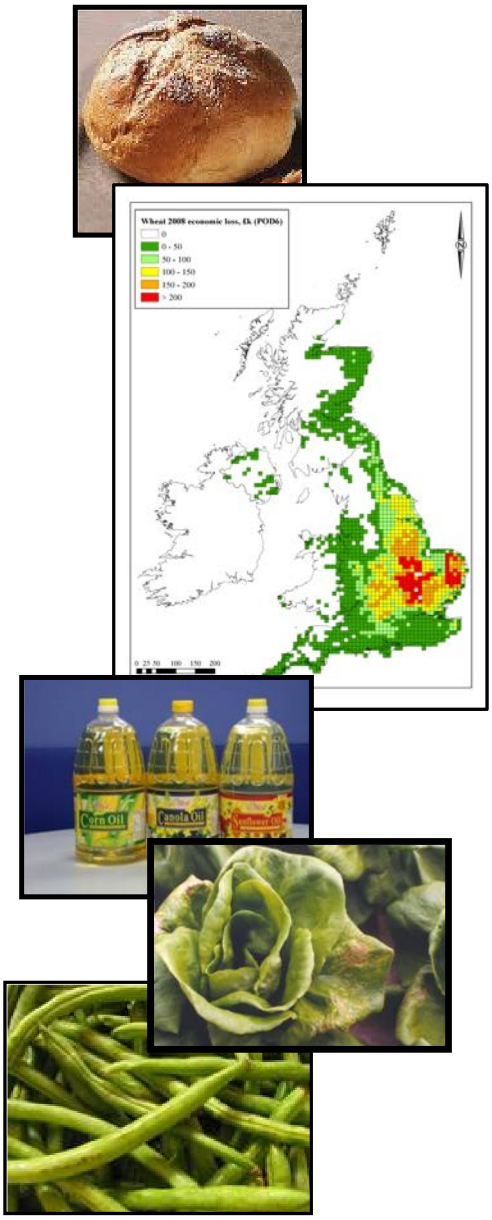

Impacts of Ozone Pollution on Food Security in the UK: a Case Study for Two Contrasting Years, 2006 and 2008

Defra contract AQ0816

November, 2011

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

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Executive Summary

Background

Many of our most important food crops respond to ozone pollution by decreasing vegetative growth, seed production and root growth leading to reductions in both quantity and quality of yield. Several horticultural crops, including the so-called “ready-to-eat” salad leaf crops, develop visible leaf damage following ozone episodes that reduces their market value.

In this study, we have quantified the impacts of ozone pollution on agricultural production in the UK according to current knowledge and have made recommendations for research that would provide understanding to help reduce future impacts on UK crop production and improve the security of our food supplies.

We have 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 a modelling approach that relates the accumulated amount of ozone absorbed by leaves (ozone flux or “phytotoxic ozone dose above a threshold of 6 nmol m^{-2} s^{-1}”, POD_6) to effects on seed or tuber yield. This method is the most biologically relevant as it allows for the modifying effects of climate and soil moisture on the phytotoxic ozone dose absorbed by the leaves but currently has only been developed for these three crops. The second method predicted effects based only on the ozone concentration in the air above the leaves and is regarded as being less accurate. This latter method uses the accumulated ozone concentration above a threshold of 40 ppb during daylight hours (AOT40) as the ozone metric.

Method of quantification and certainty of estimates

To calculate the impacts of ozone on crop production in the UK, several types of data and model outputs were drawn together. These included: 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); and response functions for effects on yield.

The certainty of the predicted crop losses varied for each crop (Table 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 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 are even 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 and pasture.

Impacts of ozone on UK crop production

At the UK-scale

The results of this study are provided in Table 1 and summarised in Table 2, taking into account the impacts of crop price variation and underestimations of ozone flux by the OSRM-SOFM model in 2006.

- Using the mean farm gate price for the period 1996 – 2009, ozone pollution impacts on the yield of UK crops in a **typical current year** (e.g. 2008) and totalled **£183 million of losses**[1], **representing 6.6% of the total value** for the 8 crops studied. Affected crops[1] include cereals (wheat 5.6% yield loss, barley 3.1% and maize 1%), root crops (sugar beet 2%, potato 0.04%), oilseed rape (7.2%), peas and beans (9.7%) and salad leaf crops (ca. 24%).

- Under climatic and ozone conditions expected to **occur more frequently in the future** (using 2006 as an example), ozone effects on total yield for the studied crops were slightly higher than those predicted for 2008 at **£205 million**[1] **representing 9.1% of the total value** for the 8 crops studied. Affected crops[1] include cereals (wheat 5.6%, barley 2.7% and maize 3.6%), root crops (sugar beet 8.2%, potato 1.3%), oilseed rape (6.6%), peas and beans (20.9%) and salad leaf crops (24%).

