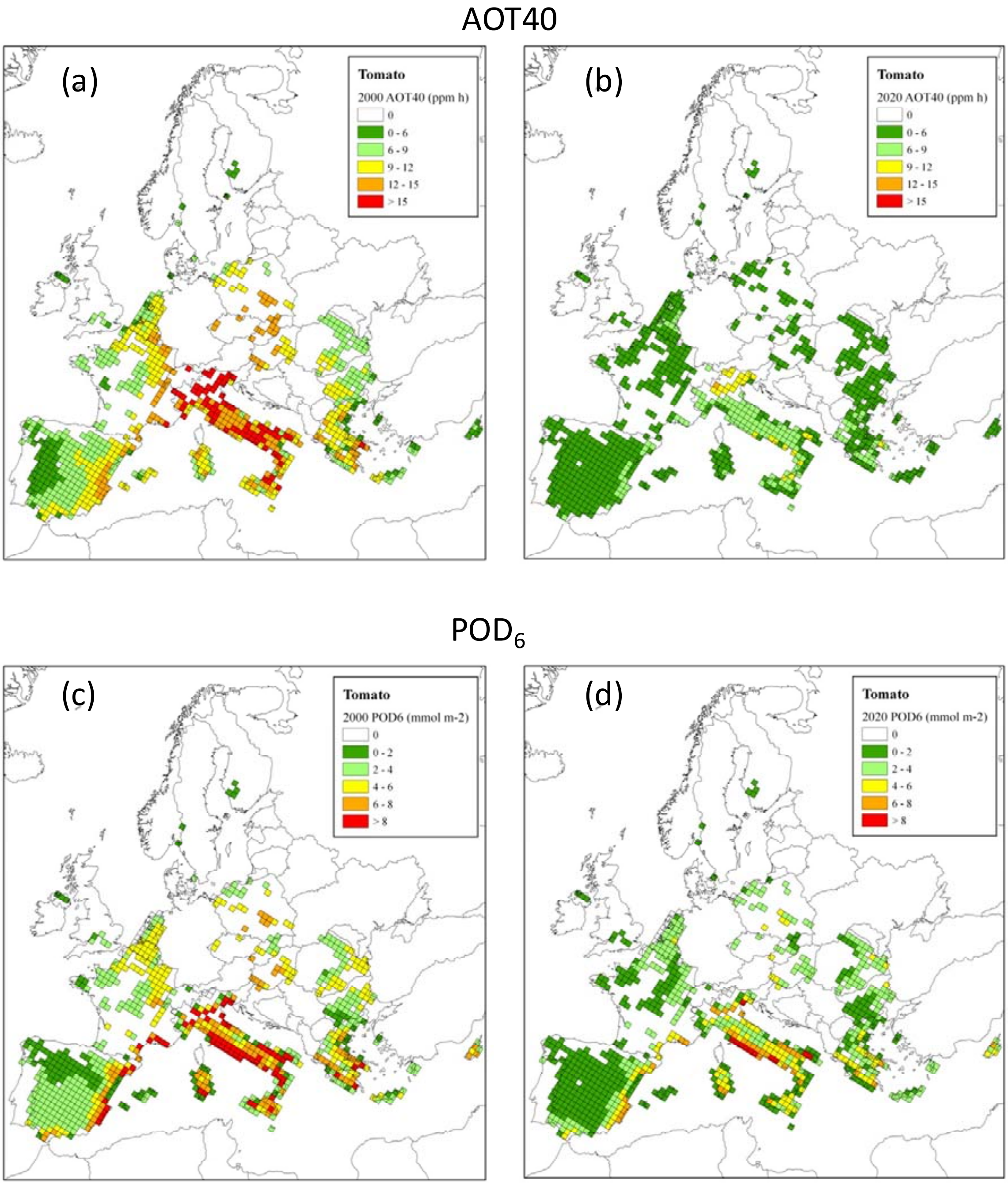


Figure 3.6 AOT40 (ppm h) for (a) 2000 and (b) 2020 and POD_6 (mmol m^{-2}) in (c) 2000 and (d) 2020 for the tomato growing areas of EU27+CH+NO (> 1 t yield per square) as as indicated by the NAT scenario.

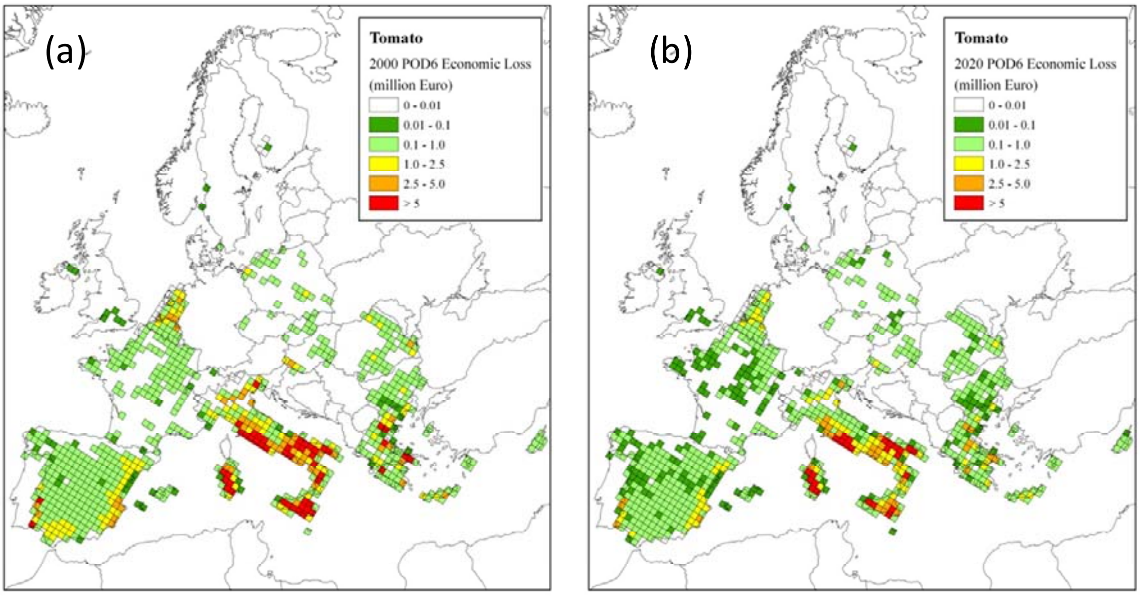


Figure 3.7 Predicted economic losses for effects on tomato in million Euro per 50 x 50 km grid square in (a) 2000 and (b) 2020 for the tomato growing areas of EU27+CH+NO (> 1 t yield per square) as indicated by the NAT scenario and flux-based methodology.

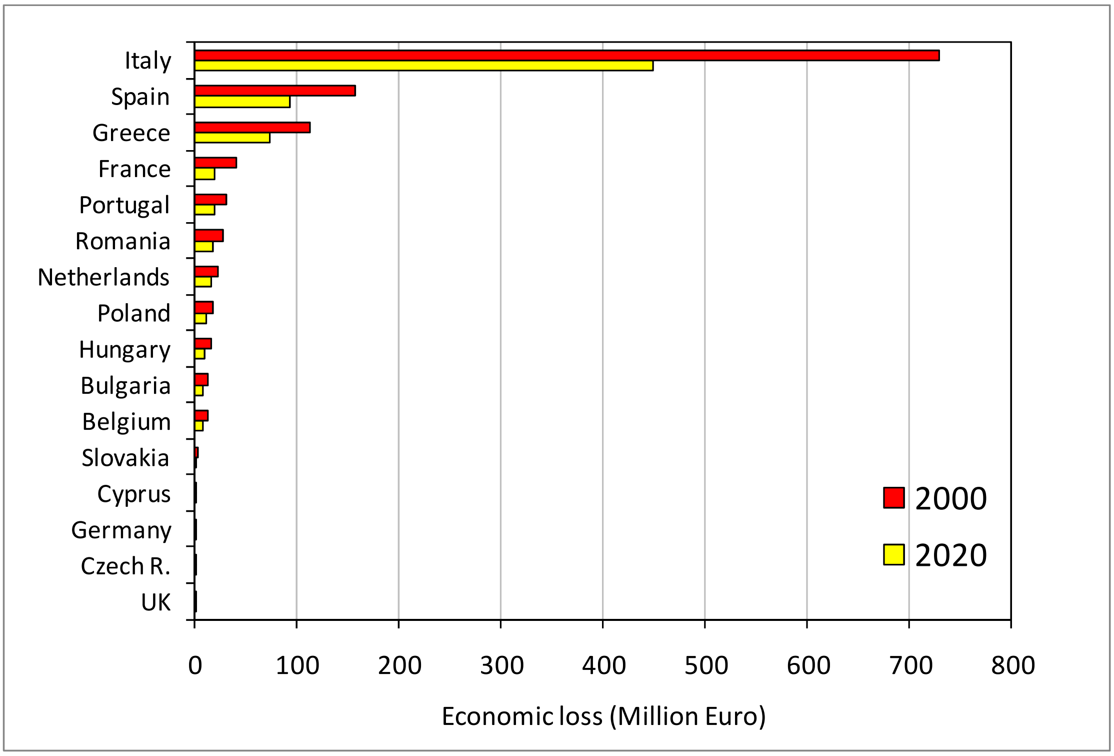


Figure 3.8 Predicted economic losses resulting from effects of ozone on tomato yield in million Euro for countries where losses exceeded €1 million as indicated by the NAT scenario and flux-based methodology.

3.5 Percentage yield losses for other crops

Within the current study it was only possible to quantify impacts on wheat and tomato using the flux-based methodology. Flux-effect models do exist for other crops such as potato (LRTAP Convention, 2010) and oilseed rape (De Bock et al., 2011), but it was not feasible to include these within the time-frame of this study. To give some indication of the areas where these and other crops such as barley, maize and sugar beet might be at risk, an AOT40-based assessment was conducted using the time interval for wheat. Following the advise provided in the Modelling and Mapping Manual (LRTAP Convention, 2010), it was not considered appropriate to conduct an economic impact assessment for these crops. Using 7h mean response functions, the sensitivity to ozone of the crops included in this study can be ranked as follows, based on the % yield loss at 60 ppb compared to 30 ppb (see Section 4.3): wheat (18%) > tomato (13%) > sugar beet (11%) and oilseed rape (11%) > maize (10%) > potato (9%) > barley (6%). As the wheat time interval was used, the results presented here assume that each crop is growing at the same time as wheat. This assumption introduces error into the analysis as the main growing period varies from crop to crop, for example in the UK, an accumulation period of 15 April to 15 July is suitable for winter wheat whilst that for sugar beet and maize is 1 June to 31 August (Mills et al., 2011a).

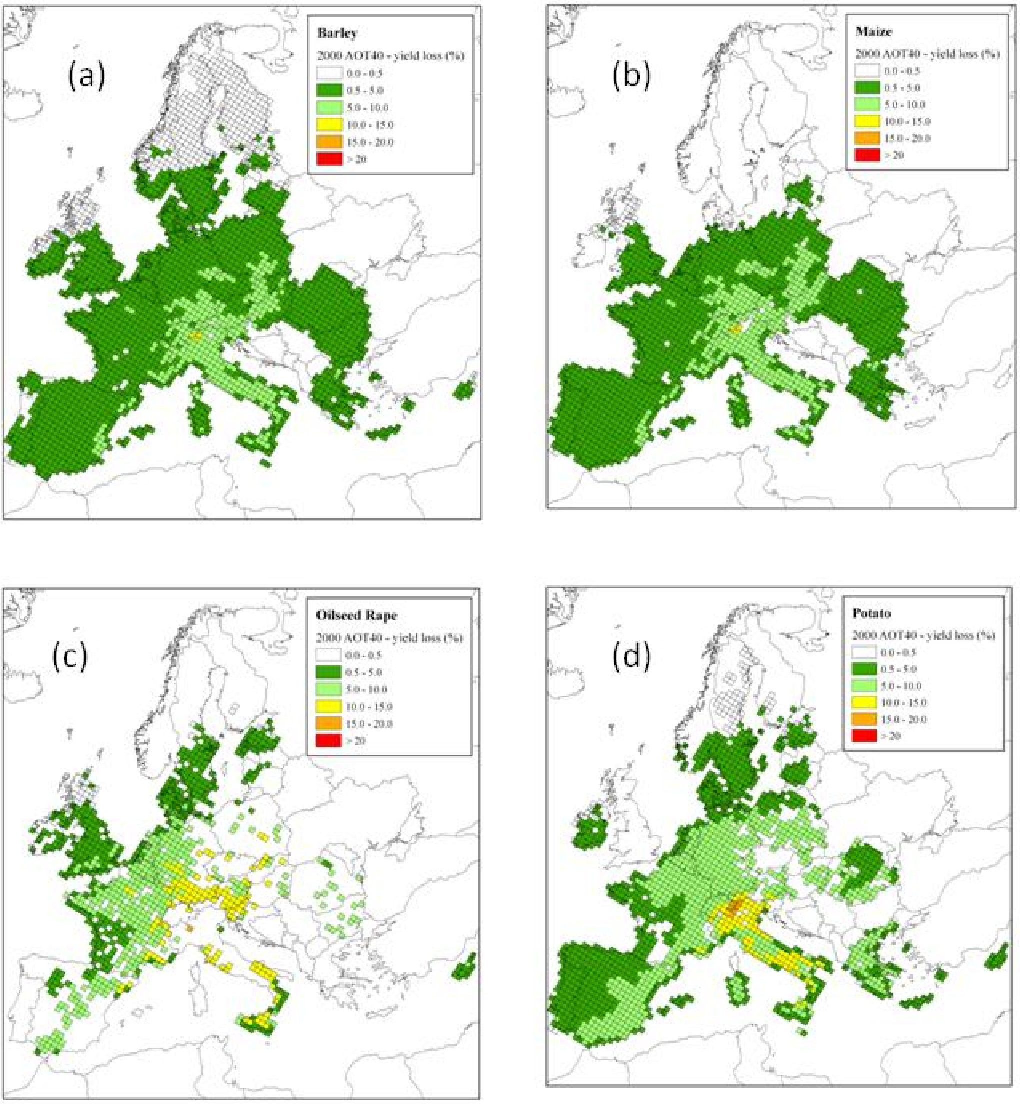
For maize and barley, predicted yield losses for 2000 were below 5% over most of Europe, with higher losses of up to 10% predicted for most of Italy, and parts of southern Spain, France, Switzerland, Austria, Germany, Hungary, Slovakia and Poland (**Figure 3.9**). Greater losses were predicted for sugar beet and potato, with most of central Europe expected to have 5 – 10% yield loss, and losses above 10% predicted for parts of Italy. Losses of 0.5 to 5% were predicted for more northern areas such as the UK, Denmark and southern Sweden. For oilseed rape, losses of 0.5 to 5% were predicted for northern growing areas, 5 – 10% in central Europe and > 10% in some parts on Italy and southern France, Germany, Austria and Hungary.

3.6 Sources of uncertainty

Uncertainty is introduced into this analysis to a varying extent at each of the stages:

Mapping AOT40 and POD_6 within the EMEP model is sensitive to the characteristics of the frequency distribution of ozone concentrations (Tuovinen et al., 2007, 2009) with both indices showing increased sensitivity with increasing threshold. However, as lower ozone concentrations contribute more to POD_6 than to AOT40, this parameter is less sensitive to threshold effects than AOT40 (LRTAP Convention, 2010, Tuovinen et al., 2007). Within this study, soil moisture was excluded equating to an assumption that the crops were irrigated when water was scarce. This may apply for tomato, but for many areas of Europe does not apply for wheat. Thus, given that soil moisture can be an important limitation to stomatal flux of ozone, the results presented here for wheat may overestimate effects. Additional sources of uncertainty associated with the simulation of the emissions, transport and deposition of ozone and its precursors are described in Simpson et al. (2003, 2007).

Crop distribution, production and economic valuation: As far as we are aware, we have used the most suitable available spatial crop distribution and production data. Transferring this data into values per EMEP grid square scale involves a degree of uncertainty, for example, due to differences in borders with NUTS3 regions, an inability to identify areas where crop production is intensely focussed within a NUTS3 region (with little in other parts of the region in some cases), and assumptions used for mixed land-use within squares. Data were mainly used for 2007 and these were converted to 2000 values using a country-specific factor introducing some uncertainty related to changes in crop production within a country. Further uncertainty was introduced by the use of 2000 production data to estimate



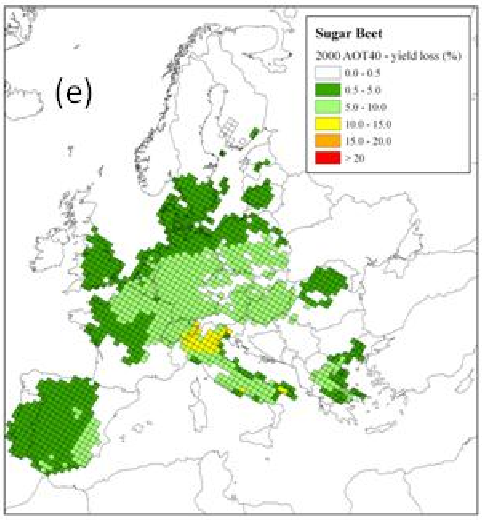


Figure 3.9 AOT40- based assessment of the percentage crop losses in 2000 from ozone effects on barley, maize, oilseed rape, potato and sugar beet.

effects in 2020 as changes in crop distribution are likely to occur within this time-scale. Choice of crop value for use in economic impact calculations can have a significant impact on the overall numbers generated as crop prices are highly volatile. For both wheat and tomato, the crop value in 2000 used was an average across all countries, and was within 10% of the long-term mean (2000 – 2009). Estimated losses for wheat would have increased by 54% if the maximum crop value of €18.41 /100 kg (2007) was used instead of the 2000 value. For tomato, the crop value used for 2000 was very close to the long-term average; valuations using the peak price would have increased economic losses by 28%. With crop prices/values predicted to increase further over the coming decades, economic impact assessments for 2020 may be significantly higher than calculated here.

Flux-effect relationships: For both wheat and tomato, confidence is gained from combining dose-response experiments from different countries with different climatic conditions, and for a range of varieties (**Figure 3.1**). These functions had a similar level of significance to those using AOT40 as the ozone parameter (LRTAP Convention, 2010; Pleijel et al., 2007). However, the more biologically meaningful flux-based method provided a better fit to mapped data than AOT40, especially when receptor-specific models and timing windows were used (Mills et al., 2011b). Measurements have shown that the DO_3SE model is able to simulate the observed daily trend in stomatal conductance (e.g. Büker et al., 2007; Klingberg et al., 2008; Tuovinen et al., 2004), is a good predictor of periods of high flux (Emberson et al., 2000b), and agrees with sap flow measurements in mature beech trees (Braun et al., 2010).

Some concerns have been raised about the application of the flux-effect relationships for wheat in southern climates. It is encouraging, however, that dose-response data from Italy fits well with that from more northern areas (**Figure 3.1**). Based on evidence that the wheat flux model may underestimate ozone flux in these areas when compared with field measurements, a separate VPD parameterisation for wheat has been included in LRTAP Convention (2010). For this pan-European study, it was not possible to include such a climate-specific parameterisation. Conversely, the tomato function was derived exclusively from data from the Mediterranean area and thus is suitably applicable to the region.

3.7 Conclusions

- This study has predicted economic losses for EU27+CH+NO in 2000 using the NAT scenario for wheat and tomato to be €3.2 billion and €1.02 billion respectively. It is not currently possible to quantify the degree of uncertainty associated with these figures.

- Predicted effects for 2020 using the NAT scenario were generally lower than those in 2000. For both wheat and tomato, economic impacts were predicted to decrease by 38% to €1.96 billion and €0.63 billion respectively. However, for wheat critical level exceedance remained high at 82.2% for the wheat growing areas. Critical level exceedance reduced from 77.8% of tomato growing areas in 2000 to 51.3% in 2020.

- The mean percentage yield losses predicted using the flux-based methodology were higher at 13.7 and 9.4% for wheat and tomato respectively than those predicted from the same data set using AOT40 (7.2% for both crops, reported for policy purposes in Harmens et al., 2011). The mean wheat yield loss of 13.7% was similar to that estimated in a global study for EU-25 using AOT40 (12.1%, Avnery et al., 2011a) and above the 9.1% predicted for current 7h mean concentrations of 31 – 50 ppb by Feng et al. (2009).

- Economic losses per grid square in 2000 were greatest for wheat in the highest producing areas in France, Germany, Belgium, Denmark and the UK, indicating that ozone flux was high enough in these central and northern areas to have an impact on wheat production. Large effects were also predicted for more southern countries such as Italy and Bulgaria.

- Economic losses due to ozone in 2000 were also predicted in the highest tomato producing areas of Europe in Italy, Spain, The Netherlands and Greece, with Italy having the highest predicted loss totalling > €700 million.

- Other crops investigated using the AOT40 approach were less sensitive to ozone. Percentage losses in 2000 were predicted to be mainly between 0.5 and 10% for barley and maize over most of Europe. Effects of 10 – 15% losses were predicted for sugar beet in northern Italy, for oilseed rape for parts of Italy and southern France, Germany, Austria and Slovenia, and for potato in northern Italy.

- This study has only considered impacts on yield quantity. Ozone also impacts on yield quality such as protein and sugar content (See Chapter 5) which will also impact on crop value.

- Further analysis using other scenarios being considered by the LRTAP Convention is required to provide a fuller picture of predicted future impacts.

4. The range of sensitivity of crops to ozone

Felicity Hayes and Gina Mills

4.1 Introduction

A wide range in sensitivity to ozone has been shown for different crops, and indices of crop sensitivity to ozone have been created based on AOT40 (Mills et al., 2007), as this parameter showed the best fit to observed responses for individual crops. In addition, the AOT40 required to give a 5% yield loss for a particular crop has been used to derive critical levels of ozone (LRTAP Convention, 2010). However, whereas the AOT40 index only considers ozone concentrations above a threshold of 40 ppb, it is possible that long-term exposure to ozone at concentrations below but close to 40 ppb may also have an impact on crop yield. The potential effects of these longer but more moderate exposures may become more important over the coming decades as it has been shown that background ozone concentrations have increased since pre-industrial times (Vingarzan, 2004) and are predicted to increase further (Jaffe and Ray, 2007; Van Aardenne and Streets, 2010). In combination with decreased episodic peaks of ozone pollution, this means that the profile of ozone exposure is predicted to be less episodic than in previous decades. An index of sensitivity to ozone based on mean ozone concentration would allow these impacts to be considered when assessing the extent of crop yield reductions due to ozone exposure, allowing estimations of yield losses to be made under a range of predicted ozone scenarios including regions where the background ozone concentrations are rising.

The vast majority of the data available for determining relative sensitivity includes only concentration-based information for the ozone metric such as daytime mean or 7h or 8h mean. We have also considered how to compare ozone sensitivity based on flux-response relationships, bearing in mind the wide range of g_{max} values for different crops.

4.2 Data collection and analysis

Data was collated from published papers where two or more ozone treatments had been used. The exposure facilities used were mainly open-top chambers (as shown in **Figure 1.3**), although occasionally other methods were used including glasshouses, controlled environment chambers, closed-top field chambers and field fumigation. Only papers that included measurements relating to crop yield were included in the database. For the purposes of this study, only food crops were considered; information relating to crops such as cotton, tobacco and biofuels was not included. The references used for each crop are shown in **Table 4.1**. Searches in published papers for data on the yield in response to ozone were also made for durum wheat, pumpkin, sunflower, rye, triticale, buckwheat, apples, millet, sorghum, carrot, lemon, cassava and chickpea. However, no suitable studies on the response of yield to ozone were found for these crops.

For each crop, ozone parameters were collated as given in the relevant paper. The vast majority of studies presented 7h mean data. For the very rare cases when this was not presented in the paper, the 7h mean was calculated using the exposure information available. For ease of analysis, 8h mean ozone concentrations were considered to be the same as 7h mean concentrations as any differences were likely to be very small. Data from ICP Vegetation sites biomonitoring sites show that there is a close correlation between 7h mean and 12h mean ozone data, with an r^2 of 0.98 with data from 2010 (**Figure 4.1**), enabling publications with ozone data presented as 12h means to be used in the database.

For each individual study, regression analysis of yield versus ozone exposure (7h mean) was used to calculate the absolute yield at zero ozone exposure. Where more than one variety was used, the absolute yield at zero ozone exposure was calculated separately for each variety. The relative yield for each ozone treatment used was then calculated in relation to this absolute yield, therefore a value of less than one indicates that there was a reduction in yield. For each crop, relative yield was plotted against ozone concentration (7 hour mean), using data from all relevant experiments, to determine a dose-response relationship. For all crops a linear dose-response relationship was assumed. The significance of the regression line of this dose-response relationship was determined using Minitab (version 16). For each crop, **the relative sensitivity** was assessed by comparing the percentage reduction in yield at a 7h mean ozone concentration of 60 ppb relative to that at 30 ppb. The point at which statistically significant changes occurred was calculated by plotting the 95% confidence interval (CI) for the linear relationship, and determining the point where the effect exceeds the upper 95% CI of the lowest treatment.

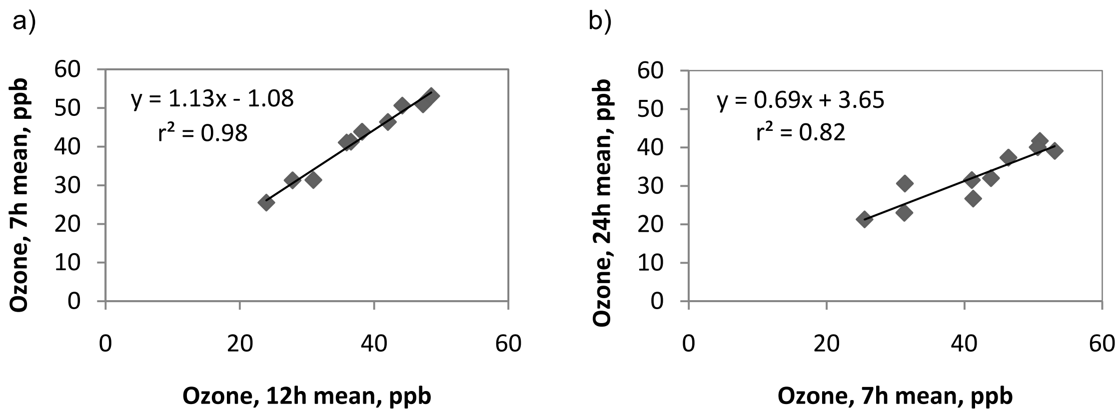


Figure 4.1 Correlation between 7h and (a) 12h or (b) 24h mean ozone concentration for ICP Vegetation biomonitoring sites in 2010.

4.3 Variation in ozone sensitivity between crops

For some species, there was data available for several varieties and independent studies which is ideal for determining ozone sensitivity. However, for several crops data was only available for a single variety or from a single study making the results less suitable for this type of analysis. The number of usable data points for individual crops was therefore very variable (**Table 4.1**) and ranged from 4 (grape, olive, orange) to 93 (wheat) and 145 (rice). A total of 23 crops had more than 4 data points, allowing their relative sensitivity to ozone to be determined.

The regression relationship and significance and r^2 of the relationship, together with the calculated percentage yield loss at 60 ppb compared to 30 ppb, are shown in **Table 4.2**. There was a significant ($p<0.05$) slope of the regression relationship with ozone for 15 of the crops tested. These were: wheat, barley, maize, sugarbeet, oilseed rape, alfalafa, peas and beans, soybean, rice, plum, tomato, lettuce, onion, turnip, and orange, with an additional strong trend ($p=0.066$) for potato.

There was a wide variation in ozone sensitivity between different crops (**Tables 4.2 and 4.3**, **Figures 4.2 and 4.3**). The most sensitive crops, with a yield reduction of >15% reduction in yield at 7h mean ozone concentrations of 60 ppb compared to 30 ppb included the most important European crop of

Table 4.1 References used to develop the database of crop yield response to ozone.

Crop	Number of data points	References used
Agricultural crops		
Alfalfa	23	Takemoto et al., 1988; Lesser et al., 1990; Temple et al., 1988; Maggio et al., 2009
Barley	59	Adaros et al., 1991; Fumagalli, 1999; Adaros et al., 1991b; Temple et al., 1985; Wahid, 2006b;
Maize	23	Rudorff et al., 1996b; Mulchi et al., 1995; Kress and Miller, 1985
Oat	6	Pleijel et al., 1994; Skarby et al., 1992
Peas and beans (including peanut)	60	Tonneijck and van Dijk., 1998; Sanders et al., 1992a; Sanders et al., 1992b; Adaros et al., 1990; Heck et al., 1988; Temple 1991; Gerosa et al., 2009; Booker et al., 2009
Potato	70	Skarby and Jonsson, 1988 ; Kollner and Krause, 2000; Donnelly et al., 2001; Lawson et al., 2001; De Temmerman et al., 2002; Pell et al., 1988; Asensi-Fabado et al., 2010;Calvo et al., 2009; Vandermeiren et al., 2005
Oilseed Rape	29	Ollerenshaw et al., 1999; Adaros et al., 1991a; Bosac et al., 1998; Kollner and Krause, 2003; Wang et al., 2008
Rice	145	Kobayashi et al., 1995; Maggs and Ashmore, 1998; Kats et al., 1985; Ariyaphanphitak et al., 2005; Ishii et al., 2004; Akhtar et al., 2010a; Pang et al., 2009; Shi et al., 2009; Rai and Agrawal, 2008; Chen et al., 2008; Yamaguchi et al., 2008; Sawada et al., 2009; Feng et al., 2003
Soybean	50	Mulchi et al., 1988; Lesser et al., 1990; Booker et al., 1997; Heagle et al., 1998; Reid and Fiscus, 1998; Fiscus et al., 1997; Miller et al., 1994; Heggestad and Lesser, 1990; Heagle et al., 1987; Betzelberger et al., 2010; Singh et al., 2010d; Morgan et al., 2006; Booker et al., 2005
Sugar beet	25	Bender et al., 1999; McCool et al., 1987; Kollner and Krause., 2003; De Temmerman et al., 2007
Sweet potato	6	Keutgen et al., 2008
Turnip	14	Heagle et al., 1985; McCool et al., 1987
Wheat	93	Kahn and Soja, 2003; Feng et al., 2003; Pleijel et al., 2006, Wahid 2006a; Akhtar et al., 2010b; Sarkar and Agrawal, 2010, Fuhrer et al., 1992;; Pleijel et al., 1991; Fuhrer et al., 1989; Ollerenshaw and Lyons, 1999; Feng et al., 2007; Gelang et al., 2000
Horticultural crops		
Brassica campestris	5	Singh et al., 2009a; Black et al., 2007
Broccoli	12	Temple et al., 1990
Lettuce	26	McCool et al., 1987; Temple et al., 1990; Goumenaki et al., 2007
Onion	9	McCool et al., 1987; Temple et al., 1990
Strawberry	6	Drogoudi and Ashmore, 2000; Takemoto et al., 1988
Tomato	41	Oshima et al., 1975; Hassan et al., 1999; Temple 1990; Reinert et al., 1997; Calvo et al., 2007; Maggio et al., 2007
Watermelon	10	Gimeno et al., 1999; Calatayud et al., 2006
Tree crops		
Grape	4	Soja et al., 1997
Olive	4	Minnocci et al., 1999
Oranges	4	Olszyk et al., 1989
Plum	10	Retzlaff et al., 1997; Williams et al, 1993

wheat, together with ‘peas and beans’, soybean, lettuce and the tree crops orange and plum. Other important European crops such as potato, oilseed rape, maize, barley and sugar beet together with tomato were classified as moderately sensitive to ozone. Rice, a globally important stable crop was also classified as moderately sensitive to ozone. Oat and broccoli appeared insensitive to ozone, based on the yield of the varieties tested. However, data for broccoli used ozone exposures with a maximum 7h mean ozone concentration of approximately 50 ppb and it is therefore possible that this species may be more sensitive to ozone at higher ozone concentrations. Response functions for those crops with >10 data points are shown in **Figures 4.2 and 4.3**, ordered by relative sensitivity.

Despite the large number of studies on some individual crop species, there are many that have had only limited study even though they are widely grown, e.g. oat. Many crops have not yet been tested

Table 4.2 Equation, significance and r^2 of the relationship for agricultural, horticultural and tree crops, ranked by sensitivity. The threshold for significant yield reduction is the ozone concentration required for a significant reduction in yield (compared to 0 ppb) based on confidence intervals of the regression relationship.

Crop	Number of data points	r^2	Significance of slope	Regression equation	Threshold for significant yield reduction (ppb)	Sensitivity (% yield loss at 60 ppb relative to 30 ppb)
Agricultural crops						
Peas and beans (including peanut)	60	0.48	<0.001	y = -0.0072x + 0.96	16	30
Sweet potato	6	0.50	0.118	y = -0.0074x + 1.00	59	28
Turnip	14	0.54	0.003	y = -0.006x + 1.00	37	22
Wheat	93	0.59	<0.001	y = -0.0049x + 0.95	9	18
Soybean	50	0.66	<0.001	y = -0.0051x + 1.01	8	18
Alfalfa	23	0.50	<0.001	y = -0.0046x + 1.10	26	14
Sugar beet	25	0.32	0.003	y = -0.0035x + 1.03	33	11
Oilseed rape	29	0.26	0.004	y = -0.0031x + 0.94	25	11
Maize	23	0.66	<0.001	y = -0.0031x + 1.03	25	10
Rice	145	0.44	<0.001	y = -0.0028x + 0.99	11	9
Potato	70	0.05	0.066	y = -0.0027x + 0.98	29	9
Barley	59	0.08	0.038	y = -0.002x + 0.99	43	6
Oat	6	0.03	ns	y = 0.001x + 1.00	---	-3
Horticultural crops						
Onion	9	0.56	0.020	y = -0.0067x + 1.08	43	23
Lettuce	26	0.18	0.035	y = -0.0065x + 1.21	43	19
Watermelon	10	0.23	0.156	y = -0.0043x + 1.02	74	14
Tomato	41	0.20	0.004	y = -0.0039x + 1.01	27	13
Field mustard	5	0.94	0.006	y = -0.0035x + 0.99	21	12
Strawberry	6	0.01	0.856	y = -0.0004x + 1.07	---	1
Broccoli	12	0.00	0.857	y = 0.0018x + 1.00	---	-5
Tree crops						
Orange	4	0.62	0.043	y = -0.0071x + 1.00	---	27
Plum	10	0.54	0.015	y = -0.0054x + 0.89	39	22
Olive	4	0.62	0.212	y = -0.0038x + 1.00	---	13
Grape	4	0.79	0.113	y = -0.0015x + 1.00	---	5

for ozone sensitivity at all, including crops such as cassava, millet and sorghum, which are staple foods for many people in developing countries, and sunflower, which is widely grown for its oil.

In this study the yield reduction with a 7h mean ozone concentration was used to compare the extent of yield loss for the different crops. Ozone data from the ICP Vegetation biomonitoring network indicates that 7h mean ozone concentrations are already in the range 40-50 ppb at several sites particularly in mid- to southern-Europe, for example Spain-Valencia, Austria- Seibersdorf, Italy-Pisa, Italy-Rome, Greece-Crete, Greece-Kalamata and Ukraine-Kiev, which all recorded 7h mean ozone concentration in excess of 40 ppb during the summer of 2010. It is therefore likely that there are already substantial yield reductions to ozone for several crops, and that the extent of crop loss due to ozone will increase further even with only a modest increase in ozone concentrations.

Table 4.3 Grouping of crops by sensitivity of yield to ozone. Values in brackets represent the percentage decrease in yield at 60 ppb ozone compared to that at 30 ppb, calculated from the regression equation (Table 4.2).

Sensitive	Moderately sensitive	Tolerant
Peas and beans (including peanut) (30)	Alfalfa (14)	Strawberry (1)
Sweet potato (28)	Water melon (14)	Oat (-3)
Orange (27)	Tomato (13)	Broccoli (-5)
Onion (23)	Olive (13)	
Turnip (22)	Field mustard (12)	
Plum (22)	Sugar beet (11)	
Lettuce (19)	Oilseed rape (11)	
Wheat (18)	Maize (10)	
Soybean (18)	Rice (9)	
	Potato (9)	
	Barley (6)	
	Grape (5)	

4.4 Variation in ozone sensitivity between varieties of individual crops

When considering the combined dataset it is not possible to identify which varieties are most sensitive to ozone as other factors such as the local climatic conditions may have influenced the response of a particular variety. However, there are several individual studies where the ozone sensitivity of a range of varieties for a single crop species were directly compared and these have shown that there can be large variation in ozone sensitivity between different varieties of the same crop. For example in a single study of four varieties of rice with a 7h mean ozone exposure of 100 ppb, the relative yield loss of the variety 'BR11' was nearly 60%, compared to only a 20% loss for the variety 'BR14' (**Figure 4.4**; Akhtar et al., 2010a). Similarly for a single study using barley, the relative yield loss with a 7h mean ozone exposure of 70 ppb was approximately 15% for the cultivar 'Haider-93', compared to nearly 50% for 'Jou-85' (Wahid, 2006b), and for a study using potato the relative yield loss with a 7h mean ozone concentration of 57 ppb was 10% for the variety 'Kardal' and nearly 30% for the variety 'Bintje' (Piikki et al., 2004). Even for crops where there is a strong and clear relationship between ozone and yield such as wheat, there can be a large variation in ozone sensitivity between varieties, for example, in India the variety 'Inquilab' was much less sensitive to ozone than 'Punjab-96' and 'Pasban-90' (**Figure 4.4**; Wahid, 2006a). Choice of which cultivar of a crop to grow is dependent on many factors including suitability for the local climate, tolerance of drought and resistance to disease. However, where ambient ozone conditions are moderate to high, then availability of information on tolerance to ozone would be beneficial for the decision process.

A comparison of ozone sensitivity of modern versus older varieties is provided in Section 2.7.

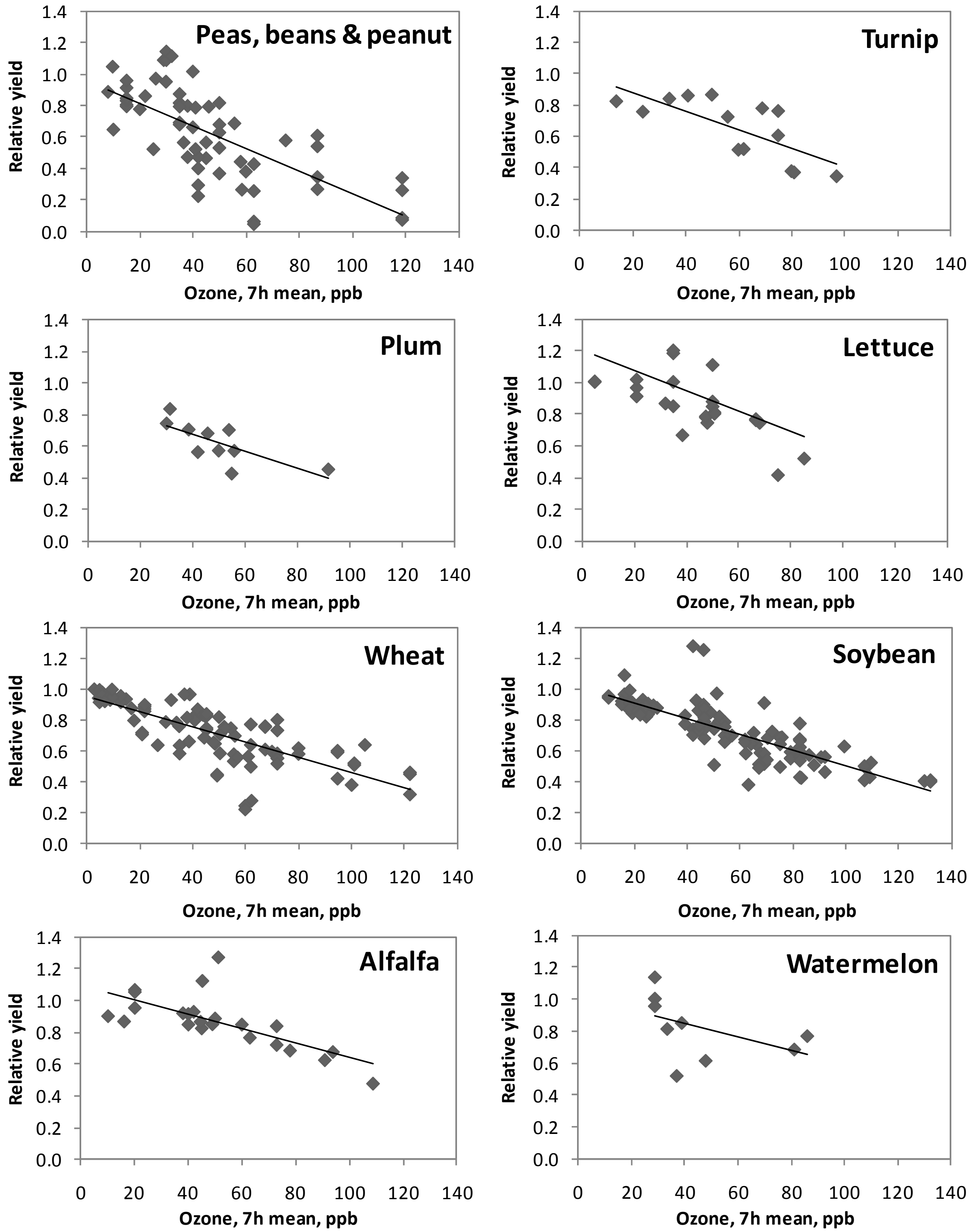


Figure 4.2 Dose-response relationships for yield for those crops with >10 datapoints, ordered by sensitivity to ozone (Table 4.3).

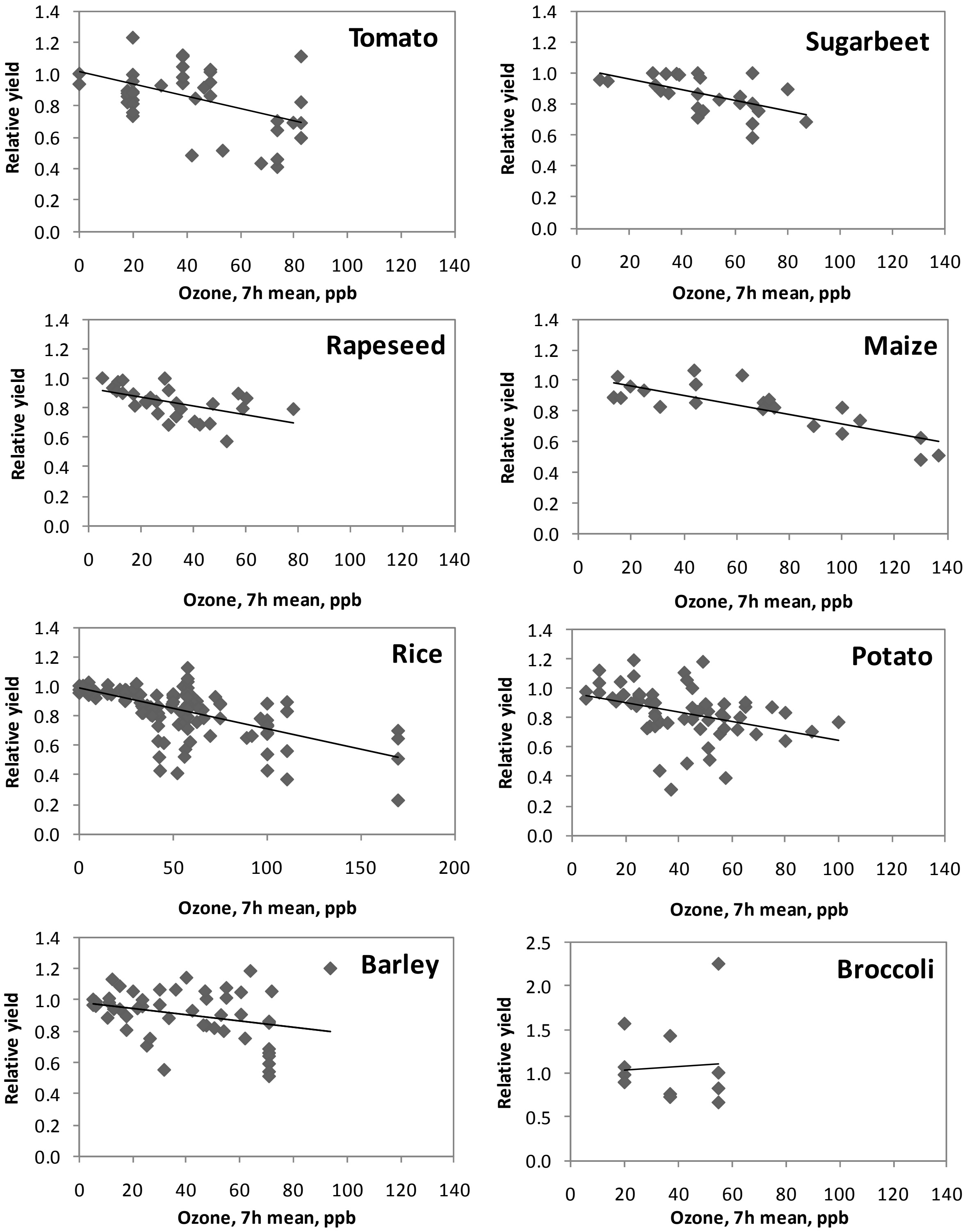


Figure 4.3 Dose-response relationships for yield for those crops with >10 datapoints, ordered by sensitivity to ozone (Table 4.3). Note the different scale on the x-axis for rice and y-axis for broccoli.

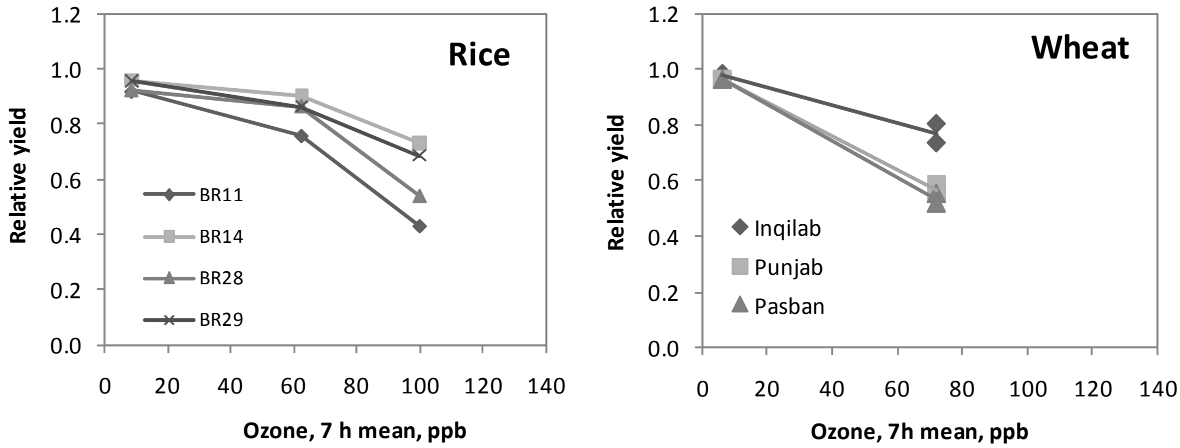


Figure 4.4 Variation in the relative sensitivity to ozone of four varieties of rice and three varieties of wheat. Re-drawn from Akhtar et al. (2010) and Wahid (2006a).