- **The potential losses** using corrections for flux model underestimates and peak crop value are 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.

- Based on AOT40, the agricultural crops studied decreased in sensitivity as follows: pea and bean > wheat > potato and oilseed rape > sugar beet > maize and barley.

- The results indicate that **crop production could be substantially reduced by ozone in the main growing areas of central England and East Anglia** under extreme ozone events, reducing the security of UK national food supplies. As such conditions usually also occur at the same time in our neighbouring European countries, we may not be able to rely on using their excess production to meet the UK's needs.

- In central England and East Anglia, there are several 10 x 10 km grid squares where crop production losses due to ozone are expected for all of the crops studied, totalling ca. £600k of economic loss per grid square.

- 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.

- AOT40-based analyses consistently over-estimated effects for wheat, potato and oilseed rape compared to impacts determined using the flux-based methodology; flux-based effects were systematically underestimated in 2006.

[1] Note: 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; Effects on pasture have not been quantified; Salad crop totals for 2006 were used as a surrogate for 2008 totals.

Table 1 Summary of expected losses in economic value in the UK due to ozone in 2006 and 2008

	Wheat		Potato		Oilseed Rape		Maize	Barley	Sugar beet	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**	**30.43***	**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**	**n.a.**
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**	**n.a.**
% economic loss	**5.64**	**9.15**	**0.04**	**2.78**	**7.22**	**6.57**	**1.03**	**3.08**	**1.97**	**9.73**	**n.a.**
Certainty of estimates	High	Medium	Medium	Low	Medium	Low	Low	Low	Medium	Low	Low

* 2007 prices available only

** 2008 prices available only

Table 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	9.1	6.6
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	10.1	6.7

Key effects for each crop

- **Wheat, the UK's most important crop economically, is one of the most sensitive crops to ozone pollution.** Of the 8 crops studied, economic impacts are predicted to be the greatest for wheat, with monetary loss estimates of £77.6 million in 2006 and £91.2 million in 2008 based on mean crop value. Taking into account underestimates of flux by the OSRM-SOFM model and using the maximum crop value, these losses could potentially have been as high as £173 million in 2006 and £132 million in 2008.

- 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 significant and represent ca. 3% of the total crop value in the UK based on mean crop prices.

- AOT40s during the main growing and grain fill period for **maize** (June-August) were higher in 2006 than 2008 resulting in 3.7 x higher economic losses (£30.4 million in 2006 compared to £8.3 million in 2008).

- Predicted impacts on economic value of the UK **oilseed rape** crop were very similar using both ozone metrics at £25 million in 2006 and £30-33million in 2008, representing 6.6 to 7.2% of the economic value.

- 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). 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.

- 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.

- The divisions of the horticultural industry that require visibly blemish-free leaves for the highest market value are particularly vulnerable to ozone effects. A first indicative assessment of losses 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.

- The **clover component of pasture, vital for nitrogen fixation,** is vulnerable to ozone at the current and expected future ozone concentrations, with the potential to reduce pasture quality, impact on milk and meat production, and lead to increased compensatory fertilizer usage with economic and environmental consequences

Policy considerations and recommendations

Improved quantification of impacts on agricultural 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 is 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.

- **Recommendation (1):** Further experimentation using current cultivars of the most important UK crops of wheat, oilseed rape and potato to improve existing response-relationships, and to develop new relationships for those crops for which no flux-effect relationships currently exist (e.g. barley, maize, sugar beet and oats). New/improved relationships should take into account effects on both yield quantity and quality.

- **Recommendation (2):** Further ozone exposure experiments should be conducted for the grass : clover mixtures currently in use and being developed for sustainable pasture allowing impacts on this potentially very vulnerable agricultural system to be quantified.

Improved quantification of impacts on the horticultural industry

This initial study has highlighted the potential for significant economic losses within the horticultural industry as a result of ozone pollution. Losses were tentatively quantified for salad leaf crops, but ozone could be damaging many other crops for which the visible appearance of leaves determines the quality of the product such as cabbage, salad onions, herbs, foliage plants etc. and hence the value.

- **Recommendation (3):** A more detailed investigation of ozone impacts on the horticultural industry is required. This should include surveys for ozone injury following episodes and on-farm measurements of stomatal conductance, climatic conditions and ozone to facilitate the development of ozone-flux based indicators of damage, facilitating a more reliable estimate of economic losses.