4.5 Effects of cumulative exposure for perennial crop plants

For the majority of crops it is appropriate to consider ozone exposure over all or part of a single growing season as the crops are grown annually. However, for some crops carry-over effects and/or the effects of cumulative exposure to ozone over several growing seasons may be important as the crop may be biennial or perennial. Of the crops studied to date these include the tree crops olive, orange, grape and plum. Experimental studies of effects of ozone on these perennial crop plants have not usually lasted for more than three years. Nevertheless, there is evidence that for at least some of these crops the effects of ozone exposure on crop yield can be cumulative from year to year. For grape (*Vitis vinifera* cv Welschriesling) there was increased sensitivity to ozone in the third year of exposure (Soja et al., 1997). Seasonal studies using grape indicated that the yield of this species had low sensitivity to ozone in the first and second years of the experiment with the vines with the highest ozone treatment having a yield loss of 15 - 20% compared to those growing in charcoal-filtered air. Furthermore, in the third year the yield loss in the highest ozone treatment was over 90%, compared to those of charcoal-filtered air. Other effects on perennial crop species during ozone exposure may also influence subsequent crop yield. It is possible that changes in biomass partitioning to maintain fruit yield may occur at the expense of tree growth, and that this may cause subsequent impacts on future yield, although this has not been studied.

4.6 Can ozone sensitivity be compared based on ozone flux?

Flux-effect data for some crops has been collated recently and used to define flux-based critical levels (LRTAP Convention, 2010; Mills et al., 2011c, as described in Chapter 1). There are flux-effect relationships currently available for wheat, potato, beans, oilseed rape, tomato, lettuce and broccoli. The flux-effects relationships were most robust for wheat (grain yield, 1000 grain weight and protein yield), potato (tuber yield) and tomato (fruit yield), and these were used to define flux-based critical levels for agricultural crops based on a 5% yield reduction (**Table 1.1**).

The calculated fluxes in the DO_3SE model are considerably influenced by the value of g_{max} for a particular crop, so that a crop with a large g_{max} such as bean (1270 mmol O_3 m^{-2} PLA s^{-1}, **Table 4.4**) will have a much higher ozone flux for a given ozone concentration and climatic conditions than a crop with a low g_{max} such as tomato (270 mmol O_3 m^{-2} PLA s^{-1}). Hence, we conclude that it is currently inappropriate to directly compare flux-based critical levels and make assumptions about ozone sensitivity based on flux totals as the difference in ozone sensitivity could be due primarily to an inherent difference in stomatal conductance.

Table 4.4 The maximum stomatal conductance (g_{max}) and impacts on stomatal flux.

Crop	g_{max} (mmol O_3 m^{-2} PLA s^{-1})
Wheat	500
Potato	750
Tomato	270
Bean	1270
Oilseed rape	490
Broccoli	670

5. Effects of ozone on food and feed quality

Karine Vandermeiren and Håkan Pleijel

5.1 Introduction

Ozone not only reduces food quantity by reducing yield but also changes food and feed quality. From an agronomic point of view, yield and nutritional quality are of utmost importance – with the former aspect being more extensively studied in the past than the latter (Ashmore, 2005). This focus on yield changes could however result in a misleading risk assessment and economic extrapolations especially in those cases where the qualitative attributes of the harvested product are crucial for industrial processing and consumer's health.

Crop quality may be affected either by changes in primary metabolite production and/or assimilate allocation and transport (e.g. carbohydrates, proteins) but also as a consequence of changes in secondary metabolism. Ozone fluxes, due to acute or chronic pollutant exposure, may cause a diversion of available resources from growth to defence (Saleem et al., 2001; Iriti and Faoro, 2009; Betzelberger et al., 2010). The altered biochemical state, including increases in antioxidant scavenging systems within the tissue, can change the response of the plant to existing environmental conditions and other stresses, both biotic and abiotic (Kangasjärvi et al., 1994; Rao et al., 2000). The biosynthesis of plant secondary metabolites may be influenced by changing either the transcription or the activity of key enzymes of secondary metabolic pathways. Phytochemicals arising from these pathways include not only compounds with a broad-spectrum antibiotic activity, but also powerful antioxidants such as vitamin C and E (Iriti and Faoro, 2004; Holstein and Hohl, 2004; Facchini, 2001). Based on their biosynthetic origins, plant secondary metabolites can be divided into three major groups: (i) flavonoids and allied phenolic and polyphenolic compounds, (ii) terpenoids and (iii) nitrogen-containing alkaloids and sulphur containing compounds. In recent years the role of some secondary metabolites as protective dietary constituents has become an increasingly important area of human nutrition research (Crozier et al., 2007).

Ozone induced changes in food and feed quality have been studied in only a limited number of crops and most investigations deal with carbohydrate and crude protein content. Despite numerous studies on the biochemical and molecular mechanisms of oxidative stress, only very little information exists on shifts of these secondary metabolites in the marketable yield products (grains, tubers, fruits, vegetables). Recently Iriti et al. (2009) published one of the few detailed reports on such changes in bean seeds (*Phaseolus vulgaris*). The seeds from the ozone-exposed plants showed higher antioxidant activity and there was a notable change in certain phytosterols, flavonols, hydroxycinnamates and anthocyanins. Changes in plant chemistry and leaf structure may also influence plant-pathogen interactions and as such, ozone may have another additional, indirect impact on final product quality, food safety and consumer's health.

5.2 Impacts of ozone on wheat and potato quality

In **wheat** (*Triticum aestivum*), the most important effects of ozone include increases in grain protein concentration and changes in baking quality (Fuhrer et al., 1990; Pleijel et al., 1999; Rudorff et al., 1996a; Vandermeiren et al., 1992). Piikki et al. (2008) confirmed that ozone increases grain protein concentration although protein yield per plant or ton of seeds was significantly reduced (see Box 5.1). Baking quality depends on both protein quantity and quality and on the α-amylase activity of the flour. These properties are evaluated by the Zeleny and Hagberg value respectively and both parameters were significantly increased by ozone.

There are indications that not only the amount, but also the composition of the proteins is affected by ozone: dry gluten/protein concentration was increased at ambient ozone levels compared to charcoal filtered open-top chambers (Vandermeiren et al., 1992) and the Zeleny value tended to show a more pronounced ozone induced increase (although not significant) compared to the protein concentration (Piikki et al., 2008). The increase in the Hagberg value indicates a lower α-amylase activity. These effects may be a consequence of a higher level of maturity at harvest, due to earlier senescence, and/or more efficient N assimilation and/or translocation to the grain compared to carbohydrates. Fuhrer et al. (1990) and Anguissola Scotti et al. (1994) did indeed report a reduced starch content in wheat grains after ozone exposure. Agrawal et al. (1983) also found a significant reduction in starch content of grains of common millet (*Panicum miliaceum).* Further information on additional nutritional consequences of ozone for wheat is rather scarce and less consistent. The P and K concentration of the flour was decreased whereas total S concentration of the flour was increased (Anguissola Scotti et al., 1994; Vandermeiren et al., 1992). Fuhrer et al. (1990) on the other hand found an increase of Ca, Mg, P and K, but no effect on the vitamin E content and on the essential amino acid index of the protein.

As long ago as the 1980s, Pell et al. (1980,1988) indicated that ozone had the potential to alter the biochemistry of **potato** tubers (*Solanum tuberosum*). This is not only important in view of their processing properties for the food industry, but changes in the nutritional value may have a serious impact because of the large quantities used for human consumption. Starch content of the tubers needs to be high to avoid excessive fat absorption during frying, whereas the reducing sugar concentration should be low to prevent dark brown discoloration of the fried product.

The CHIP study, covering seven different sites across Europe, reported positive effects of ozone on potato tuber quality by decreasing the content of reducing sugars (i.e. glucose and fructose) and increasing the vitamin C content; reduction of the starch content on the other hand, had a negative impact on the quality (Pell et al., 1988; Vorne et al., 2002; Vandermeiren et al., 2005). These effects may be due to reduced assimilate allocation from leaves to tubers (Plessl et al., 2007). According to Köllner and Krause (2000), ozone peaks induce an even more pronounced decrease of the carbohydrates than constant concentrations. Interestingly, in **sugar beet** (*Beta vulgaris*) prolonged ozone exposure caused a comparable (but not significant) reduction of the sugar content, leading to an overall sugar yield reduction (De Temmerman et al., 2007). Also in **sweet potato** (*Ipomoia batastas* L. Lam), a reduction in starch and glucose content has been reported (Keutgen et al., 2008).This is of special importance because the most important food products from sweet potato tubers are starch and alcohol (also produced from starch and fermentable carbohydrates). Tuber carbohydrates may also represent the basic raw material for sugar syrup, noodle production, flour and snacks (Woolfe, 1992). On the other hand, a reduced ratio (glucose+fructose)/starch due to chronic ozone load, is advantageous for chip quality.

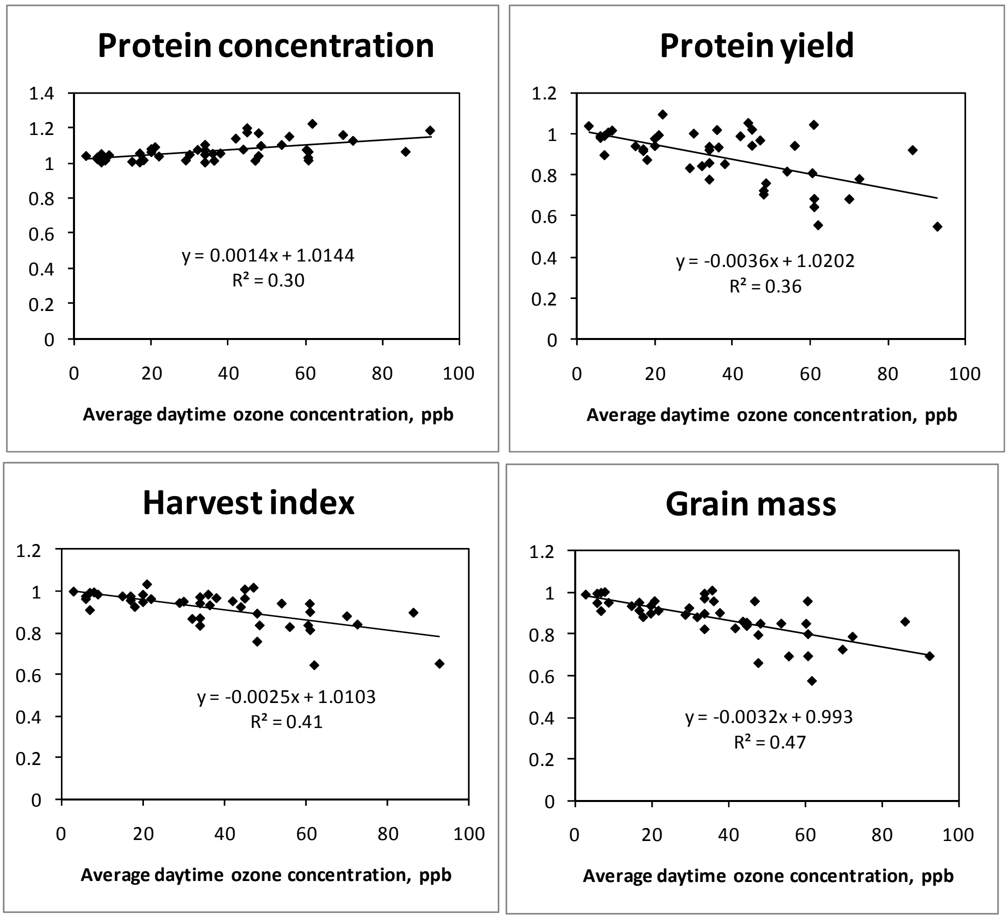
In the European CHIP project no effects were observed on citric and malic acid, two components that may influence flavour and colour. Glycoalkaloids such as α-solanine and α-chaconine are naturally occurring phytotoxins in **potato** that may cause a bitter taste and gastroenteritis if they occur in too high concentrations: 3-6 mg kg^{-1} body mass is even considered lethal to humans (Morris and Lee, 1984). High nitrate values in foodstuffs constitute another potential health hazard because of the precursor role in the formation of nitrites. However, ozone did not cause an increase of either of these compounds (Speroni et al., 1981; Vorne et al., 2002). Season long ozone exposure tended to increase tuber nutrient element concentrations. This was significant for N and Mn (Foster et al., 1983; Fangmeier et al., 2002). Piikki et al. (2007) also found a positive correlation between N, P, K and Mg concentrations in tubers with ozone exposure, and suggested that the more progressed senescence of ozone exposed plants was associated with a larger extent of reallocation of mobile nutrients from the haulm to tubers. The slight modifications in free amino acid and macronutrient contents of **sweet potato** tubers were considered of minor importance for tuber quality (Keutgen et al., 2008).

In conclusion, for wheat and potato, prolonged exposure to elevated ozone causes a limitation of the carbohydrate supply and increase in protein concentrations of tubers and grains. This may be a consequence of impaired photosynthesis, increased senescence and investment of carbohydrates in the antioxidant defence system and in leaf growth to compensate for the primary ozone damage.

Box 5.1 Ozone impacts on grain quality in wheat

Hakan Pleijel

Globally, wheat is the largest source of vegetable protein in human food. The protein content of wheat also determines the suitability for use as bread or pastry flour. For this report, a combined dataset comprising 45 datapoints from open-top chamber experiments with wheat (see photo in Figure 1.3) conducted in Belgium, Denmark, Finland, Sweden, Switzerland and the USA was analysed in relation to quality factors. The protein concentration increases with increasing ozone, but this is offset by decreased grain weight leading to an overall decrease in the protein yield per tonne of grain. Increasing ozone also decreases the harvest index (proportion of biomass within the seeds) and the individual grain mass (also often described as the 1000 grain weight). These quality factors were less sensitive to ozone than wheat seed yield when responses to 60 ppb relative to 30 ppb were calculated (as described in Section 4.3) of 12% for protein yield, 9% for harvest index and 11% for grain mass compared to 18% for seed yield. Nevertheless, the effects of increasing ozone concentrations on wheat grain quality have the potential to impact on security of food supplies in countries such as India where wheat grain demand exceeds supply and protein yield is especially important.



5.3 Impacts of ozone on the quality of oil producing crops

Besides the carbohydrate and protein content, the oil content and fatty acid composition of seeds are an important quality aspect, particularly for oil producing crops such as soybean (*Glycine max*), oilseed rape (*Brassica napus*), mustard (*Brassica campestris*) and peanut (*Arachis hypogaea*). In general, there is an inverse relationship between seed oil and protein content but environmental factors may alter the seed oil:protein ratio.

Oilseed rape is the third most important world source of vegetable oil (Lühls and Friedt, 1994) whilst the protein content of the residual seed meal is similar to soya and used as feed supplement. Moreover, the seeds are rich in linoleic and linolenic acids, essential fatty acids and precursors of the omega 6 and omega 3 fatty acid families. Seed quality of winter oilseed rape, in terms of crude protein and oil content, was reduced by elevated ozone, which represents an additional economic loss to the decrease in seed yield (Ollerenshaw et al., 1999). De Bock et al. (2011) confirmed the decrease in oil percentage in spring oilseed rape, however there was an increase in the percentage of protein (Vandermeiren et al., unpublished). The presence of immature green seeds in *Brassica* species reduces oil quality because their chlorophyll content adversely affects colour and flavour (Ward et al., 1995). Bosac et al. (1998) reported a reduction of the carbohydrate contents of the oilseed rape seeds. With an equal total accumulated ozone exposure, a moderate increase in ozone concentrations on an 8 hr/day basis caused a much more pronounced change in fatty acid content in oilseed rape seeds (*Brassica napus* cv. Licolly) in comparison with short term high ozone peak levels (Kollner and Krause, 2003).

An important health-related quality parameter for most *Brassicaceae* is their glucosinolate (GSL) content. GSLs are a group of N and S containing secondary plant metabolites that represent an important inducible plant defence system. These components possess a wide range of antifungal, antibacterial and antimicrobial activities and have been attributed anti-carcinogenic properties (Talalay and Fahey, 2001). In animal feed however, they decrease digestibility and may cause goitre and haemolytic anaemia if supplemented at excessive rates (Stoewsand, 1995). Preliminary results of a 3-year open-top chamber experiment did not show significant changes in the GSL content in seeds of spring oilseed rape although ozone did cause a shift from indol to aliphatic GSLs in broccoli (*Brassica oleracea* L. cv Italica) (Vandermeiren et al., unpublished). In another acute fumigation experiment with *Brassica napus* L. subspecies oleifera, used as green feed, the treatment caused a decrease of GSL for one line with an endogenous high GSL content (Gielen et al., 2006). Despite the inconsistency in responses, these findings do confirm a sort of cross talk between biotic and abiotic plant defence mechanisms suggesting that distinct stresses may activate the same, or at least overlapping, signal transduction pathways (Sharma and Davis, 1994).

Contrasting results have been reported for the impacts of ozone on the seed quality of **soybean** (*Glycine max*). As early as the 1970s, Frey (1972) found that seeds harvested from soybean plants grown under 490 ppb ozone had 21% more protein and 4% less oil compared to control plants. At more realistic exposure levels, a general decrease in the oil:protein ratio was found both in open-chamber field studies (Howel and Rose, 1980) and in open field studies (Kress and Miller, 1983; Grunwald and Endress, 1984). In contrast, Grunwald and Endress (1988) found that the oil content of soybean seeds increased with increasing ozone exposure, largely as a result of increased amounts of linoleic and stearic acid, but the protein content remained essentially unchanged and the oleic acid content was decreased. Mulchi et al. (1988) reported only small changes in percentage protein (increased by 0.7% and similar to cultivar differences) and no changes in oil content. Heagle et al. (1998) found that the effects of ozone on seed oil content were cultivar-specific, observed no effect on seed protein content, minor suppression of oleic acid and small increases in linoleic acid concentration. Hence, the inconsistency in the response of soybean to ozone are likely due to the use of different cultivars; other environmental factors might also influence the oil:protein ratio. Although Keen and Taylor (1975) reported an increase of the isoflavonoids daidzein, coumestrol and sojagol in ozone injured soybean leaves, no data are available concerning their content in the seeds. These compounds accumulate to high levels in the defence reaction to certain pathogens, but are also known as phytoestrogens, mimicking the biological activity of oestrogens.

Seed quality of **mustard** in terms of nutrients (Ca, Mg, K, P, Zn), protein and oil content was reduced in non-filtered compared to filtered open-top chambers (Singh et al., 2009a). Apparently ozone can also modify seed coat colour of this species, increasing the proportion of seeds with yellow, yellow/green or green seeds relative to the more usual light/dark brown seeds (Black et al., 2000; Stewart et al., 1996). Naturally occurring yellow seeds have a higher economic value due to their substantially greater oil and protein content, lower fibre content and thinner seed coats relative to brown seeds, which increase their digestibility and value in animal feed. Stewart et al. (1996) postulated that this shift in seed colour could be due to changes in seed coat pigments, mainly polyphenols, or slowed seed maturation.

In **peanut**, ozone effects on market grade characteristics were small and no effects were observed in the protein contents of the seeds (Burkey et al., 2007). There was no change in oil content although stearic acid was increased and lignoceric acid was decreased, but these components represent less than 5% of the total fatty acid content in peanut seeds.

5.4 Impacts of ozone on the quality of other vegetables and fruits

Soja et al. (1997) showed that ozone exposure over two years caused a large decrease in sugar content of **grape** (*Vitis vinifera*) and the juice quality was more sensitive to ozone exposure than grape yield (Soja et al., 2004). In **watermelon** (*Citrullus lanatus*) exposure to ambient levels of ozone also slightly decreased the soluble solids content (SSC) which is an indirect method of assessing sugar content, i.e. sweetness (Gimeno et al., 1999). In **rice** (*Oryza sativa* L.), on the contrary, reducing and total soluble sugar content increased in non filtered open-top chambers compared to filtered air conditions; concentrations of starch, protein, P, N, Ca, Mg and K decreased (Rai et al., 2010). Agrawal et al. (2006) showed that seed quality in **mung bean** (*Vigna radiata* L.) near Varasani city in India declined due to the combined effect of ozone and other pollutants. Beans cultivated near and in cities with high ozone concentrations had lower seed protein, which could have serious implications for the nutrition of the urban population. Reductions in the iron content of **spinach** and the beta-carotene content of **carrot** were also observed in India (Agrawal, 2007). It should also be noted that ozone-induced visible injury on foliage leaf crops is considered to be a yield quality effect (see Section 1.4).

5.5 Impacts of ozone on the forage quality of grasslands

In the case of perennial grasslands (pastures and rangelands), relevant long-term effects of ozone may develop over several years. Decreases in forage quality of grasslands have been demonstrated both in North America (Booker et al., 2009; Powell et al., 2003) and Europe (Fuhrer et al., 1994), which has economic implications for their use by ruminant herbivores. Decreased nutritive quality of forage can lead to lower milk and meat production from grazing animals, thus linking air quality with impacts on animal production systems (Krupa et al., 2004). Forage quality is determined by its digestibility (largely dependent on cell-wall components as cellulose, hemicellulose and lignin), nutrient content (proteins, sugars, starch, minerals) and the presence/absence of anti-nutrients (e.g. tannins, nitrates, alkaloïds, cyanoglycosides, oestrogens, mycotoxins).

Most ozone response studies have dealt with effects on digestibility traits and nutrient contents. Too little data are available to draw a general conclusion with regard to effects of ozone on the mineral and anti-nutrient content of forage crops: mineral contents were found to increase (Blum et al., 1982), decrease (Fuhrer et al., 1994), or remained unchanged (Pleijel et al., 1996). Digestibility is inversely related to ADF (acid detergent fiber = lignocellulose and protein bound cell walls), whereas the free-range voluntary forage intake is inversely related to NDF (neutral detergent fibre = insoluble fractions comprising total cell-wall constituents) (Van Soest, 1994). These properties can change due to direct effects of ozone on secondary metabolism resulting in increased levels of phenolic acids, flavonoids and related compounds (Keen and Taylor, 1975; Booker and Miller, 1998; Saviranta et al., 2010) that may negatively affect ruminant microorganisms and enzyme systems. Since ozone is also known to promote leaf senescence, the increased fraction of senescing tissue in pastures or other types of grasslands can decrease forage digestibility due to increased lignification and a decreased leaf/stem ratio (Runeckles and Krupa, 1994; Fuhrer and Booker, 2003).

Early-season ozone exposure has been shown to decrease the relative feed value of *Poa pratensis*, a common high-yielding perennial pasture grass in Europe, by an average of 8%. This is sufficient to have nutritional implications for its utilization by herbivores as a result of predicted decreases in voluntary intake and digestibility (Bender et al., 2006). Doubling of ambient ozone concentrations also resulted in decreased yield and quality of bahiagrass (*Paspalum notatum*), an economically important C_4 grass in the southern USA (Muntifering et al., 2000). Differences in responses between primary-growth and re-growth forage, early and late-planted grass, suggest that the impact of ozone might be modified by forage management practices such as timing and frequency of harvesting in relation to ozone episodes during the growing season. At ambient and elevated ozone exposure, the nutritive quality of little bluestem (*Schizachyrium scoparium*), a tanniferous legume, and that of sericea lespedeza (*Lespedeza cuneata*), a C_4 bunchgrass, was decreased by less than 2% and ca. 7%, respectively, in comparison to charcoal filtered exposure (Powell et al., 2003). Such a treatment also resulted in 10 to 20% decrease in nutritive value for *Trifolium subterraneum* (Subterranean clover), an important ozone sensitive species of great pastoral value in the Mediterranean region (Sanz et al., 2005). This response was confirmed in free-air fumigation experiments with other clover species, *Trifolium pretense* (red clover) and *Trifolium repens* (white clover), where ozone also caused an increase of lignin and decreased digestibility (Muntifering et al., 2006a). Earlier field and greenhouse studies on ladino white clover had already indicated changes in nutritive constituents in ozone enriched environments, with differential responses between sensitive and tolerant clones (Burns et al., 1997). Forage quality of red clover was affected as a result of the increase in the total phenolic content of the leaves by ozone (Saviranta et al., 2010).

A decline in relative feed value of another important livestock forage crop alfalfa (*Medicago sativa*) in Alberta, Canada, was strongly linked to ambient ozone concentrations, based on a multivariate analysis of air pollutant and meteorological data (Lin et al., 2007). The lower foliage seemed to be the most affected (Muntifering et al., 2006b). Based on non-filtered versus charcoal-filtered air greenhouse experiments, Howell and Smith (1977) speculated that ozone-induced damage of alfalfa could affect voluntary intake by ruminants adversely by the slower rate of digestion and the implication of larger ruminal fill associated with slower fiber digestion, although the nutrient content was not changed. Comparable experiments by Thompson et al. (1976) showed no treatment effects on changes in protein efficiency ratio (tested with rats) or nitrogen digestibility (in vitro tests), but crude fiber concentration, beta-carotene and vitamin C were reduced in non-filtered air. Skärby and Pell (1979) did not find evidence of changes in the phytoestrogen coumestrol in alfalfa leaves. Recently, Frei et al. (2010) demonstrated that ozone even reduced the feed quality of rice straw, a major feed resource for ruminant livestock. Increases in crude ash, lignin and phenolics concentration adversely affected the digestibility as demonstrated by incubation experiments simulating rumen digestion *in vitro*.

Changes in forage quality can also result from shifts in species composition. Differential ozone sensitivities between grasses and legumes have been found to cause a shift in the grass/legume ratio in favour of grasses, and hence, in protein concentrations and other quality traits relevant for animal nutrition (Rebbeck et al., 1988; Ashmore and Ainsworth, 1995; Fuhrer, 1997, 2009). Data from investigations by Blum et al. (1983) and Rebbeck et al. (1988) suggest that ambient levels of ozone in the south-eastern USA can have a negative impact on forage quality of tall fescue (*Festuca arundinacea*) - ladino clover (*Trifolium repens*) pastures due to yield reductions of clover. On the other hand, in open-top chamber experiments in Sweden, Pleijel et al. (1996) did not find significant ozone effects on quality parameters of a grass-clover mixture (fiber content, energy content, protein). Measurable changes in forage quality are most likely to occur in pastures with high clover proportion and less frequent cutting. Under high cutting frequency, most leaves in the pasture remain young and healthy and under these circumstances there is no large difference in chemical composition between grasses and clover (Fuhrer, 1997). Interestingly, adverse effects of ozone on clover productivity and nutritive quality were mitigated in mixtures with ryegrass. Gaps created by the disappearance of clover, were populated by ryegrass of which the nutritive quality was hardly affected by ozone (González-Fernández et al., 2008).

The effects of ozone on species composition and nutritive quality clearly illustrate that yield-based risk assessments may under- or overestimate the impacts of elevated ozone on grassland productivity and quality for animal production. The implementation of an index integrating both productivity and forage quality, such as the consumable food value, could greatly increase the economic relevance of ozone dose-response relationships destined to underpin air pollution abatement legislation (González-Fernández et al., 2008).

5.6 Secondary effects of ozone on food and feed quality

Least investigated are the secondary effects of ozone on food and feed quality through changes in the incidence of viral, bacterial and fungal diseases and the impact of insect pests that may occur as a consequence of changes in plant chemistry and leaf surface characteristics (Tiedemann, 1993; Rao et al., 2000; Ashmore, 2005; Plessl et al., 2007; Bidart-Bouzat and Imeh-Nathaniel, 2008). This may have positive or negative consequences for the product quality and safety e.g. because postharvest storage of fruits, vegetables and seeds is limited by disease development (Tzortzakis et al., 2008). Increased incidence of toxigenic fungi on crops due to climate change could also create another additional risk in e.g. cereals as carcinogenic aflatoxin production by *Aspergillus flavus* may be a potential fungal response to oxidative stress (Kim et al., 2005).

5.7 Conclusion

In addition to the detrimental effects of increasing ground-level ozone concentrations on agricultural and horticultural yield, the more ‘hidden’ changes in qualitative and nutritional properties of the marketable end products constitute an essential, yet insufficiently documented element in an over-all risk assessment of the consequences of ozone for the food and feed chain. These qualitative and nutritional characteristics will become increasingly important from a commercial and industrial viewpoint, and hence a higher priority for future research, especially in those countries where demand for food is increasing.

In staple crops the often observed shift from carbohydrate to protein production and/or translocation to sink organs may have both positive and negative implications for industrial processing and nutritional qualities of consumable end products. Moreover, a decrease in seed oil percentage can cause an additional financial disadvantage for producers and global production, and changes in forage quality may have an effect on animal production. The magnitude of the economic impact of ozone on crops may be under- or overestimated if effects on food and feed quality changes are not taken into consideration (Shortle et al., 1988; Booker, 2007). Although macronutrients constitute the main element in the evaluation of the nutritional quality, effects on micronutrients also have consequences for food and feed quality and human health.

The next phase in the development of critical levels for the protection of food and feed production and economically reliable risk evaluation of ground-level ozone pollution requires further development of flux-effect relationships for relevant combinations of yield-quality parameters (e.g. starch-, protein-, oil-yield) of the most important food and feed crops (Fuhrer et al., 1997; Piikki et al., 2008; De Bock et al., 2011); a start to this activity includes the setting of critical levels for protein yield and grain mass of wheat (Mills et al., 2011c). Total loss of consumable food value (fractional reduction in yield × fractional reduction in nutritive quality) could possibly be much more significant than biomass yield reductions alone in the assessment of the true economic impact of ozone on herbaceous vegetation under current and future global-climate scenarios (Booker, 2007). Clearly, continued research dealing with ozone impacts on quality and nutritional value is necessary to provide exposure-response information for the development of regional emission reduction strategies.

6 Ozone effects in a changing climate

Sally Wilkinson, Harry Harmens, Karine Vandermeiren, Bill Davies and Gina Mills

6.1 Introduction

The continuing rise in the global population and associated global anthropogenic emissions of greenhouse gasses such as CO_2, CH_4 and nitrous oxides (N_2O) are causing a change in the global climate (IPCC, 2007). Tropospheric ozone is now considered to be the third most important greenhouse gas after CO_2 and CH_4. For the next two decades, a warming of about 0.2°C per decade is projected for a range of emission scenarios. Even if the concentrations of all greenhouse gases and aerosols had been kept constant at year 2000 levels, a further warming of about 0.1°C per decade would be expected (IPCC, 2007). Depending on emission scenario, the predicted range of global warming by 2100 is on average ca. 2 – 4°C with warming predicted to be greater at higher northern latitudes. Globally averaged mean water vapour and evaporation are projected to increase. Increases in the amount of precipitation are very likely at high latitudes, while decreases are predicted in most subtropical land regions. A warmer future climate will also imply fewer frost days and increased summer dryness with greater risk of drought especially in the mid-continental areas. In terrestrial ecosystems there is evidence of earlier timing of spring events and poleward and upward shifts of plant and animal ranges, linked to global warming. Projected climatic changes will have an impact on the response of plants to ozone (Tausz et al., 2007).

As global ozone exposures increase over this century, direct and indirect interactions with climate change and elevated CO_2 will modify plant dynamics (Booker et al., 2005; Fiscus et al., 2005) and as such, it is vital to evaluate the impact of ozone on crops within a framework of future climatic conditions. The opposite also applies: ozone itself can modify the response of plants to a range of naturally occurring environmental stresses such as drought (Bell 1987; Heggestad et al., 1985; Mills et al., 2009; Wilkinson and Davies, 2009, 2010). Other important interactions may arise from the fact that ozone alters the performance of herbivorous insect pests and of plant pathogens, which will themselves be influenced by climate change, e.g. as a result of greater survival under milder winter conditions. As vegetation is an important sink for atmospheric CO_2 and ozone impacts of the combined effects of CO_2 and ozone on vegetation, consequence for the land carbon sink and feedbacks to the global climate should also be considered (ICP Vegetation report in preparation). Recently, Sitch et al. (2007) included impacts of ozone on vegetation in global climate modelling. They concluded that the negative impact of ozone on the land carbon sink could contribute as much to global warming as the direct impact of ozone on radiative forcing.

There is significant potential for the predicted changes in the climate to influence the response of crops to ozone through an effect on the rates of stomatal flux as the flux of ozone into the stomata is highly dependent on climatic conditions (see Box 2.1). Effects can be direct – e.g. temperature, CO_2 and humidity effects on stomatal conductance or indirect via an influence on soil water potential (SWP) and plant development (Harmens et al., 2007; Vandermeiren et al., 2009). In addition, climate change might affect the detoxification of ozone inside the leaves.

6.2 Ozone impacts in an increasingly warmer climate

The stomatal response to leaf temperature has a species-specific maximum temperature at which stomatal opening occurs and an optimum temperature for stomatal conductance (g_s) (Emberson et al., 2000a). The impact of climate warming on g_s will depend on which part of the temperature response function corresponds with the current ambient temperature. In temperate, moist climates an increase in temperature is likely to result in an increase of g_s and therefore an increase in the stomatal uptake of ozone. In contrast, a decrease of g_s and stomatal uptake of ozone may occur for those plants already at their optimum temperature for g_s as the climate warms.

The complexity of the interactions between the factors involved in climate change is well illustrated by consideration of the impacts of global warming on the canopy uptake of ozone. When considered as a single factor, increased temperature is likely to increase stomatal uptake of ozone providing the optimum for g_s has not been reached (see **Figure 6.1**). However, the response to warming will also be affected by the following indirect effects of increased warming: added stimulation of tropospheric ozone formation, an increase in VPD and decrease in SWP (soils will dry out faster due to enhanced soil evaporation and enhanced canopy evapotranspiration); and earlier and enhanced plant development, resulting in a forward shift of the period within the year when plants are absorbing ozone. Thus, the overall impact of warming on the canopy flux of ozone is difficult to predict and will depend on the severity and timing (e.g. summer or winter) of warming and changes in precipitation together with any changes in seasonal patterns in the occurrence of peak episodes of ozone. Izrael (2002) predicted that the projected warming accompanied by a 30% increase in tropospheric ozone and 20% decline in humidity would decrease the grain and fodder productions by 26% and 9% respectively, in North Asia. Little is known about the impacts of a few degrees rise in temperature on the antioxidant status of leaves and thus on ozone detoxification.

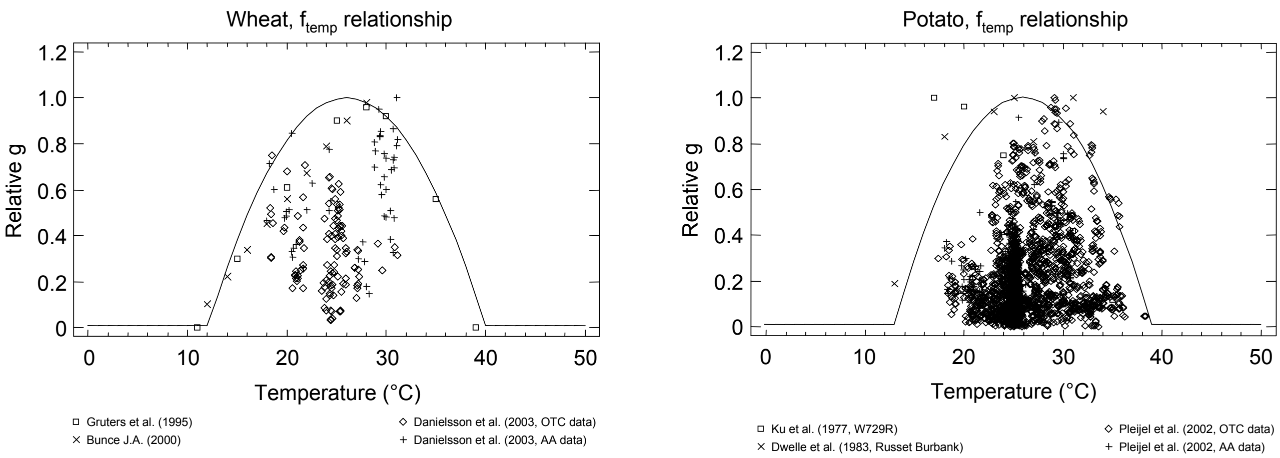


Figure 6.1 Parameterisation of wheat and potato stomatal conductance models. The function shown (f_{temp}) describes the dependence of the relative stomatal conductance (g) on temperature (see Chapter 3 of the Modelling and Mapping Manual (LRTAP Convention, 2010) for details).

6.3 Interactions between ozone and elevated CO_2 concentrations

Many short- and long-term studies have shown that elevated CO_2 reduces stomatal conductance (e.g. Ainsworth, 2008; Curtis and Wang, 1998; Drake et al., 1997; Kim et al., 2010; Morgan et al., 2003) and thus will decrease ozone uptake. A lower stomatal aperture in a CO_2-enriched world will improve water use efficiency at the leaf level and potentially also at the canopy level, depending on the magnitude of impact of elevated CO_2 on leaf area index. For example, Booker et al. (2004) and Bernacchi et al. (2006) found that high CO_2 (and ozone) reduced water use in soybean. Improved water use efficiency is likely to reduce crop susceptibility to environmental stresses such as high temperature, drought, high VPD and salinity. On the other hand, reduced evapotransporation will enhance leaf temperature, potentially affecting the uptake of ozone (see above). In free-air concentration enrichment (FACE) studies, rises in canopy temperatures between 0.6 and 1.1°C have been reported at elevated CO_2 concentrations and such increases should be added to those predicted for global warming (Kimball et al., 2002).

In a number of crop species, ozone injury to leaves was reduced substantially by elevated CO_2, e.g. spring wheat (Mortensen, 1990; Mulholland et al., 1997, 1998a,b; Cardoso-Vilhena et al., 1998), snap bean (Cardoso-Vilhena et al., 1998) and potato (De Temmerman et al., 2002). Indeed, in most studies elevated CO_2 leads to a reduction of ozone induced yield losses (Fiscus et al., 1997; Volin et al., 1998; Craigon et al., 2002; Morgan et al., 2003; Feng and Kobayashi, 2009). The off-set in yield losses through CO_2 enrichment has been used in models for predicting future food availability (see Bernacchi et al., 2006; Jaggard et al., 2010). In addition to impact on crop yield, elevated CO_2 and ozone also affect yield quality. For example, in potato significant interactions between ozone and CO_2 were observed regarding the glucose and reducing sugar content in tubers (Vorne et al., 2002).

It is important to note that results from recent field trials at Free Air CO_2 Enrichment (FACE) sites in Europe and the USA (Bernacchi et al., 2006; Long et al. 2005; Ainsworth, 2008), have indicated that the potential mitigating effect of elevated CO_2 might be less than predicted from earlier chamber, greenhouse or controlled environment studies. Thus, there is still considerable uncertainty about the magnitude of yield stimulation in a CO_2-enriched world and subsequent protection from yield losses in a higher ozone environment and there is an urgent need for more open-air ozone exposure studies in a CO_2-enriched and warmer atmospheres to determine their combined impact on important staple crops (Ainsworth, 2008; Feng et al., 2009; Long et al., 2005; Leutzinger et al., 2011).

6.4 Interactions between ozone and increased drought frequency

Since ozone episodes frequently co-occur with climatic conditions associated with drought and an increased frequency of drought is predicted for the coming decades (IPCC, 2007), it is important to understand how crops will respond to the combined stresses of ozone and drought in order to predict future impacts on food security. It has been widely reported that drought-induced stomatal closure will limit ozone uptake, thereby mitigating ozone-induced crop yield losses (e.g. Bermejo, 2002, Fuhrer, 2009, Fagnano et al., 2009). However, recent studies have shown that drought does not always reduce ozone-induced damage to plants in sensitive species (Mills et al., 2009; Wilkinson and Davies 2009, 2010), and that the genetic variability in ozone sensitivity may be related to the extent to which ozone reduces the sensitivity of stomatal closure to soil drying (see below). Other studies have also shown that the expected protective effect of drought on deleterious plant responses to ozone did not occur (e.g. Heggestadt et al., 1985; Robinson et al., 1998; McLaughlin et al., 2007, Biswas and Jiang, in press).

In drying soil, stomata of some species close much less sensitively in ozone-polluted air, and ozone can even open stomata under well-watered conditions in some cases (Mills et al., 2009, Wilkinson and Davies 2009, 2010). Because it has been shown that the extent of this effect is genetically determined (Wilkinson et al., 2011), it can be predicted that genotypes susceptible to this effect will receive a greater ozone dose. This reduced stomatal closing response to ozone will also directly increase plant water loss, reducing turgor and therefore increasing vulnerability to the drought episode (particularly when combined with a reduced root biomass – Grantz et al., 2006), with secondary impacts on leaf water potential and xylem cavitation likely. We predict that this will eventually cause secondary reductions in growth and yield, and/or increased injury, abscission, senescence and death (Wilkinson and Davies 2009, 2010, **Figure 6.2**), particularly if the vulnerable plants begin to experience additional/subsequent stresses such as wind, biotic attack, high light/VPD or flood/storm conditions. Repercussions are discussed in depth in Wilkinson and Davies (2010). Recent data (Wilkinson et al., 2011) describe a growing number of species, spanning grasses, forbs and trees, and including some crops (notably *Phaseolus vulgaris*), that exhibit ozone-induced stomatal opening either in the presence or absence of soil drying, that is genotype-dependent.

Under some conditions, ozone initially increases both stomatal aperture and leaf surface area growth of some species, however we propose that such genotypes will be unable to sustain leaf tissue water status at a sufficient level for the continuation of these elevated rates of growth (see Wilkinson and Davies 2009, 2010). Tissues will eventually become water-stressed, particularly under drought, inducing secondary stomatal closure and reductions in biomass growth/productivity via hydraulic signals and xylem cavitation. This hypothesis is depicted in **Figure 6.2**. Thus the ozone-induced growth elevations described above are thought to be temporary.

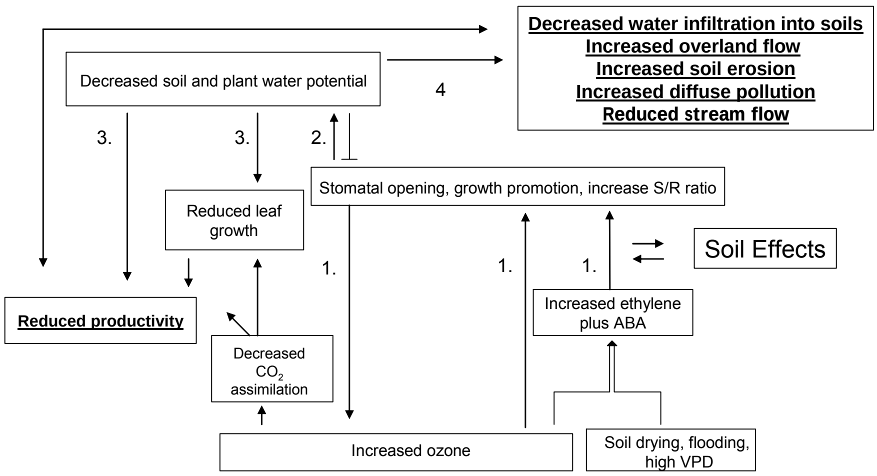


Figure 6.2 Schematic of ozone effects on plant water relations and implications for hydrology. Stages are marked on figure as 1. Stomata open, water loss increases and above-ground biomass increases. 2. Plant and soil water potentials decrease, particularly under drought. 3. Plant injury, reduced productivity. 4. Catchment effects (soil and water). From Wilkinson and Davies (2009).

6.5 Combined impacts on weeds, pests and diseases

The occurrence of plant pests (weeds, insects or microbial pathogens) is an important constraint, with global average yield losses estimated at about 40% (Oerke et al., 1994), and production costs significantly dependent on the extent of measures necessary for plant protection. Consequently, changes in the occurrence of pests due to increased ozone and its interaction with other climatic changes are of economic importance.

Virtually nothing is known about effects of elevated ozone on crop-weed interactions (see Fuhrer and Brooker, 2003), but ozone may potentially affect the ability of weeds and crops to compete for common resources.

For insect pests, the main effect of climate warming in the temperate zone is believed to be a change in winter survival, while in the northern latitude shifts in phenology in terms of growth and reproduction, may be of prime importance (Bale et al., 2002). Species-specific responses of insect pests to increasing ozone concentrations have been observed (see Fuhrer, 2003). Most studies have related changes in insect performance to changes in foliar concentrations of nitrogen, carbohydrate and phenolics (Pleijel et al., 1999; Heagle et al., 1994; Hummel et al., 1998). In general, in an atmosphere containing higher levels of both ozone and CO_2, increased populations of some insect pests can be expected.

Impacts of climate change on specific host-pathogen systems are variable (Coakley et al., 1999; Chakraborty et al., 2000). For example, ozone effects on plants can lead to altered disease susceptibility, but the effect is inconsistent. In wheat, leaf rust disease was strongly inhibited by ozone, but largely unaffected by elevated CO_2, both in the presence and absence of ozone stress (Von Tiedemann and Firsching, 2000). The interaction between ozone and pathogens may be determined primarily by the timing of ozone exposure relative to the presence of inoculation. The outcome of plant-pathogen interactions may strongly vary with timing, stage of plant development, predisposing factors, and environmental conditions (Fuhrer, 2003).

7. Contrasting concerns from Northern and Southern Europe

7.1 Ozone effects on crops in Northern Europe

Håkan Pleijel

7.1.1 Ozone concentrations - from north to south

In Northern Europe there are both factors favouring and limiting ozone effects on crops. Ozone concentrations are generally lower than in central and southern Europe. The gradient in ground-level ozone is however considerable from the southern part of the region, in particular Denmark and southernmost Sweden which are similar in this respect to central Europe, towards the north and partly also towards the east (Karlsson et al., 2009).

Also, the distribution of ozone concentrations over the year differs substantially between the south and the north. The arctic and subarctic parts of the region are characterised by a very pronounced, and in some years relatively high, spring peak in ozone, while summer concentrations are relatively low (Klingberg et al., 2009). This spring peak occurs mostly, but not exclusively, before the growing season has started and there are observations in Northern Norway of visible injury on plants early in the growing season which are possibly attributable to ozone (Manninen et al., 2009). The strong spring peak in ozone (Monks, 2000) is probably, at least partly, associated with the very low ozone deposition velocity to snow, which promotes relatively high concentrations near the ground, in combination with strong ozone formation when the photochemical season starts after the polar winter (Simpson et al., 2002). Reflection of photochemically active radiation by snow, rather than absorption of this type of radiation by vegetation and soil, can also favour ozone formation since a substantial fraction of the radiation has a second chance to participate in photochemistry.

Although some crops are grown in the subarctic and, especially in the case of pasture, arctic parts of the region, they are likely to be exposed to significantly lower ozone concentrations during the course of the growing season than crops grown in the southern part of the region, where agriculture is also more important, productive and a much larger number of crops are grown.

7.1.2 Northern climate effects on ozone uptake and sensitivity

It is well established that ozone uptake by plants is strongly modified by climatic variables (Pleijel et al., 2004). The gas exchange through the stomata, the tiny pores on the leaf surface which can open and close, is regulated by several factors (see Box 2.1), especially meteorological variables. In the Nordic region temperatures are relatively low and often in a range where they may limit stomatal conductance of crops and thus the ozone uptake of the plants. This is important from a climate change perspective, as future higher temperatures may promote ozone uptake even at constant ozone concentrations through stimulation of stomatal opening.

Most of northern Europe is characterised by relatively or strongly humid conditions. Both air and soil humidity are important from an ozone uptake perspective. Dry soil limits plant uptake of water. In response, plants will reduce their gas exchange in order not to desiccate, which decreases ozone uptake. Severe droughts are relatively rare in the region, partly because rainfall is fairly (and in the Atlantic region very) abundant and occurs throughout the year, but also since the low temperatures limit evaporation and transpiration. In addition, air humidity is mostly high and does not represent an important limitation to gas exchange normally, and thus to ozone uptake. Dry air (high vapour pressure deficit) tends to physically promote transpiration, i.e. water vapour loss from the stomata.

Similar to the response to dry soil, plants close stomata in response to high air vapour pressure deficits, but in northern Europe vapour pressure deficits are mostly below the level at which such a reaction is induced.

One further aspect of climate of importance for ozone risk assessment is solar radiation. In darkness there is very low stomatal conductance since photosynthesis cannot take place. Stomata open in sunlight permitting photosynthesis. Stomatal limitation by solar radiation disappears to a large extent at modest levels of solar radiation. In the northern part of Europe summer days are very long and thus permit plant ozone uptake during many hours per day. In the far north there is sunlight for 24 hours a day during part of the summer. This is important not only because the daily period of ozone uptake becomes longer, but also because dark hours represent a period of recovery from oxidative stress in general, including ozone. It has been shown that the weak but significant solar radiation during much or all of the night in the Nordic climate can promote ozone effects in e.g. clover (Futsaether et al., 2009), possibly as a consequence of limited recovery from oxidative stress. This aspect of ozone risk at high latitudes requires further study.

7.1.3 Ozone sensitive crops and responses

Highly or moderately sensitive crops (Mills et al., 2007; see Chapter 4 for update) are grown mostly in the southern parts of the Nordic Region. Among the more sensitive is wheat, which has exhibited clear ozone responses in experiments using realistic concentrations in the region (Denmark, Sweden and Finland). Important to note is that not only is grain yield per se influenced, but quality aspects are also influenced, such as the grain mass and volume weight (Piikki et al., 2008). Protein concentration is often higher in ozone exposed wheat grain, while protein yield per unit area is adversely affected (illustrated in Box 5.1).

Potato is a moderately ozone sensitive crop. Many different cultivars of potato are grown in the northern European region and only a few have been tested for ozone sensitivity. As far as can be judged based on available data there is a considerable variation in ozone sensitivity among different potato cultivars (Piikki et al., 2004). A large number of quality aspects are relevant for potato. These differ with the intended end use of the crop. Experiments conducted in Sweden and Finland have shown that the accelerated senescence induced by ozone exposure reduce concentrations of sugars (glucose and fructose), which is benefit for certain uses of potato. In the same experiments, the concentration of citric acid was stimulated, while that of malic acid was reduced by ozone according to experiments conducted in Sweden and Finland (Piikki et al., 2003). Generally, the observed pattern of potato quality responses to ozone includes both positive and negative aspects.

Pasture is a very diverse type of land use. It ranges from very extensively managed land to intensively managed crops. The latter type often consists of a mix of grass and clover. Many clover species, which contribute high protein levels to the forage produced, are known to be ozone sensitive and often more so than the grasses. Thus, clover tends to be outcompeted by the grasses at a faster rate if ozone concentrations are elevated. In the Nordic countries several experiments have shown that many of the locally used clover varieties are highly ozone sensitive (e.g. Pihl Karlsson et al., 1995; Futsaether et al., 2009) and exhibit visible injury and reduced growth at current levels of ozone exposure. In some pasture experiments conducted in the region the presence of clover was reduced by ozone, but not all.

7.1.4 Prospects for the future

Obviously it is hard to predict how the risk for ozone effects on crops will develop in the future. There are several different trends to consider in any attempt to forecast the likely development over the present century:

Rising background ozone concentrations. There is increasing evidence that tropospheric ozone over the Northern Hemisphere is subject to very large scale, indeed inter-continental transport. Since emissions of ozone precursors are increasing in some parts of the world this may lead to advection of ozone into Northern Europe. This problem may grow significantly during this century, depending on the development of the emissions of ozone precursors including methane (Prather et al., 2003). Especially in the northernmost parts of the continent local emissions contribute relatively little to ground-level ozone; hence hemispheric transport is the largest contributor. In fact there are observations in the north of the region, both in Sweden and Norway, to indicate that ozone concentrations are increasing (Karlsson et al., 2007; Manninen et al., 2009).

Declining peak concentrations. Reductions of ozone precursor emissions in Europe have led to a decline in peak concentrations of ground-level ozone. This holds particularly for those regions where the ozone load was highest and substantially affected by regional emissions of more reactive volatile organic compounds. This is of limited importance for northern Europe, especially in the most northern parts. Although the decline in peak concentrations is an important aspect of air quality improvement, rising background concentrations can also significantly contribute to ozone effects on crops once they reached a certain threshold level.

Spring peak may overlap with early growing season. Of critical importance for the assessment of the development in the northern part of the region is wether an earlier onset of the growing season will overlap with the spring peak in ozone in the future. This could lead to a considerable increase in the risk for ozone effects on vegetation. If the spring peak has a strong link to the duration of the snow cover this risk may not be manifested.

In terms of food security, it seems reasonable to conclude that significant effects of ground-level ozone occur on crops in the southern and middle part of the region today, although smaller and, in terms of acute visible injury, less dramatic than in southern Europe. These effects include reductions in yield in sensitive crops, but also quality effects and a reduction of clover in pastures. Over the coming decades ozone risks are likely to rise in the region as a result of rising hemispheric background concentrations and intercontinental transport as well as climate change effects on ozone formation and uptake.

7.2 Ozone effects on crops in Mediterranean Europe

Victoria Bermejo, Ignacio Gonzalez-Fernandez, Esperanza Calvo, Rocío Alonso

7.2.1 Ozone concentrations in Mediterranean areas

The highest ozone concentrations in Europe are usually recorded in the Mediterranean areas, where high emission rates and climatic conditions favour the production, accumulation and transport of highly polluted air masses.

Regional emissions of ozone precursors are added to pollutants emitted in central Europe and northern Mediterranean areas that are further exported towards the Mediterranean basin during the summer (Duncan et al., 2008). In addition, many species characteristic of the Mediterranean vegetation emit high rates of biogenic volatile organic compounds (Keenan et al., 2009), which have high ozone formation potential. Typical summer weather conditions, characterized by the occurrence of long lasting anticyclones, intense solar radiation and heat-waves, favour sun-dependent chemical reactions of ozone precursors of anthropogenic and natural origin leading to high ozone concentrations (Cristofanelli and Bonasoni, 2009; Millán et al., 2006). These climatic conditions also allow the export of polluted air masses towards cleaner areas, broadening the area affected by ozone pollution (e.g. Kouvarakis et al., 2000). On the contrary, dust episodes from the Sahara desert affecting southern Europe can reduce background ozone levels under situations with elevated concentrations of particulate matter (Cristofanelli and Bonasoni, 2009). The result is that spring and summer ozone concentrations in this area commonly exceed the international guidelines defined as phytotoxic for vegetation (Gabrielsen et al., 2009).

7.2.2 Ozone sensitive crops and responses

Current ambient ozone concentrations have been reported to induce negative impacts on the production and quality of over 20 agricultural and horticultural crop species of economical importance in the Mediterranean region (Fumagalli et al., 2001). Yield reductions, as high as 39% for some crops, have been observed experimentally in potato, tomato, bean, watermelon, artichoke and lettuce (Calvo et al., 2007, 2009; Gerosa et al., 2009; Gimeno et al., 1999; Goumenaki et al., 2007; Sanz et al., 2002). Also ozone-induced effects on fruit quality like reduced sugar concentration, delayed fruit ripeness or alterations in nutritional value, have been observed in bean, tomato and watermelon (Bermejo, 2002; Gimeno et al., 1999; Iriti et al., 2009), resulting in a decrease in their marketable value. These effects are of great significance considering that these species are amongst the most widely grown horticultural crops in the Mediterranean area. For example, in Spain, over 4 million tonnes of tomato were produced in 2009 worth € 1.5 billion (MARM, 2010). Furthermore, ozone can predispose some crops to pest infections. Tomato virus infection rates were increased at elevated ozone exposure in open-top chambers (Porcuna, 1997). In other cases, high ozone episodes have caused elevated economic losses in commercial fields over large areas in the Mediterranean region due to the appearance of visible injury on leafy crops, such as lettuce, spinach and chicory (Velissariou et al., 1999; Fumagalli et al., 2001; Sanz and Calvo, 2010). Ozone-induced visible symptoms in watermelon have been used for biomonitoring the extension of areas under risk of ozone damage on crops in Spain (Gimeno et al., 1995), and records of visible injury in leafy crops such as lettuce and spinach are also available indicating that ozone damage to horticultural crops is affecting large areas.

Besides horticultural crops, ozone can also induce negative physiological effects on other irrigated species. Orchard species like citrus trees, that have great economical significance in the Mediterranean area, have also shown negative responses to ozone pollution (Iglesias et al., 2006, see also **Tables 4.2 and 4.3**).

7.2.3 Mediterranean climate affects ozone uptake and sensitivity

Climatic conditions, and especially soil water content, are key drivers of plant physiology in the water-limited environments of the Mediterranean area (Chaves et al., 2002). Indeed, drought stress can reduce the ozone stomatal deposition rate, the flux of ozone towards the leaf interior, thus diminishing the ozone ability to damage plants (Alonso et al., 2008; González-Fernández et al., 2010). In southern Europe, the high summer ozone levels occur when the seasonal drought is more intense and plants are less physiologically active. This is the reason why observed ozone impacts on natural ecosystems are often less severe than expected. Seasonal drought stress is a common situation for natural vegetation and rainfed crops. On the other hand, irrigated crops, such as horticultural species, do not experience water shortage, thus they are more subject to ozone injury throughout the summer months. Moreover, high ozone levels in spring can be more damaging since plants sustain high gas exchange rates due to warm temperatures, intense solar radiation and high plant-available soil water content (González-Fernández et al., 2010).

7.2.4 Prospects for the future

The future evolution of ozone concentration in the Mediterranean area of Europe is expected to vary following changes in ozone precursor emissions and climatic conditions, leading to either reductions or increases of ozone background levels (Dentener et al., 2006). Whether the risk of ozone effects on crops will correspond to changes in ozone levels is still uncertain due to the interaction of many climatic factors affecting plant physiology and their responses to ozone, namely air temperature, humidity and soil water availability. Furthermore, stomatal flux-response relationships for Mediterranean vegetation are still subject to considerable uncertainties in terms of ozone deposition modelling and dose-response relationship derivation. There is a clear need to further enhance the database on the impacts of ozone on vegetation under Mediterranean climatic conditions, in order to develop robust stomatal flux-effect relationships and quantify future ozone impacts in the light of climate change.

8. Case-studies of national- and local-scale risk assessments

8.1 Flux-based assessment of crop losses for the UK in 2006 and 2008

Gina Mills, Felicity Hayes, David Norris, Jane Hall, Mhairi Coyle, Howard Cambridge, Steve Cinderby, John Abbott, Sally Cooke and Tim Murrells

In this study, we quantified the impacts of ozone pollution on agricultural production in the UK according to current knowledge (see Mills et al., 2011a for full details). We based our analysis on two contrasting ozone years: 2006, representative of a hot, dry and high ozone year that is likely to become more common in the future, and 2008 a typical example of a current year. Two methods of quantifying impact were used. For three crops, wheat, oilseed rape and potato, economic losses were estimated using the flux-based methodology using available response functions. In the absence of suitable flux-based functions for maize, barley, sugar beet and peas and bean, we used AOT40-based functions to estimate economic impacts accepting that this approach is less accurate.

8.1.1 Method of quantification and certainty of estimates

To calculate the impacts of ozone on crop production in the UK, a similar approach was taken to that described in Chapter 3, with results calculated using the UK 10 x 10km Ordnance Survey grid. The economic analysis was conducted in £UK; the exchange rate in July 2011 was £1 = €1.14 and $1.63. Several types of data and model outputs were drawn together, including: crop distribution and production data from, for example, Eurostat and Defra agriculture and horticulture statistics databases; ranges in crop values by year (£/t); ozone concentration fields modelled from monitoring site data; modelled ozone flux using the Ozone Source Receptor Model with the Surface Ozone Flux Model post processor (OSRM-SOFM, Abbott and Cooke, 2010, 2011); and response functions for effects on yield from LRTAP Convention, 2010 (wheat (see **Figure 3.1**), potato), De Bock et al., 2011 (oilseed rape) or presented here for maize, barley, sugar beet, and peas and bean in **Figure 3.2**.

The certainty of the predicted crop losses varied for each crop (**Table 8.1**). Those based on ozone flux can be regarded as the most certain on a biological basis but uncertainty was introduced by underestimations of ozone flux by the OSRM-SOFM model, particularly in 2006, when compared with flux calculated using site-specific data (**Table 8.2**). Another factor decreasing the certainty of the results was the volatility of farm-gate crop values, for example, the wheat value doubled between 2006 and 2008. For this reason, the mean crop value over the period 1996 to 2009 was used as the main indicator for economic loss calculations. Both this and the apparent underestimation of ozone flux by OSRM-SOFM may mean that economic losses could be greater than predicted here. Other factors that reduce the certainty of the results include interpolation of ozone concentrations across the UK from data from a limited number of rural monitoring sites; application of response functions using data for cultivars grown in the 1980s and 1990s but not grown now; lack of flux-effect relationships for several of the crops studied and difficulty of accurately mapping crop distribution and production on a 10 x 10km grid. Assuming the flux method was used where available, the overall certainty of the results decreased in the order: wheat > potato, oilseed rape and sugar beet > barley, maize, peas and beans > salad leaf crops (**Table 8.1**).

8.1.2 Summary of main results

An important conclusion from this study was that the ozone impacts in 2008 were almost as high for the eight crops studied as those in the more extreme year, 2006 (**Table 8.1** and **Figure 8.1**). Using

Table 8.1 Summary of predicted economic losses in £UK in 2006 and 2008. Note £1 = €1.14 and $1.63

	Wheat		Potato		Oilseed Rape		Maize	Barley	Sugarbeet	Peas and beans	Salad leaf crops
2006	**POD6**	**AOT40**	**POD6**	**AOT40**	**POD6**	**AOT40**	**AOT40**	**AOT40**	**AOT40**	**AOT40**	**AOT40**
Million ha grown	1.83		0.14		0.50		0.13	0.88	0.13	0.05	0.01
Production, million t	14.73		6.07		1.64		1.25	5.23	7.37	0.18	n.a.
Total value, £ million	1385		753		379		849	497	214	28	105
Lost production, million t	0.83	1.81	0.08	0.41	0.11	0.11	0.05	0.14	0.60	0.04	n.a.
Lost value at mean price, £ million	**77.63**	**169.97**	**9.91**	**50.47**	**24.95**	**24.92**	**30.43**	**13.31**	**17.45**	**5.93**	**25.27**
Lost value at peak price, £million	**115.20**	**252.24**	**14.00**	**71.34**	**32.41**	**32.26**	**30.4**	**21.43**	**20.46**	**8.68**	**25.27**
% economic loss	**5.61**	**12.28**	**1.32**	**6.71**	**6.59**	**6.58**	**3.58**	**2.68**	**8.17**	**20.93**	**24.00**
2008											
Million ha grown	2.08		0.14		0.60		0.12	1.01	0.12	0.05	0.03
Production, million t	17.22		6.54		1.97		1.19	6.04	7.63	0.20	n.a.
Total value, £ million	1619		811		455		808	574	221	31	458
Lost production, million t	0.97	1.58	0.002	0.18	0.14	0.13	0.01	0.19	0.15	0.02	n.a.
Lost value at mean price, £ million	**91.24**	**148.07**	**0.30**	**22.51**	**32.87**	**29.90**	**8.33**	**17.65**	**4.37**	**3.02**	**59.93**
Lost value at peak price, £million	**147.53**	**239.44**	**0.35**	**31.85**	**43.96**	**40.82**	**8.33**	**28.42**	**5.12**	**4.33**	**59.93**
% economic loss	**5.64**	**9.15**	**0.04**	**2.78**	**7.22**	**6.57**	**1.03**	**3.08**	**1.97**	**9.73**	**13.07**
Certainty of estimates	High	Medium	Medium	Low	Medium	Low	Low	Low	Medium	Low	Low

Table 8.2 Total values for the economic losses and mean % yield losses for the wheat, maize, barley, potato, sugar beet, oilseed rape, peas and beans and salad leaf crops in 2006 and 2008. Notes: (1) flux-based values were used for wheat, potato and oilseed rape, AOT40-based values were used for maize, barley, sugar beet, peas and beans, and a value based on the cost of damaging ozone episodes was used for salad leaf crops; (ii) effects on pasture have not been quantified; (iii) salad crop totals for 2006 were used as a surrogate for 2008 totals; (iv) percentage economic losses are the mean of the losses per crop.

Total values	**2006**	**2008**
Lost value at mean price, £million	204.9	183.0
Lost value at peak price, £million	267.9	263.3
Mean % economic loss	9.11	6.59
with flux model correction		
Lost value at mean price, £million	268.6	184.3
Lost value at peak price, £million	359.3	252.5
Mean % economic loss	10.08	6.66

the mean farm gate price for the period 1996 – 2009, ozone pollution impacts on the yield of UK crops in 2008 (a typical current year) totalled £183 million of losses, representing 6.6% of the total value whilst those in 2006 (a typical future year which occurs occasionally now) totalled £205 million representing 9.1% of the total value for the 8 crops studied. The potential losses using corrections for flux model underestimates and peak crop value were predicted to be £359 million in 2006 and £252.5 million in 2008, representing an average of 10.1% and 6.7% yield loss for the two years respectively (**Table 8.2**).

2006

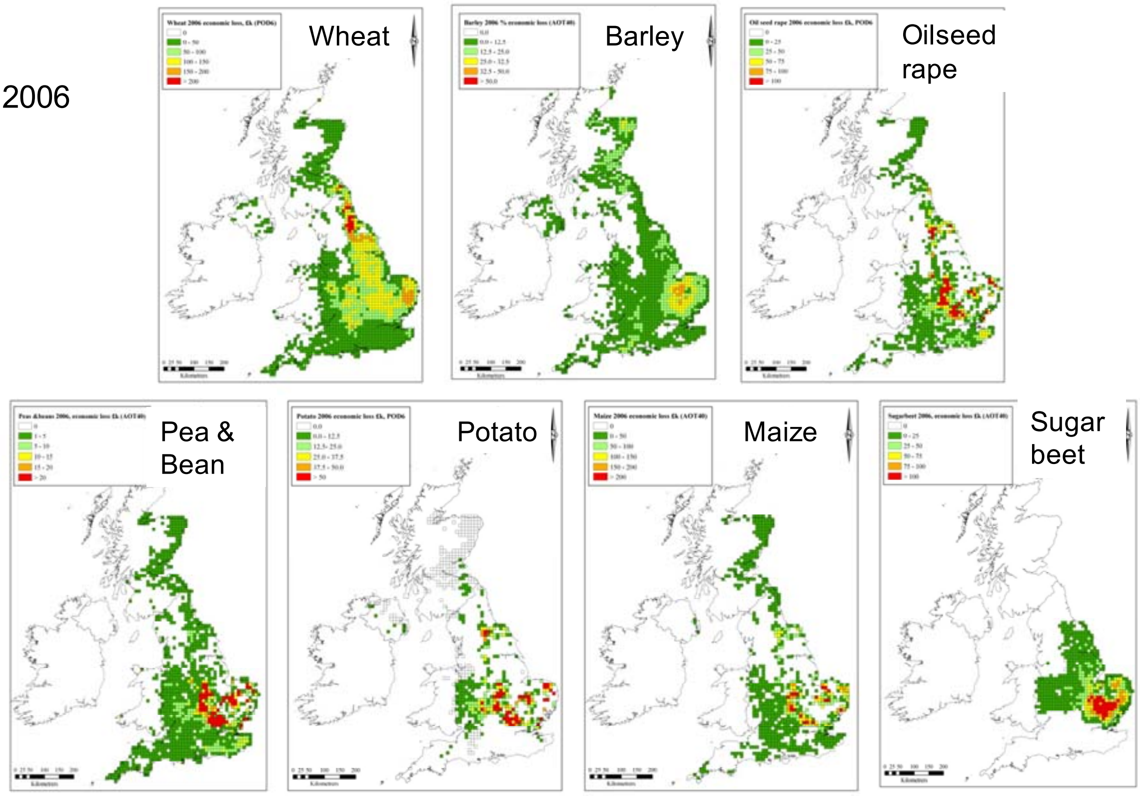


Figure 8.1 The economic impacts of ozone on UK crops in 2006 (£k loss per 10 x 10km grid square, note £1= €1.14). Maps ordered by production area in the UK .Those for wheat, potato and oilseed rape were prepared using the flux-based methodology whilst those for barley, sugar beet and peas and beans were prepared using AOT40 as the ozone metric.

2008

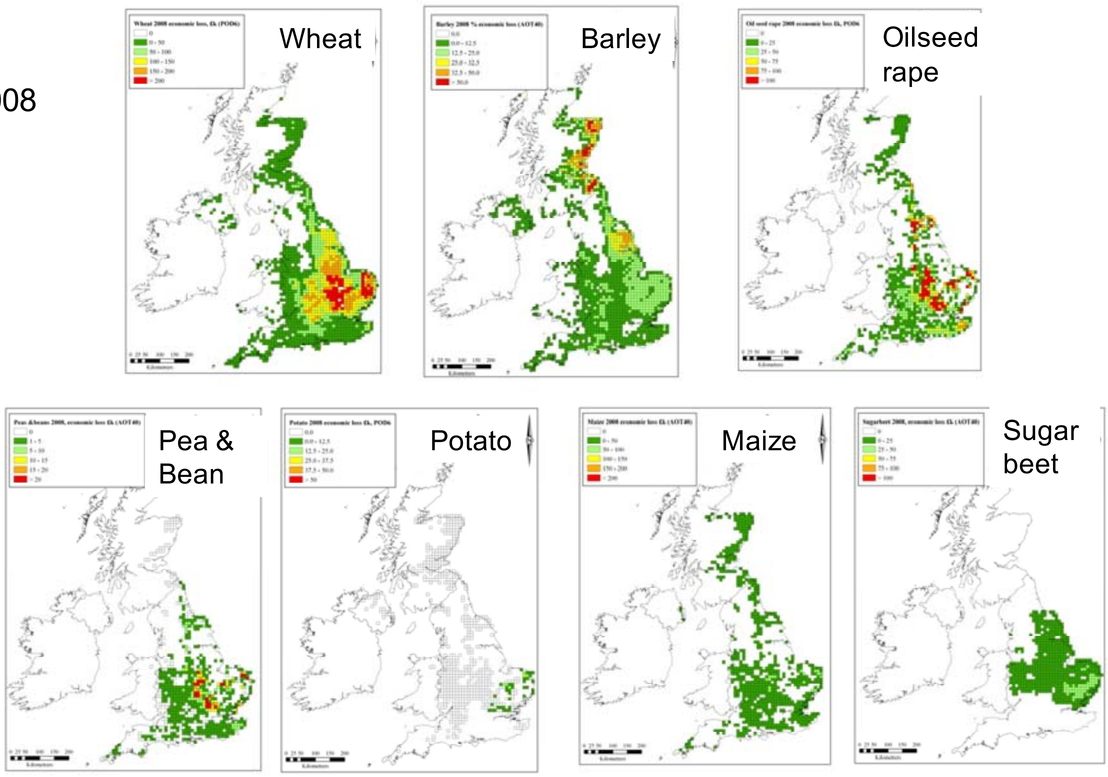


Figure 8.2 The economic impacts of ozone on UK crops in 2008 (£k loss per 10 x 10km grid square, note £1= €1.14). Maps ordered by production area in the UK. Those for wheat, potato and oilseed rape were prepared using the flux-based methodology whilst those for barley, sugar beet and peas and beans were prepared using AOT40 as the ozone metric.

This study also indicated that the areas of the UK that are potentially the most vulnerable to ozone impacts are the main growing areas of central England and East Anglia where some of the highest ozone concentrations are experienced. Losses per 10 x 10 km grid square of greater than £200,000 were predicted for wheat and greater than £100,000 were predicted for maize, sugar beet and oilseed rape in parts of these areas. Indeed there were some grid squares where total crop production losses due to ozone for all of the crops studied was ca. £600k of economic loss. Should there be times of food shortages these effects may be particularly relevant. During such times the UK may not be able to rely on excess production from neighbouring European countries to meet the UK's needs as ozone pollution levels are likely to also be high in these countries too, also impacting on their crop production.

The year by year spatial and temporal differences in climatic conditions and ozone concentrations in the UK mean that in different years and regions, different crops may be vulnerable. For example, predicted impacts for early season crops were similar in 2006 and 2008, but predicted effects for late season crops were much greater in 2006 than 2008. An important difference between the two methodologies is that the flux method differentiated between the drier conditions in 2006 and wetter conditions in 2008 (**Figures 8.1 and 8.2**). Although the mean accumulated flux for the wheat growing areas was ca. 25% higher in 2006 than 2008, the economic impacts were very similar (5.61% and 5.64% loss in 2006 and 2008 respectively). This was due to greater ozone flux and therefore impact in the main wheat growing areas of East Anglia and Central England in 2008 than in 2006.

Throughout this study, AOT40-based analyses appeared to consistently over-estimate effects for wheat, potato and oilseed rape compared to impacts determined using the flux-based methodology. Even accounting for underestimation of fluxes in 2006, AOT40-based predictions were higher than those based on flux for wheat and potato although they were similar for oilseed rape.

<u>Impacts on cereals</u> Overall, the economic impacts were predicted to be the greatest for wheat, the most extensively grown crop in the UK with monetary loss estimates of £77.6 million in 2006 and £91.2 million in 2008 based on mean crop value (**Table 8.1, Figures 8.1 and 8.2**). These represented 5.6% of the total UK production of £1.38 billion in 2006 and £1.62 billion in 2008. Taking into account under/over estimates of flux by the OSRM-SOFM model and using the maximum farm-gate price crop value in the period 1996 to 2009 of £139.5 per tonne for milling wheat, these losses could potentially have been as high as £173 million in 2006 and £132 million in 2008 representing 8.4% and 5.5% of total crop production. Although barley is moderately tolerant to ozone pollution, the economic losses at £13.3 and 17.7 million for 2006 and 2008 respectively are nevertheless of significance and represent ca. 3% of the total crop value in the UK based on mean crop prices. It is of note that economic losses of greater than £50,000 per 10 x 10 km grid square were predicted in Scotland in 2008, potentially impacting on barley supply for the malting industries. The other cereal crop studied was maize, a crop that in the last decade has been grown much more extensively in the UK. Although a flux-effect model is not available for this crop yet, the AOT40-based approach used did indicate that maize production could be impacted in years such as 2006 when ozone concentrations were high during the main grain fill period (June-August). Indeed, the potential impact on maize was strikingly different for the two years studied with economic losses predicted for 2006 being 3.7 x higher than those for 2008 (£30.4 million in 2006 compared to £8.3 million in 2008).

<u>Impacts on oilseed rape</u> For oilseed rape, a flux-effect model (De Bock et al., 2011) has only been developed for one cultivar (one that is grown in the UK) and has a relatively low significance (r^2 = 0.19, p = 0.02). In contrast, the relationship between AOT40 and relative yield is highly significant (r^2 = 0.95, p = 0.041) and includes data for 6 cultivars. Predicted impacts on economic value of the UK oilseed rape crop were very similar using both ozone metrics at £25 million in 2006 and £30-33 million

in 2008, representing 6.6 to 7.2% of the economic value (**Table 8.1, Figures 8.2 and 8.3**). Impacts in both years were predicted to be greatest in parts of central England, East Anglia and Yorkshire.

Impacts on root crops Although potato and sugar beet are moderately sensitive to ozone pollution (Mills et al., 2007), significant economic losses were predicted for both crops in 2006 when relatively high ozone concentrations occurred during the main growing periods in late spring and summer. For potato, economic losses predicted using the flux-based methodology were substantially higher for 2006 than 2008 (£9.9 million compared to £0.3 million, using mean price, **Table 8.1**). Predictions using the AOT40-based method were higher, but were only twice as high in 2006 than in 2008 (£50.5 million compared to £22.5 million). Economic losses predicted for sugar beet using the AOT40-based methodology were £17.5 million in 2006 and £4.4 million in 2008. In 2006, the highest AOT40s in the UK were found in East Anglia, the main growing areas for sugar beet and an important growing area for potato.

Impacts on legumes Most pea and bean cultivars are very sensitive to ozone. This study has shown that the ozone concentrations during the growing period for pea and bean were sufficient to induce greater than 12% yield losses in an area covering most of England south of a line from Chester to Hull, and extending westwards into Wales. Because of varietal differences in sensitivity, the relationship between AOT40 and relative yield was weak ($r^2 = 0.14$, $p < 0.01$). This, combined with the lack of a flux model for these crops, meant that there was only low certainty associated with the predictions for these highly sensitive crops. Keeping these caveats in mind, the economic losses predicted for combined pea and bean were twice as high in 2006 than in 2008 at £5.9 million and £3.0 million respectively, based on the mean crop value, representing 20.9% loss in 2006 and 9.7% loss in 2008 (**Table 8.1**). Further research is required to improve the certainty associated with these figures.

Impacts on salad leaf crops The divisions of the horticultural industry that require visibly blemish-free leaves for the highest market value are particularly vulnerable to ozone effects as many crops such as lettuce, spinach and salad onion can develop visible foliar damage (chlorotic and/or necrotic lesions) at the ozone concentrations experienced in the UK during the highest ozone episodes. Based on biomonitoring work with white clover, ozone concentrations above 60 ppb may well be sufficient to cause such damage. A first indicative assessment of losses based on the number of episodes in which the ozone concentration exceeds 60 ppb suggests that total economic impacts on lettuce and salad leaf crops in 2006 might have been similar to those expected for much more extensively grown crops such as maize and oilseed rape (**Table 8.1**). Not only would ozone pollution impact on profits due to reduced quality and weight of salad leaf crops, it would also impact on profit by additional staff time required to remove damaged leaves prior to the crop being marketed. Further details, including maps of incidences of potentially damaging ozone episodes can be found in Mills et al. (2011a).

8.1.3 Policy considerations and recommendations

Improved quantification of impacts UK crops This study was limited in scope by the small number of UK crops (3) for which the more biologically relevant flux-based methodology for quantifying impacts was available. As shown for potato, for some crops economic losses predicted using the AOT40-based approach can be almost an order of magnitude higher than those predicted using the flux-based approach. Further experimentation is required using current cultivars of the most important UK crops to provide flux-effect relationships for effects on yield quantity and quality. A more detailed investigation of ozone impacts on the horticultural industry is also required to improve quantification of economic losses associated with foliar leaf injury.

Improved spatial modelling of ozone flux The largest source of uncertainty in the flux-based assessment was from the spatial modelling of ozone flux in the UK. To align with other policy-related work within Defra, ozone flux was modelled using the Lagrangrian OSRM model to calculate ozone concentrations throughout the boundary layer together with the SOFM post-processor to model ozone flux to crops. Other models are available, including those that use the Eulerian approach (e.g. CMAQ and EMEP4UK). Modelling methods require further refinement to improve consistency and accuracy in predicting ozone concentration and flux.

Informing cost-benefit analysis for ozone precursor emission controls Together with the improved quantification described above, further research to apportion effects driven by peaks of ozone during episodes (mainly caused by emissions of precursors in the UK and nearby European countries) or increased background ozone (caused by hemispheric transport of precursor emissions from e.g. SE Asia) would facilitate cost-benefit analysis for UK emission control strategies.

Improved tools for farm-scale decision making Ozone impacts on crop production may be currently being misdiagnosed by farmers, with additional fertilizers and pesticides being used to try to compensate for lack of vigour or early crop dieback, leading to added farm costs and environmental impacts. Some studies have shown that ozone can render some species more susceptible to insect and fungal attack and there is a growing body of evidence that ozone reduces drought tolerance in crops as well as other plant species. Such interactions would benefit from further study if future impacts in a changing climate are to be appropriately quantified and planned for and appropriate guidance can be provided for farmers.

8.2 Evaluation of the ozone-related risk for wheat at the local scale

Ludger Grünhage, Jürgen Bender, Hans- Jürgen Jäger, Rainer Matyssek & Hans-Joachim Weigel

8.2.1 Introduction

According to the Council Directives of the European Union, air quality has to be assessed and managed by means of sampling points for fixed measurement of ozone concentrations in our case (Directive 2008/50/EC, 2008). In this context, local risk assessments for ozone have to be based on the parameters routinely measured by the European air quality monitoring networks and if necessary on meteorological parameters measured by a nearby measurement and observation station of the national meteorological services. Here we provide a brief overview of the first results of an ozone risk evaluation for wheat at a local scale in Germany based on the LRTAP Convention’s AOT40- and flux-based methodology. The study was performed by Working group NA 134-03-03-02 "Effects of Air Pollutants on Vegetation" of the Commission on Air Pollution Prevention of VDI and DIN – Standards Committee KRdL, Germany, using data from the air quality monitoring station Radebeul-Wahnsdorf of the German federal state Saxony, the station with the longest time series of near surface ozone concentration (4 m above ground) for rural sites in Germany. As shown in **Figure 8.3**, the ozone concentrations at this site have increased by 0.47 ppb per year between 1974 and 2010.

8.2.2 AOT40-based and flux-based assessments for Radebeul-Wahnsdorf

The exposure concentration-based critical level for agricultural crops as well as the stomatal flux-based critical level for wheat were deduced from ozone fumigation experiments with predominantly spring wheat cultivars in open-top chambers (LRTAP Convention, 2010).

Within open-top chambers the fumigation concentration measured at the top of the canopy reflects the concentration at the upper boundary of the leaf's laminar boundary layer. The LRTAP Convention's risk evaluation approach for unenclosed field conditions is based on the assumption that the ozone concentration at the top of the canopy provides a reasonable estimate of the ozone concentration at the upper surface boundary of the laminar boundary layer near the flag leaf if the roughness sub-layer near the canopy is not taken into account. Because ozone concentration is

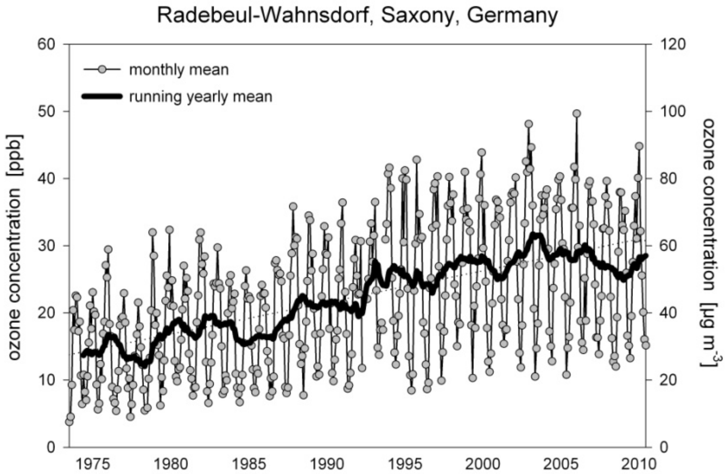


Figure 8.3 Ozone time series at the Saxon state air quality monitoring station Radebeul-Wahnsdorf, Germany.

not measured at the top of canopies by the European air quality monitoring networks, the ozone concentrations measured at a reference height above ground must be transformed to that at the top of the canopy. As stated in the LRTAP Convention's Modelling and Mapping Manual (2010) such a conversion can best be realized by an appropriate deposition model. If no meteorological data are available, then a conversion based on tabulated gradients is recommended.

The exposure concentration (AOT40)-based critical level for agricultural crops of 3 ppm.h (LRTAP Convention, 2010) was exceeded from 1995 onwards at the Saxon state air quality monitoring station Radebeul-Wahnsdorf (**Figure 8.4**). The working group (NA 134-03-03-02) interprets such exceedances of the AOT40-based critical level as a potential for risk of damages relative to "pre-industrial" ozone burden. While AOT40-based critical levels are suitable for estimating risk of damages only, stomatal flux-based critical levels and the associated responses functions should be used for assessing economic losses (LRTAP Convention, 2010). The deposition model CRO_3PS (Grünhage et al., 2011b) allows an appropriate conversion of ozone concentrations measured by the air quality monitoring stations at a reference height above ground to that at the top of the canopy, for the calculation of the toxicologically relevant Phytotoxic Ozone Dose above the flux threshold of 6 $nmol \cdot m^{-2} \cdot s^{-1}$ (POD_6). An evaluation of ozone-related risk for wheat at the local scale was conducted for two soil moisture conditions: (1) a risk evaluation for a situation with no soil water limitation on stomatal behaviour, which can be interpreted as a worst-case assessment; and (2) a risk evaluation under "actual" soil water content (not groundwater influenced), i.e. the soil water content is a function of amount and distribution of precipitation and of evapotranspiration.

The two cases provide the range of potential POD_6 and yield losses in a respective year due to soil water content and weather conditions. Potential yield losses can be estimated via stomatal flux-effect relations for relative grain yield, grain mass and protein yield (LRTAP Convention, 2010; Grünhage et al., submitted, Mills et al., 2011c):

$$\text{relative grain yield} = 1.00 - 0.038 \cdot POD_6 \qquad (1)$$

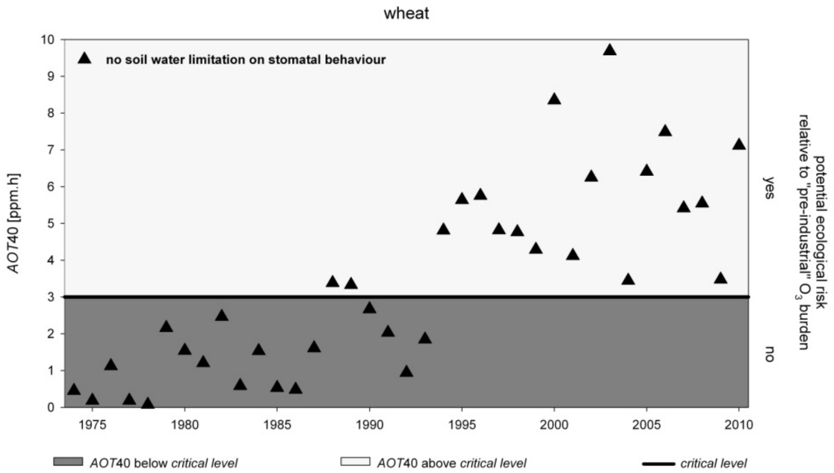


Figure 8.4 AOT40 values and exceedance of the AOT40-based critical level for agricultural crops between 1974 and 2009 at the Saxon state air quality monitoring station Radebeul-Wahnsdorf, Germany. Ozone concentrations at measurement height were converted to that at the top of the canopy applying the tabulated gradient for crops (LRTAP Convention, 2010). The AOT40 index was calculated from April 15 to July 15 during daylights hours (global radiation >50 W·m^{-2}).

$$\text{relative grain mass} = 1.00 - 0.033 \cdot POD_6 \quad (2)$$

$$\text{relative protein yield} = 1.01 - 0.025 \cdot POD_6 \quad (3)$$

…

An example of a local worst-case risk evaluation (no soil water limitation on stomatal behaviour) for relative grain yield is given in **Figure 8.5** for the monitoring station Radebeul-Wahnsdorf. From the mid 1980s onwards the critical level of 1 mmol m^{-2} for wheat grain yield (LRTAP Convention, 2010) is exceeded every year (up to a factor of 5) and potential grain yield losses between 15 and 20% interpreted as relative to "pre-industrial" ozone burden were estimated since 1995.

A comparison of the AOT40 (**Figure 8.4**) and POD_6 (**Figure 8.5**) values for the years 2003 and 2004 illustrates that an increasing exceedance of the AOT40-based critical level is not necessarily related to an increasing risk of damage. While the potential relative grain yield loss in 2003 and 2004 is nearly the same, the AOT40 value for 2004 is in the range of the exposure concentration-based critical level but exhibits the highest value of the whole assessment period in 2003. It seems that these observations can be partially attributed to the threshold problem: In comparison to the POD_6 index, the AOT40 index shows a higher sensitivity for the respective threshold as highlighted by Tuovinen et al. (2007). Beyond that both indices consider different ozone concentration ranges: While the AOT40 index is calculated from ozone concentrations above 40 ppb only, concentrations above approx. 25 ppb contributes to the POD_6 index (LRTAP Convention, 2010; Grünhage et al., 2011a).

8.2.3 Target values to communicate the degree of risk of wheat yield loss

The stomatal flux-effect relationships underlying experiments were conducted in the 1980s/1990s in Sweden, Finland, Belgium and Italy. Taking into account the POD_6 values in the non-filtered treatments in Belgium (conducted in the 1980s) of 3-4 mmol m^{-2} NF and the upper margin of the POD_6 value before 1980 at Radebeul-Wahnsdorf of 3 mmol m^{-2}, the working group (NA 134-03-03-02) recommended a POD_6 of 3 mmol m^{-2} as the target value. Relative yield losses should be related to this target value and the use of a three colour scale (traffic lights) was recommended to indicate and communicate the degree of risk for ozone damage as illustrated in **Figure 8.6**. The results of this worst-case evaluation for Radebeul-Wahnsdorf show a clear increase in the risk for yield loss from the mid 1970s to 2010 with a high risk for losses due to ozone during the last 15 years.

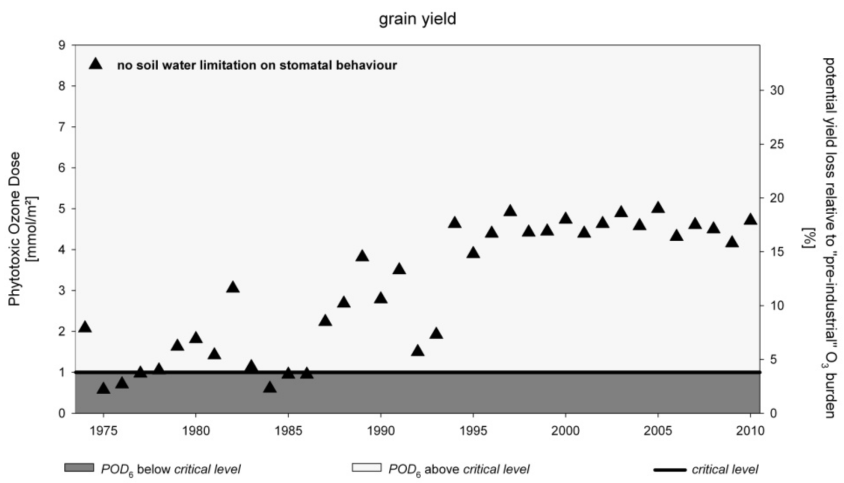


Figure 8.5 Phytotoxic Ozone Dose (POD_6) and potential grain yield loss for Radebeul-Wahnsdorf, Saxony. Worst-case risk evaluation according to the LRTAP Convention's Mapping Manual (LRTAP Convention, 2010)

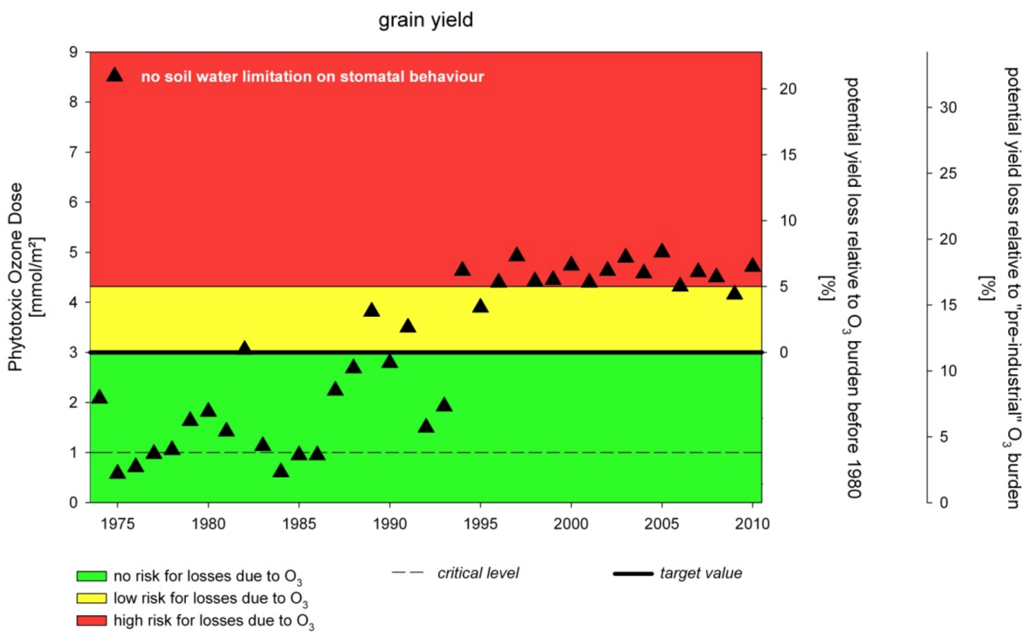


Figure 8.6 Phytotoxic Ozone Dose (POD_6) and potential grain yield loss for Radebeul-Wahnsdorf, Saxony. Worst-case risk evaluation according to the LRTAP Convention's Mapping Manual (LRTAP Convention, 2010) and the recommendations of the working group NA 134-03-03-02 "Effects of Air Pollutants on Vegetation" of the Commission on Air Pollution Prevention of VDI and DIN – Standards Committee KRdL (Grünhage et al., 2011b).

8.2.4 Conclusions

The results of this risk evaluation study applied to the local scale clearly show a high risk for potential yield losses during the last 15 years in Central Europe. This example shows how the flux-based risk evaluation developed for application at the EMEP level can be applied at the local-scale. Such an approach would be applicable in other areas using data from European air quality monitoring networks and if necessary additional data from the national weather services.

Acknowledgements

We would like to thank the Saxon State Agency for Environment, Agriculture and Geology (LfULG) and the German Weather Service for providing the ozone and meteorological data, respectively.

9. Current knowledge of the impacts of ozone on food crops in South Asia

Lisa Emberson and Patrick Büker

9.1 Introduction

Rapid industrialisation and economic growth across many parts of Asia have resulted in increased emissions of ozone precursor pollutants and hence elevated ozone concentrations. Asia is now the world's biggest emitter of NO_x, a major ozone precursor, and its NO_x emissions are predicted to further increase over the coming decades (Royal Society, 2008). Asia is also projected to see a huge increase in the proportion of the population living in urban areas (from 40% in 2007 to 66% by 2050). Continued growth is a key feature of economic policies in Asian countries such as China, India and Thailand; with other countries across the region striving to reach similar growth rates. As such, the pollution burden will continue to grow unless aggressive emission control policies are introduced and successfully implemented. In 2005, approximately 40% of people in South Asia still lived on less than $1.25 dollars a day and approximately 40% of children under 5 were malnourished (United Nations, 2010). Ozone impacts on agricultural productivity will thus have particularly important consequences for the poor and those reliant on agriculture for a livelihood in this part of the world.

In Asia there are currently no air quality standards to protect agriculture from ground level ozone; ozone standards established in some Asian countries to protect human health will not protect agriculture as they are above critical levels for crop yield response and are only implemented in urban areas. Intergovernmental efforts to raise awareness of the need for ozone standards, such as those pursued by the South Asian countries Malé Declaration on Control and Prevention of Air Pollution and It's likely Transboundary Effects for South Asia (http://www.rrcap.unep.org/male/; Malé Declaration, 2010), have yet to be successful in gaining political support for action to be taken to reduce the threat posed by ground level ozone on Asian agriculture.

Food security of many countries of South Asia is under threat due to the rapidly increasing population which increased from 1.1 to 1.5 billion from 1990 to 2005 (World Bank, 2010). As such, it is imperative that our knowledge of the potential ozone impacts on agriculture across the South Asian region be improved. This knowledge can be enhanced by conducting experimental assessments of the impact of ozone on crops and by using this information to perform regional scale modelling studies to assess the risk posed by ozone to regional scale agricultural production. Here we review the approaches that have been used to evaluate the impacts of ozone on crop yields in South Asia.

9.2 Experimental evidence

Although evidence of visible injury due to ozone on potato leaves in Punjab, India was reported by Bambawale in 1989, it's likely that the implications for agricultural production were barely explored under natural field conditions in this region until the early 1990s. In the following sections we review methods that would be considered suitable for extraction of data to build dose-response relationships that are fundamental to regional scale assessments of ozone risk to agricultural production.

9.2.1 Transect studies

Transect studies expose plants (e.g. bio-indicators are commonly used to provide consistency in results) to ambient levels of pollution across a transect or pollution gradient. The differences in crop parameters can then be related to the prevailing pollutant conditions, though care has to be taken in interpreting data where pollutants other than the target pollutant are also at high concentrations (e.g. often NO_x concentrations can also be elevated in locations with high ozone concentrations). Transect studies offer a low cost option to assess the magnitude of air pollution impacts. As such, they tend to be favoured in the Asian region where resources are limited to perform air pollution studies.

Transect studies have been performed using a number of crops in South Asia. In India, studies have used tobacco (*Nicotiana tabacum*) and found that percentage of leaf injury increased from 8% to ~30% on a transect away from an urban area; corresponding concentrations (6 hr mean concentrations from 10.00 - 16.00 hrs) for the urban site were 58 ppb for NO_2 and 34 ppb for ozone and for the rural site 10 ppb for NO_2 and 66 ppb for ozone, clearly demonstrating the importance of ozone in leading to visible injury (Agrawal, 2005). A similar study in Lahore, Pakistan again showed a correlation between the 6 hr mean ozone and NO_2 concentrations with ozone injury symptoms on tobacco Bel W3 (Wahid, 2003). Agrawal (2003) conducted a field study in sub-urban and rural locations of Varanasi, India to evaluate the impact of urban air pollutants on wheat (*Triticum aestivum* L. cv. HD2329), mustard (*Brassica campestris* L. cv. Pusa Jaikisan) and mungbean (*Vigna radiata* L cv. Malviya jyoti) plants. During the summer (March to June), with mean 6 hr ozone concentrations of 55 ppb, mung bean showed reductions of 32% in yield as compared to the plants grown at a site having mean ozone concentrations of only 14 ppb. Mean 6 hourly NO_2 and SO_2 concentrations were 14 and 6 ppb, respectively. This study clearly demonstrated that ozone plays a greater role in inducing yield losses during the early part of the summer when its formation increases due to the favourable meteorological conditions of high temperature, high incident solar radiation, long photoperiod and low humidity.

In a field study with pea (*Pisum sativum* L. cv. Arkel), yield reductions of 38% were observed at seasonal 6 hr mean ozone concentrations of 42 ppb as compared to a site having mean concentrations of 12 ppb ozone, 10 ppb NO_2 and 4 ppb SO_2 (Rajput and Agrawal, 2004). At the same seasonal mean ozone concentration, yield of a late sown variety of wheat (*T. aestivum* cv. HUW468) was reduced by 17% (Rajput and Agrawal, 2005).

9.2.2 Chemical protectant studies

A common chemical protectant study method available for ozone is the antioxidant EDU ((N-[2-(2-oxo-1-imidazolidinyl) ethyl]-N-phenylurea)), a chemical that provides protection against ozone when applied in appropriate quantities (dependent upon species and cultivar) as a soil drench, foliar spray, stem injection or gravitational infusion at frequent intervals over the crop growth period (Feng et al., 2010). However, there is still uncertainty as to the mechanism by which EDU confers protection to ozone (Paoletti et al., 2009) which can cause some unease in its demonstration of ozone effects at ambient concentrations.

EDU is known to suppress acute and chronic ozone injury on a variety of plants. Bambawale (1989) first used EDU in India to confirm that leaf injury on potato (*Solanum tuberosum*) in a rural location near Jalandhar, in northern India was due to the prevalence of high ozone concentrations. The study showed that application of EDU reduced the foliar injury symptoms in plants as compared to non-EDU treated ones. Since that time, EDU has been widely used across South Asia to assess crop yield losses due to ozone; results of these studies are described in **Table 9.1**.

From **Table 9.1** it is clear that the EDU method has been successfully used for a number of crops (mung bean, wheat, soybean, clover, Indian black gram, rice and palak) providing protection against damaging ambient ozone concentrations such that the effect of ozone on growth parameters such as yield loss can be determined. Three things should be pointed out in relation to these EDU experiments: firstly, the level of other pollutants, namely SO_2 and NO_x, needs to be considered since

Table 9.1 Selected EDU studies on assessing the effects of ozone on cereal and legume crops in South Asia.

Reference	Country/ location Land use	Mean pollutant Concentrations (ppb)			EDU conc. (ppm)	Crop	Cultivar	% reduction in non-EDU treated plants
		SO_2	NO_2	O_3				
Agrawal (2003)	India, Varanasi (Suburban)	13	36	42	400	Mung bean (*Vigna radiata* L.) .	Malviya Jagriti	12
Agrawal et al. (2005)	India Varanasi (Suburban)	-	-	42	300	Wheat (*Triticum aestivum* L)	M 533 M234	13 19
Agrawal et al. (2004)	India Varanasi (Suburban)	22.4	25.3	56	500	Wheat (*Triticum aestivum* L.)	HD2329 HUW234 HUW 468	35 46 14
Agrawal et al. (2005)	India Varanasi (Suburban)	-	-	34	500	Mung bean (*Vigna radiata* L.)	Malviya Jyoti	27
Singh et al. (2010c)	India Varanasi (Suburban)	-	-	58.7	400	Mung bean (*Vigna radiata* L.) .	Malviya Janpriya	33
Wahid et al. (2001)	Pakistan Lahore (Suburban) Roadside Rural Remote rural	- -	40* 63** 27* 34** 2* 1**	14* 26** 48* 70** 44* 75**	400	Soybean (*Glycine max L.*)	NARC- I	32 53 62 74 49 64
Singh et al. (2010b)	India Varanasi (Suburban)	-	-	30-46 µg g/L	300	Clover (*Trifolium repens* L.)	Vardan Bundel	Vardan more sensitive than Bundel
Singh & Agrawal (2010)	India Varansai (Suburban)			27-60	400	Wheat (*Triticum aestivum* L)	HUW468	27
Singh et al. (2010a)	India Varanasi (Suburban)	-	-	41-60	400	Indian black gram (*Vigna mungo* L.) cv.	Barkha, Shekhar TU-94-2)	16[1] 24[1] 8[1]
Tiwari & Agrawal (2010)	India Varanasi (Suburban)	-	-	36	150 mg/L	Carrot (*Daucus carota* L.)	Pusa Kesar	23
Singh et al. (2009b)	India Varansai (Suburban)	-	-	34-54	400	Wheat (*Triticum aestivum* L.)	HUW468 HUW510 HUW234 Sonalika PBW343	26 20 11 10 2
Wang et al. (2007)	Yangtze Delta, China	-	-	†	150-450 300	Rice (*Oryza sativa* L.) Wheat (*Triticum aestivum* L.)	Jiahua 2 Yangmei 185	0 13
Tiwari & Agrawal (2009)	India Varanasi (Suburban)	-	-	52-73	300	Palak (*Beta vulgaris* L.)	Allgreen	27 and 14[2]

* Post monsoon** Pre monsoon

† Only no. of exceedances of [O_3] limits recorded: [O_3] frequently exceeded 40 ppb, occurred less often for 50 ppb and were less frequent above 60 ppb.[1] harvest index[2] Relative Growth Rate: 27% reduction (0-30 Days after germination), 14% reduction (30-60 Days after germination).

these will also affect plant productivity and there is some concern that EDU may also protect for NO_x since this is also an oxidant which may have a similar pathway to damage as ozone; secondly, it is important to define the level of EDU to be applied since this varies by crop type; and thirdly, it is important to be aware that investigators are now using EDU to investigate a range of different crop responses to ozone, these include a variety of biochemical, physiological and yield responses and that beneficial effects may vary for each of these parameters. These considerations aside, the data collected in Table 9.1 clearly shows that ambient ozone levels found at sites across South Asia seem capable of causing yield losses frequently in the range of 10 to 20% for a number of important crops of the region.

9.2.3 Filtration and fumigation studies

Although studies using closed chambers have been conducted in Asia (Agrawal, 1982; Khan and Khan, 1998), the use of closed chambers may result in significant experimental artefacts when attempting to quantify ambient effects. **Table 9.2** provides a summary of open-top chamber data from filtration and fumigation studies that have been conducted in South Asia. As for the EDU studies, a wide variety of crops have been investigated including bean, barley wheat rice, mustard, soybean and oilseed rape; and of these crops, a reasonable number of different cultivars have been used in the studies, enough to show that there are considerable varietal differences in sensitivity to ozone within the same crop species. These studies have been conducted at sites in India, Pakistan and Malaysia though it should be noted that the tendency is for the same sites to conduct a number of different experiments, for example, in India much of the work is performed in Varanasi and in Pakistan most of the studies are conducted at a location close to Lahore. Again, as for EDU, a variety of different response parameters have been investigated; **Table 9.2** shows yield responses though a variety of different yield parameters have been often recorded. The filtration studies, which provide an indication of the yield response to ambient ozone concentrations, show yield losses commonly in the region of 10 to 20%, similar to the results for the EDU studies.

A recent review by Emberson et al. (2009) has collated and pooled data for wheat, rice and legume species from studies conducted across Asia using fumigation/ filtration and chemical protectant experimental methods. Under ozone concentrations commonly found across the Asian region (indicated by the arrowed vertical lines in the graphs) wheat, rice, and legume species (namely mung bean and soybean) are at risk from reduced yields with losses commonly in the region of 5 to 30% (Emberson et al., 2009). Nevertheless, **Figure 9.1** clearly shows that there is a tendency for Asian crops and cultivars, growing under Asian environmental and management conditions, to be more sensitive to ozone than the North American relationships for the same species would have suggested.

9.2.4 FACE studies

FACE studies elevate ozone concentrations above ambient under field environmental conditions without any enclosures, and hence are the best available approach to understand the long-term ecosystem-level effects of ozone that are increasingly recognised as significant (Ashmore, 2005). However, few FACE studies provide dose-response relationships, and they cannot be used to assess the effect of current or below-current ozone levels; therefore, data from studies using closed or open-top chambers are also important as discussed above. Despite the significance of rice and wheat as major crops in Asia, standardised experimental studies on the ozone impacts on these crops have been rather limited (Emberson et al., 2009). A step toward that direction is the FACE ozone experiment in Jiangdu, China (see **Box 9.1**).

Table 9.2 Selected Open Top Chamber (OTC) studies on the effects of ozone on cereal and legume crops in Asia. CF = charcoal filtered chambers, NF = non-charcoal filtered chambers.

Reference	Country/ Land use	Pollutant concentrations (ppb)			Crop	Cultivars	Yield reduction (%)
		SO2	NO2	O3			
Ahmed (2007)	Pakistan (Suburban)	-	CF: 11.7 NF: 6.9	CF: 8.3 NF: 61.6	Bean (*Vigna radiata* L.)	NM- 92 NM- 51	48 52
Wahid (2006b)	Pakistan (Urban fringe)	CF: 5 NF: 16	CF: 10 NF: 30	CF: 6 NF: 71	Barley (*Hordeum vulgare* L.)	Haider-93 Haider- 91 Jou- 87 Jou- 85	13 30 34 44
Wahi. (2006a)	Pakistan (Urban fringe)	CF: 5 NF;15	CF:10 NF: 28	CF: 6 NF: 72	Wheat (*Triticum aestivum* L.)	Inqilab- 91 Punjab- 96 Pasban- 90	43 39 18
Wahid et al. (1995a)	Pakistan (Suburban)	-	CF: 5.3 NF: 12.6	CF: 5 NF: 35.6	Rice (*Oryza sativa* L.)	Basmati 385 IRRI- 6	38 34
Wahid et al. (1995b)	Pakistan (Suburban)	-	CF: 8.2 NF: 23.3	CF; 5.3 NF: 35.6	Wheat (*Triticum aestivum* L.)	Pak- 81 Chakwal- 86	47 35
Ishii et al. (2004)	Malaysia (Peri urban)	CF: 4.3 NF;11.9	CF; 6.2 NF; 9.5	CF; 15 NF: 32.5	Rice (*Oryza sativa* L.)	MR- 84 MR- 185	3 6
Maggs and Ashmore (1998)	Pakistan (Suburban	-	CF: 5.3 NF: 23	CF: 5 NF; 42	Rice (*Oryza sativa* L.)	IRRI- 6	57
Rai et al. (2007)	India (Suburban)	CF: 2.2 NF: 8.8	CF: 6.1 NF: 39.8	CF: 3.2 NF: 40.1	Wheat (*Triticum aestivum* L.)	HUW- 234	21
Agrawal (2006)	India (Suburban)	CF: 2 NF: 7.7	CF: 2.2 NF: 14.5	CF: 3.1 NF: 38.5	Rice (*Oryza sativa* L.)	Saurabh- 950	11
Agrawal (2007)	India (rural)	CF: 2 NF: 6.1	CF: 2.1 NF: 13.4	CF: 4.6 NF: 47.9	Mustard (*Brassica campestris* L.)	Kranti	16
Singh et al. (2010d)	India (suburban)	-	-	NF: 70 and 100	Soybean (*Glycine max* L.)	PK 472 Bragg	19 32 (Yield response to stress)
Wang et al. (2008)	Yangtze Delta, China			CF: 15.6 NF: 103.6 and 109.2	Oilseed rape (*Brassica napus* L.)	Huyou 19	9.8 and 21.5 (Total biomass)
Rai et al. (2007)	Indian (suburban)	CF: 1.2 to 2.8 NF:4.8 to 11	CF: 5.8 to 6.5 NF:38 to 43	CF: 3.6 to 4.8 NF: 36-48	Wheat (*Triticum aestivum* L.)	HUW 234	8.4 (Harvest Index)

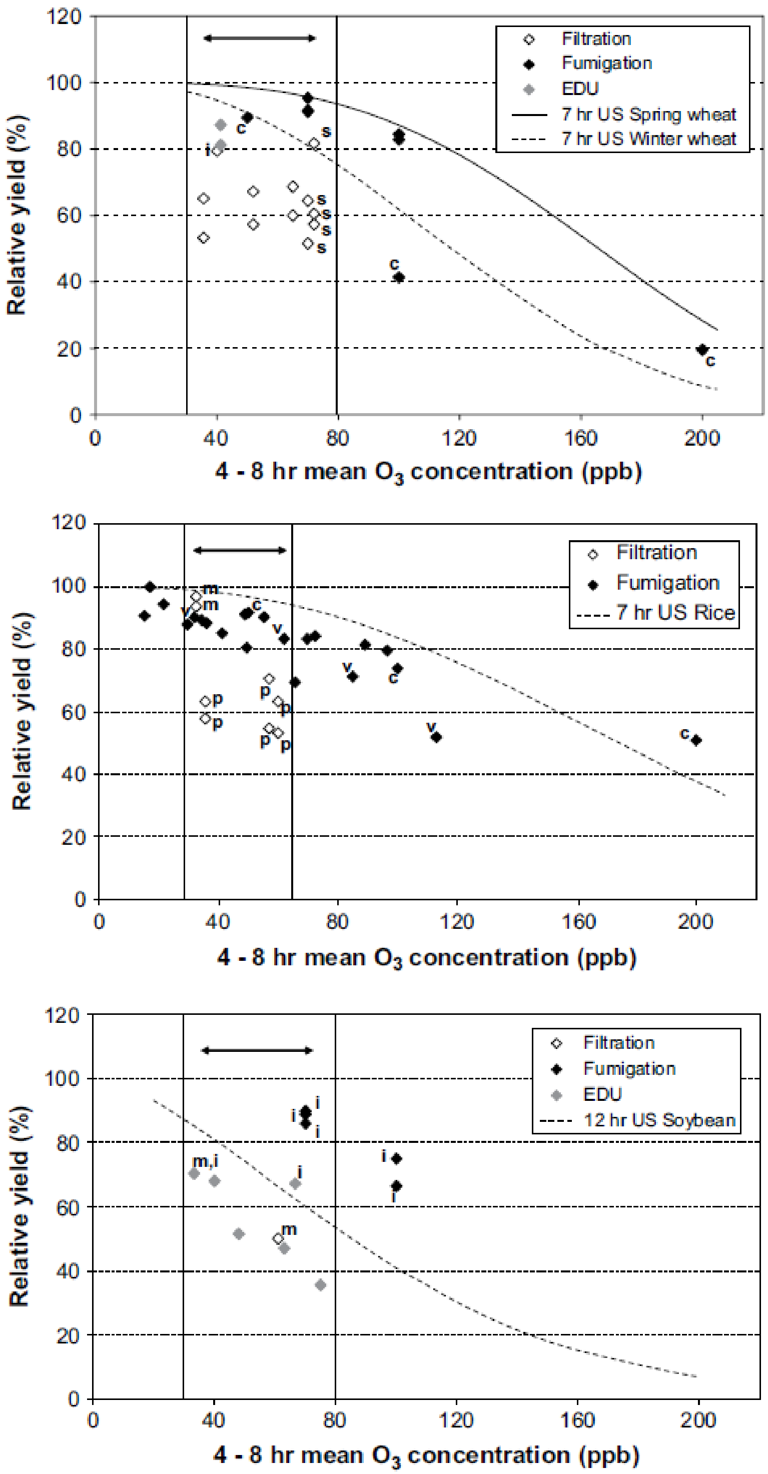


Figure 9.1 Asian yield loss data against 4–8 h growing season mean ozone exposure for a) Wheat, b) Rice and c) Legumes. North America dose–response relationships based on 7 or 12 h growing season mean ozone exposures are also shown. For further details see Emberson et al. (2009).

Box 9.1 Ozone impacts on crops in China: insights from open-air field experiments

Zhaozhong Feng

Rapid urbanization and economic development has resulted in high ozone concentrations in many cities and rural areas, especially in Yangtze River Delta and Pearl River Delta. The highest 1-h ambient O_3 concentration reached 196 ppb. During our measurements, AOT40 in ambient air reached ~8 ppm.h during wheat and rice growth seasons. Several crop loss scenarios have been established or projected by using field measurements and models. However, a recent field investigation indicated that current ambient O_3 concentration in the region of Yangtze River Delta induced yield loss by 3% in rice, 17% in wheat and 6% in oilseed rape, and the total economic loss reached $0.15 billion US (Yao et al., 2008). Moreover, 300 ppm EDU significantly increased grain yield by 12.7% for winter wheat grown in ambient air despite no visible foliar injury during the development. In contrast, EDU at tested concentrations from 150-450 ppm did not provide beneficial effects on the growth and grain yield of rice (Wang et al., 2007).

Under open-air field ozone enrichment systems, elevated O_3 (~ 125% of daily 7-h ambient [O_3]) significantly decreased the grain yield of winter wheat from 0.78 to 0.62 kg m^{-2} (20.2%) when averaged across four local cultivars and three growing seasons, and there was no significant difference between cultivars in response to ozone (Zhu et al., in press). For rice, elevated O_3 (~130% of daily 7-h ambient [O_3]) induced yield loss by 12% across four cultivars covering *japonica*, *indica* and *hybrid*. However, significant differences between cultivars were observed with larger yield loss in two *hybrid* cultivars (≥15%) while no significant reduction was found in selected *japonica* and *indica* cultivars (Shi et al., 2009). These results indicate the rising threat of surface ozone to the production of major cereal crops worldwide in the near future.

9.3 Modelling based risk assessment and economic losses

To our knowledge, only very few risk assessment studies investigating the impact of ozone on agriculture have been performed in Asia and these have been confined to the East Asian region. Wang and Mauzerall (2004) estimated economic losses for wheat, rice, maize and soybean for China, South Korea and Japan and estimated economic losses at US$ 5 billion, using 7 and 12 hr mean ozone dose-response relationships derived in North America. These losses were represented by percentage yield losses of up to 9% for the cereal crops and 23 to 27% for soybean (a species recognised as very sensitive to ozone). The magnitude of these losses was in agreement with a similar study (which only estimated yield rather than economic losses) conducted by Aunan et al. (2000), here yield losses of between 1 to 4% were estimated for wheat, rice and corn in China.

In Asia, the paucity of observed ozone concentration data means that currently, the only option for risk assessment is the use of modelled data. There is still significant uncertainty associated with modelled ozone concentrations primarily due to lack of appropriate emission inventories and extremely limited opportunity for model evaluation (Engardt, 2008). Regional ozone modelling using the atmospheric dispersion model MATCH (Engardt, 2008) has identified elevated concentrations across north eastern parts of South Asia, encompassing the fertile agricultural lands of the Indo-Gangetic Plain, the most important agricultural region in South Asia and one of the most important agricultural areas in the world. Modelling has also identified the spring and early summer months as having the highest ozone concentrations; these periods coincide with peak growing seasons for many important South Asian crops. Similar assessments are needed elsewhere in Asia; for example in East Asia, especially since the Eastern coastal plain of China is predicted to experience a large increase in surface ozone concentrations in the near future.

A provisional economic loss assessment for South Asia has been performed by Jamir et al. (in prep.) using European dose-response relationships to estimate yield losses caused by surface ozone concentrations. Yield losses were converted into production losses (based on Food and Agriculture Organisation (FAO) crop production statistics) from which economic losses were estimated in relation to the crop commodity price. This method follows standard approaches to evaluate reductions in agricultural yields caused by anthropogenic air pollutants (e.g. Wang and Mauzerall, 2004). Economic losses for South Asia were estimated to be in the region of ~US$ 4 billion per year for 4 staple crops (wheat, rice, soybean and potato) for the South Asian countries of Bangladesh, Bhutan, India, Nepal, Pakistan and Sri Lanka. The largest losses were found in India (~US$ 3 billion), Pakistan (~US$ 0.35 billion) and Bangladesh (~US$ 0.5 billion) mainly in the fertile, agriculturally important Indo-Gangetic plain. A recent field investigation indicated that current ambient ozone concentration in the region of Yangtze River Delta induced yield losses of 3% in rice, 17% in wheat and 6% in oil rape, and the total economic loss was estimated to be 0.15 billion US dollars (Yao et al., 2008). The implications of these economic losses for food security need careful consideration. For example, changes in supply will affect both consumer- and producer-crop price with implications for agricultural livelihoods and consumer accessibility to nutritionally important foodstuffs (Jamir et al., in prep.). Such effects may be enhanced in urban centres where rapid increases in urbanisation are likely to result in the urban poor becoming more vulnerable to losses in productivity both from rural as well as peri-urban agricultural production.

A number of different protocols for assessing the risks posed by a range of air pollutants including ozone to vegetation are being developed and piloted by APCEN, the Air Pollution Crop Effect Network (www.sei-international.org/apcen). One method in particular was identified for priority development to “ground truth” the provisional modelling based risk assessments and provide evidence of the real impacts of ozone on crop biomass and yield. This was an ethylenediurea (EDU) chemical protectant method that allowed quantification of yield losses of selected crops under ambient ozone concentrations (see Section 9.2.2). EDU protocols were developed by APCEN for a variety of species (mung bean (*Vigna radiata L.*), wheat (*Triticum aestivum* L.), spinach (*Spinacea oleracea* L.), potato (*Solanum tuberosum* L.) and pea (*Pisum sativa*)), using pilot studies carried out at locations in Varanasi, India (Singh et al., 2010c). These species were selected as they are known to be ozone - sensitive (Agrawal et al., 2005; cf. Tiwari et al., 2005) and are of economic importance in South Asia.

APCEN trained users from the crop experimental network of the Malé Declaration (an intergovernmental body established to control and prevent transboundary air pollution in South Asia (Hicks et al., 2001)) in the application of the protocol for mung bean. This experiment was performed at five sites in South Asia (in Bangladesh, India, Nepal, Pakistan and Sri Lanka) during the 2006/07 and 2007/08 growing season. To aid the interpretation of the results, passive samplers were used to provide four-weekly mean ambient ozone concentrations and micro-loggers to monitor temperature and relative humidity at all study sites (Büker et al., in prep.).

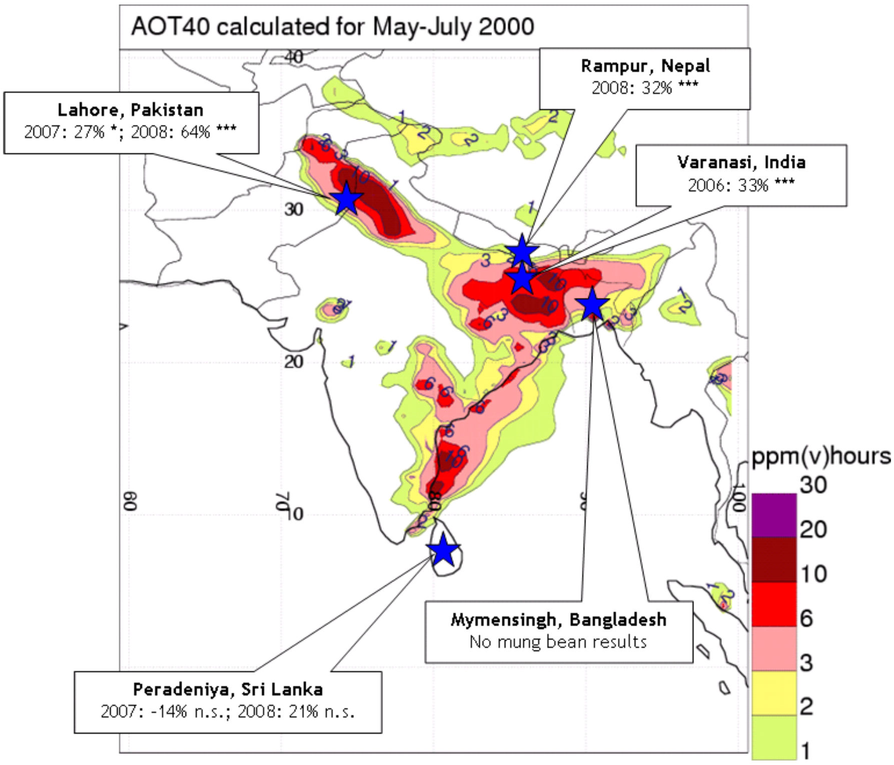


Figure 9.2 A provisional risk assessment for South Asia prepared using MATCH modelled ozone concentrations for the year 2000 presented as 3-month AOT40 concentrations for May to July. Also shown are the results of the EDU chemical protectant study for mung bean conducted at the South Asian experimental sites (indicated by blue stars) during equivalent months. The significance of the experimental results (n.s. = not significant; * p ≤ 0.05 and *** p ≤ 0.001 and yield losses (%) are indicated (Büker et al., in prep.).

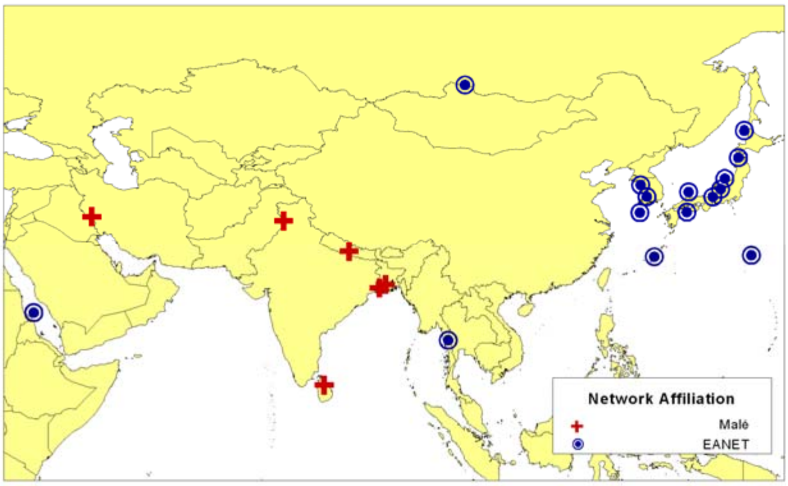


Figure 9.3 Map showing location of current rural ozone monitoring stations across Asia. Blue circles indicate the EANET monitoring sites and red crosses indicate the Malé Declaration sites (Emberson and Agrawal, 2008).

Preliminary results of these data are shown in relation to ozone concentrations presented as AOT40 for the period May, June and July which coincides with the important “pod filling” mung bean growth period (**Figure 9.2**). The results showed that those areas identified from the modelling study as being at greater risk from prevailing ozone concentrations correlated well with those sites where statistically significant damage was recorded during the experiments. The sites with the greatest ozone damage were those in Pakistan, India and Nepal where between 2006 and 2008 robust statistically significant yield losses for mung bean ranged from 32 to 64%. In contrast, statistically significant yield losses were not recorded in Sri Lanka (Büker et al., in prep.).

9.4 The limitations, uncertainties and knowledge gaps in current understanding of ozone impacts on food security in Asia

Here we review the most important knowledge gaps that limit our current understanding of both the magnitude and extent of ozone impacts on crop productivity across Asia.

Limited monitoring of rural ozone concentrations exists across Asia To our knowledge there are only two established networks that have been monitoring rural/ remote ozone concentrations across Asia according to standardised protocols:- i) the Acid Deposition Monitoring Network East Asia (EANET) (http://www.eanet.cc/) which monitors continuous ozone concentrations recording monthly means with associated maximum and minimum values (EANET, 2001); and ii) the Malé Declaration (http://www.rrcap.unep.org/ew/air/male/index.cfm) that employs passive samplers to provide mean monthly ozone concentrations. **Figure 9.3** shows the location of these ozone monitoring stations.

Comparison of the network monitored data with published site-specific data showed reasonable agreement (Emberson and Agrawal, 2008) but also emphasised the need for monitoring networks to have a good spatial coverage in rural and/or remote locations to ensure monitored data provide a true indication of the ozone concentrations to which agricultural crops may be exposed.

Understanding the seasonal cycle of ozone concentrations is also extremely important when making impact assessments of ozone on agricultural crops. Those crops whose growing seasons extend over the months February to June will be exposed to far higher ozone concentrations and be at greater risk from damage. As such, integral to any agricultural risk assessment will be knowledge of the crops growing season and how this varies with climate and local management practices across the region.
The EANET and Malé Declaration monitoring sites provide valuable information describing the seasonal cycle of ozone concentrations for locations across the Asian region. However, when considering possible ozone impacts on agricultural productivity it is also important to understand the variability in diurnal ozone profiles, since it is during the day that crops will be most physiologically active and hence vulnerable to ambient ozone concentrations. These profiles are also likely to vary substantially with urban, rural and remote geographical locations (e.g. Mittal et al., 2007).

Emission inventory uncertainties associated with regional scale modelling studies Regional scale modelling studies provide useful insights into the spatial and temporal variability in ozone concentrations both under current and projected future conditions. However, results should be treated with caution for two important reasons. Firstly, these models rely heavily on emission inventories, Asian emissions in particular are changing rapidly year on year and have strong seasonality and diurnal variation, factors unlikely to be captured by global emission inventories (Van Aardenne and Streets, 2010). Secondly, model development is dependent upon model evaluation but such comparison is problematic due to the limited availability of monitored data across Asia (see above).

Lack of standardised pan-regional experimental studies In Asia ozone studies have been performed on a relatively *ad hoc* basis (to date there have been no co-ordinated experimental campaigns like NCLAN or the EOTC chamber studies that were conducted in North America and Europe respectively). The studies conducted so far have also often been limited by financial resources and therefore have tended to use cheaper methods (e.g. chemical protectant studies and filtration studies in OTCs).

The review of existing experimental studies describing ozone impacts to crops highlights the gaps in our knowledge including:- i) the limited number of different crops and cultivars studied; ii) the limited number of locations (and hence meteorological and pollution climate conditions) under which these studies have been conducted; and iii) the inconsistency in the use of experimental methods/protocols making it difficult to pool data.

Modelling Chapters 1 and 3 described the evolution of new flux-based methods for ozone risk assessments for agriculture in Europe (LRTAP Convention, 2010). The reliance of these methods on meteorological input and crop-specific parameterisation make them easier to modify so as to be suitable for application under different climatic conditions (i.e. modified for Asian conditions). As such capacity should be built in the region to apply these new methods across Asia.

Coordination of ozone impacts research Finally, the importance of an overseeing body to co-ordinate these assessment activities should not be underestimated. This would ensure the development of appropriate policy interventions that consider ozone impacts in the context of other environmental stresses (such as climate change). In South Asia such a body has developed under the Malé Declaration that aims to engender international support and mandates to control and prevent air pollution. The establishment of international agreements similar to the Malé Declaration that encompass the whole of Asia is a big challenge for the future, but once in place could provide great benefits through the co-ordination, steering and interpretation of integrated research studies from which to develop mitigation and adaptation options for both air pollution and climate change.

10. Conclusions and recommendations

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10.1 Effects in Europe and Asia within a global context

Several recent reports have highlighted many challenges to the security of global food supplies, with concerns rising over how the growing population will be fed in the coming decades. Already nearly one billion people experience hunger and lack access to sufficient quantities of carbohydrates, fats and proteins. In this report we have described the current evidence for impacts of ozone pollution, a hidden threat to food security. We have shown how ozone has the potential to impact on food availability by impacts on production, food utilization by impacts on nutritional value and food stability by introducing year-to-year variability in yield quantity and quality; ozone may also impact on food access by being one of the factors contributing to increased prices as crop yields fall/stabilize. Ozone pollution negatively impacts on the quantity and/or quality of several of the world's most important staple food crops such as rice, wheat, maize and soybean which together account for 40% of human calorie intake globally (Avnery et al., 2011a). In areas of the world where demand already outweighs supply, the "hidden" threat from ozone impacts on crop production will add to the combined threats to food security in areas of rapidly increasing population. The current report has also highlighted the interactions between ozone and other climate change components such as drought and elevated CO_2 and how ozone effects can occur at relatively low ambient concentrations when climatic and soil conditions are conducive to ozone uptake by crops.

The quantification of global impacts of ozone pollution on food security currently relies on the use of concentration-based ozone metrics such as AOT40 and 7h mean ozone concentration. All such studies have highlighted the potential for ozone to impact on yield by between ca. 3 and 20% depending on crop. For example, Van Dingenen et al. (2009) predicted global yield loss of between 3% and 5% for maize, 7% and 12% for wheat, 6% and 16% for soybean, and 3% and 4% for rice, which represents an economic loss of $14-$26 billion. Predictions for 2030 using the A2 scenario indicate that losses may increase to 4 – 9% for maize, 5 – 26% for wheat, 15 – 19% for soybean, with losses for the more stringent B2 scenario being only a few percentage points lower (Avnery et al., 2011b). The current study has, for the first time, quantified ozone impacts on wheat yield in Europe using the flux-based methodology. We have shown that in Europe, ozone pollution could be causing an average of 13% yield loss for wheat, with an economic loss of €3.2 billion predicted if soil moisture is not limiting. The predicted mean wheat yield loss was similar to that estimated in a global study for EU-25 using AOT40 (12.1%, Avnery et al., 2011a). It should be noted that studies quantifying impacts on a global or regional scale have only considered impacts on crop yield quantity; so far no evaluation is available on the impacts on food and feed quality which are also affected by ozone. Hence, the studies conducted so far, including those described here, might have underestimated the total impacts of ozone on food security.

There is field evidence that indicates that the modelled effects reported here are actually occurring in ambient ozone. Pleijel (2011) analysed all available published data on the beneficial effect of filtering out ozone on wheat yield. Averaged over 30 experiments conducted in 9 countries of North America, Europe and Asia, there was a 9% increase in wheat yield when the ozone concentration was decreased from 35 to 13 ppb (pre-industrial concentration) in the filtered air treatment. A meta-analysis of published data on ozone effects on crops has compared effects of current (31 – 50 ppb) and future (51 – 75 ppb) ozone against a baseline ozone concentration of <26 ppb (Feng and Kobayashi, 2009). Losses in current ozone relative to the baseline concentration were indicated to be for potato 5.3%, barley 8.9%, wheat 9.7%, rice 17.5%, bean 19.0%, soybean 7.7%. Biomonitoring studies conducted by the ICP Vegetation have shown that increasing ambient ozone is associated with increasing effect on sensitive cultivars when compared with resistant cultivars (Mills et al., 2011b) and that the spatial distribution of effects correlates more strongly with flux- than with AOT40-based maps. As described in chapter 9, biomonitoring studies with the chemical protectant EDU have shown that ozone could be impacting on a number of crops in South Asia by as much as 10 – 20% (Emberson et al, 2009). Thus, these studies do provide support for the ranges of effects of ozone on staple food crops that have been predicted by modelling at the regional and global scale.

Despite the overwhelming evidence that current ozone concentrations are causing yield losses, new ozone-tolerant crop cultivars are not being developed for a future higher-ozone world (Ainsworth et al., 2008; Booker et al., 2009). Recent successes in identifying quality trait loci (QTL) associated with ozone tolerance in rice indicate the breeding for ozone tolerance in food crops is possible (Frei et al., 2008; Frei et al., 2010) yet currently, there is little if any industrial effort in this direction. There is mounting evidence from studies using both European (Barnes et al., 1990; Velissariou et al., 1992; Pleijel et al., 2006) and Chinese varieties (Biswas et al., 2008a,b) that more recently bred cultivars of spring wheat are more sensitive to ozone, in spite of rising background ozone concentrations. For rice, a field study in China has shown much higher sensitivity to ozone in hybrid varieties than conventional inbred varieties (Shi et al., 2009). The fact that ozone tolerance is inherited (Fiscus et al., 2005) makes an understanding of the ozone sensitivity of modern genomes crucial for future breeding programmes to ensure ozone sensitivity is not inadvertently bred into new varieties (Biswas et al., 2008b). Given these facts, and the interactions between the effects of ozone and climate, it will be important to consider how the introduction of climate-specific plant physiological traits (e.g. enhanced water use efficiency in regions prone to drought) may influence sensitivity to ozone, especially given the tendency of this pollutant to occur under hot, dry sunny conditions that enhance ozone formation.

In stark contrast to the gains in crop productivity made during the Green Revolution, evidence suggests that growth in crop yields in developing countries in, for example, South Asia has stabilised or been in decline over recent years. This has been attributed to a number of different factors including declining soil fertility and climate change. The evidence presented here would suggest that ozone may be an important contributing factor to the yield gap that currently exists across much of Asia (Emberson et al., 2009). Options for mitigating ozone impacts by shifting crop growing periods to try to avoid the highest ozone periods and using crops with different growth cycles seem unlikely to significantly reduce impacts (Teixeira et al., 2011). Thus, the detrimental effects of ozone on yield have important implications for sustainable agriculture given pressures on cultivated land area e.g. from expansion of crops for bio-energy production, and on agricultural supply given increasing demand from the rapidly expanding population.

The transboundary nature of ozone pollution requires international as well as national efforts to effectively reduce emissions of nitrogen oxides and volatile organic compounds and hence ozone impacts on agricultural productivity. Such emission reductions would have co-benefits for climate change and human health. Reducing ozone impacts on vegetation and health has been identified as a priority area in the Long-term strategy of the LRTAP Convention. Consideration of the evidence of ozone being a serious threat to agricultural production across the Asian region has already led to intergovernmental agreements such as the Malé Declaration, and initiatives including the Atmospheric Brown Clouds Project and the GAP (Global Air Pollution) Forum, to include ozone in their activities and research programmes. To fully realise the benefit of such international agreements there is an urgent need to develop effective policy interventions to reduce the threat to agriculture from ground level ozone. This would require improved dialogue between policy makers, stakeholders and scientists which could then lend support to the procurement of scientific evidence appropriate for policy development, enhancing the development and modification of existing policies of relevance to ozone impacts on agriculture (e.g. agricultural, transport and industrial policies), and utilising opportunities for engagement across policy fields (e.g. to encompass food security and climate change issues).

10.2 Conclusions from this study

1. Current levels of ambient ozone concentrations are reducing crop yield across the globe, with both episodic ozone peaks and background concentrations contributing to effects. With ozone concentrations predicted to continue to rise in many areas in the next decades, further yield losses are expected in the future.

2. Sensitivity to ozone varies between crop species and cultivars. Most sensitive are peas and beans, and other important food crops such as wheat and soybean are also sensitive. Tomato, maize, rice and potato are amongst the moderately sensitive species, whereas oat is tolerant to ozone.

3. Sensitivity to ozone varies between cultivars, which means that there is scope for exploiting ozone resistance within breeding programmes. In general, modern cultivars of crops such as wheat seem to be more ozone sensitive than older, traditional cultivars, suggesting that breeding for high crop productivity might have resulted unintentionally in breeding more ozone-sensitive cultivars.

4. Compared to the impact on yield quantity, less information exists on the impacts of ozone on food and feed quality and few dose-response relationships have been derived. However, impacts have been found on important parameters for food security such as the protein yield of wheat, sugar content of potato, and oil quality in oilseed rape.

5. The current study confirms that yield losses for important ozone-sensitive food crops are often in the range of 10 - 20%. Using the ozone flux-based approach, yield losses for wheat and tomato in Europe are estimated to be 13.7 and 9.4% respectively, which amounts to economic losses of €3.20 and 1.02 billion respectively in the year 2000. The greatest economic losses can be found in parts of western and central Europe (due to a combination of relatively high ozone flux and productivity) for wheat, and in Italy for tomato.

6. Although national emission scenarios indicate that ozone effects on wheat and tomato in Europe will decline in 2020, substantial exceedance of the critical levels for effects on yield will remain (82.2% and 51.3% of EMEP grid squares in the wheat and tomato growing areas respectively).

7. Due to favourable climatic conditions for ozone uptake, losses for crops such as wheat could be as high in central to northern Europe (where wheat is grown extensively) as in more southern areas of Europe, despite experiencing lower atmospheric ozone concentrations. The risk of crop losses might increase for northern Europe in a future, warmer climate when spring peak ozone concentrations might start to overlap with earlier growing seasons.

8. Despite generally high atmospheric ozone concentrations in Mediterranean areas, climate conditions (such as drought, low air humidity) do not necessarily result in high ozone uptake (fluxes) in rain-fed crop systems. However, significant effects of ozone are likely where the crops are irrigated. Prediction of ozone effects on crops in the Mediterranean part of Europe are more uncertain than those for central and northern Europe as flux models and dose-response functions are still being developed.

9. A case study for the UK has shown that ozone effects on crop yield were almost as high in a cooler wetter year with lower ozone (2008) when conditions were highly conducive to ozone uptake as in a relatively hot, dry year (2006) when higher ozone concentrations coincided with climatic conditions that were less conducive to ozone uptake. Ozone fluxes and thus predicted effects were greatest in the main crop growing areas in central and eastern UK, with several crops including wheat, barley, oilseed rape, sugar beet, peas and beans, maize and potato being impacted.

10. A local-scale study for a wheat growing area of Germany has shown a steady increase in AOT40 over the period 1975 to 2010, with the flux-based critical level exceeded from the mid 1980s onwards (no soil water limitation was assumed). A target value and traffic light system for potential risk of crop losses has been developed for communicating the risk of damage due to ozone.

11. There is evidence from air filtration and chemical protectant studies that current ozone concentrations are already reducing crop growth and yield in South Asia, with impacts of ozone in the range 10 - 30% reported for several staple food crops such as wheat, maize, rice and bean. European and American dose-response relationships appear to underestimate the impacts of ozone on crops in Asia.

12. Very few field-based experiments have been conducted on the combined impacts of ozone and climate change on crops. In general, chamber-based studies have shown that elevated CO_2 tends to reduce stomatal conductance and stimulate crop yield, hence there may be some mitigation of the impacts of ozone by reduced uptake as CO_2 concentrations continue to rise. However, recent field-based studies have indicated that the positive effect of CO_2 identified in chamber studies might have been overestimated. Although drought might protect crops from ozone damage due to a reduction in stomatal conductance and hence ozone uptake, recent research indicates that several species can become more sensitive to drought after prolonged ozone exposure.

10.3 Recommendations for policy development

1. More stringent reductions of the emissions of precursors of ozone are required across the globe to further reduce both peak levels and background concentrations of ozone and hence reduce the growing threat from ozone pollution to food security.

2. It would be of benefit to better integrate policies and abatement measures aimed at reducing air pollution and climate change as both combine together to affect food security.

3. Improved quantification of impacts of ozone within the context of climate change is urgently required to facilitate improved future planning of availability of food at a range of scales (national, regional, global).

4. There is an urgent need to raise political awareness of the adverse impacts of ozone on food security in regions such as South Asia where some of the most important staple foods of wheat, rice, maize and bean are ozone sensitive and productivity is likely to be adversely affected by ozone.

5. Crop breeding programmes should test cultivars for ozone sensitivity to develop more resistant cultivars aiming to ensure that ozone does not diminish the yield gain of the higher yielding cultivars being developed.

6. Future crop management strategies should consider ways of reducing ozone fluxes into crops, including for example withholding irrigation during episodes of peak ozone concentrations and consideration of use of chemical protectants.

10.4 Recommendations for further research

1. Further development of the ozone flux-based method and establishment of robust flux-effect relationships is required:

    - o Additional field-based ozone experiments should be conducted for current and newly developing cultivars, with effort focussed on regionally-important staple food crops.
    - o Dose-response functions should be derived for impacts of ozone on nutritionally-important aspects of yield quality as well as on quantity.
    - o Experiments are needed on the interacting effects of climate change and ozone, including quantifying impacts of reduced soil moisture availability, rising temperature and incidences of heat stress, and impacts of rising CO_2 concentration.
    - o Development of climate region-specific parameterisations for flux models to improve the accuracy of predictions.

2. Improved methods for spatial modelling of impacts of ozone on food security:

    - o For Europe, quantification of impacts for a range of future ozone scenarios incorporating predicted changes in crop price and quantification of the range of uncertainty.
    - o Improved regional modelling of the input factors for flux calculations, including modelling of soil moisture content, establishment of thresholds for irrigation application and updated mapping of the locations where irrigation facilities exist.
    - o For South Asia (and other developing areas), a network of ozone monitors is urgently required to facilitate improved ozone mapping and prediction of impacts.
    - o Development of methodology for mapping combined effects of ozone and climate change on food security.

3. Whilst technical methodology for ozone precursor emission reductions are being developed and international negotiations are taking place to reduce national and transboundary ozone, the development of crop management practices that will reduce or alleviate ozone stress is required, including:

    - o Testing of current varieties for ozone sensitivity to provide farmers with a list of ozone-resistant cultivars for use in regions where negative impacts of ozone are likely.
    - o Improved recognition of ozone sensitivity within crop breeding programmes, facilitating the selection of ozone-resistant cultivars.
    - o Development of locally-applicable crop management practices that provide farmers with methods of reducing impacts, including, for example, appropriate cultivar selection, withholding irrigation during the highest ozone episodes and possible use of chemical protectants.

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Ozone pollution: A hidden threat to food security

This report synthesises current knowledge on the effects of the gaseous air pollutant, ozone, on the quantity and quality of crop yield and discusses the implications for food security. Several of the world's most important staple food crops such as rice, wheat, maize and soybean, which together account for 40% of human calorie intake globally, are sensitive to ozone pollution. For the first time, ozone effects on wheat and tomato yield in Europe have been quantified using the flux-based methodology that takes into account the modifying effect of climate, soil and plant factors on the amount of ozone taken up through leaf pores. This report also summarises current concerns on ozone pollution impacts on food crops in northern Europe, Mediterranean Europe and south Asia, and describes case studies on impacts at the national (UK) and local (Saxony, Germany) scales. Impacts of ozone on food and feed quality are also considered together with a review of ozone impacts on food security within a changing climate. Recommendations are made for future policy aiming to protect crop plants from this "hidden" threat to yield quantity and quality.

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