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) .

- **Recommendation (4):** 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

It is not currently possible to determine whether effects are 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). Together with improved quantification described above, further research to apportion effects would facilitate cost-benefit analysis for UK emission control strategies.

- **Recommendation (5):** To inform policy development, new experiments are required to quantify the beneficial effect of different emission control strategies (including for scenarios being considered by the UK and the LRTAP Convention for 2020 and 2030) on crop yield, including effects of reducing peak concentration within an ozone climate where background ozone is increasing.

Improved tools for farm-scale decision making

Although not included within the remit of this study, the following points have arisen during the course of the study that are worthy of consideration for future research plans, leading to improved 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. Further work is needed to understand interactions between ozone and nitrogen, and the extent to which fertiliser input can offset the effects of ozone.

- There is a growing body of evidence that ozone reduces drought tolerance in crops as well as other plant species. Other studies have shown that ozone can render some species more susceptible to insect and fungal attack. Such interactions would benefit from further study if future impacts in a changing climate are to be appropriately quantified and planned for.

- In order to provide guidance to farmers on how to avoid impacts of ozone, the following research would be beneficial:
    - A review of current knowledge on effectiveness of potential avoidance strategies
    - A screen of the ozone sensitivity of most commonly used UK cultivars
    - Studies of the potential for avoiding ozone damage by withholding water in irrigated crops, thereby closing the stomatal pores on the leaf surface and preventing ozone uptake (reaching a balance between reduced ozone uptake and drought-reduced crop growth).
    - Screening of currently available or soon-to-be registered possible chemical protectants for ozone damage.
    - Cost-benefit analysis of proposed strategies at the farm-scale.

- Assuming suitable avoidance strategies are available, the feasibility of using an early warning system for farmers and growers that would signal the need to take evasive action could be explored.

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1. Introduction

1.1 Aims

- To conduct a flux-based assessment of losses in yield due to ozone exposure in the UK for four crops, and to quantify economic losses
- To conduct an AOT40-based assessment for six UK crops (including two for which flux-based assessments will be conducted as above), and to quantify economic losses
- To assess the implications of ozone exposure for the horticultural industry by quantifying the risk of loss of salad leaf crop value due to visible leaf injury
- To identify knowledge gaps and make recommendations for further research

1.2 Background

Sustainably securing global food supplies for the rapidly growing population is one of the most important challenges facing mankind in the coming decades. International initiatives, such as the FORESIGHT global food and farming futures project (http://www.bis.gov.uk/foresight), have identified several components to this challenge which need to be addressed in order to protect the food system: sustainable balance of food demand and supply; ensuring adequate stability in food prices; achievable global access to food and ending hunger; managing the contribution of the food system to the mitigation of climate change; and maintaining biodiversity and ecosystem services whilst feeding the world. In the UK, increasing pressures on land together with the increasing population and growing threat from climate change mean that we have to produce our food more sustainably and reduce impacts from as many environmental stressors as is possible. One such environmental stress is ozone pollution. At the global scale, ozone has been predicted to pose as big a threat to food security as climate change by 2030 (Royal Society, 2008). Until this study was conducted, there has been no detailed assessment of the potential for ozone to impact on crop production and food security in the UK under current and potential future conditions.

Formed from complex photochemical reactions involving anthropogenic and biogenic emissions of nitrogen oxides (NO_x), carbon monoxide (CO) and non-methane volatile organic compounds (NMVOCs), the background ozone concentration has steadily increased over recent decades (RoTAP, 2011). Superimposed on the increasing background concentration are ozone episodes in which the concentration rises above the background, sometimes for several days at a time, when conditions are especially conducive to ozone formation. Many of our most important food crops respond to ozone pollution by decreasing vegetative growth, seed production and root growth leading to reductions in both quantity and quality of yield. Several horticultural crops, including the so-called “ready-to-eat” salad leaf crops, develop visible leaf damage following ozone episodes that reduces their market value. In this study, we have quantified the impacts of ozone pollution on agricultural production in the UK according to current knowledge and have made recommendations for future research that would help to develop ways of reducing future impacts on UK crop production and further securing our food supplies. We have based our analysis on two contrasting ozone years: 2006 (representative of a hot, dry and high ozone “future” year) and 2008 a typical example of a current year.

1.3 UK crop production and choice of crops

Ozone impacts on crop production have the potential to impact on the UK national economy with £8 billion (9%) of the gross value added by the agri-food sector in 2008 being from agriculture and fishing (Defra, 2010). The UK also accounted for 11% of the manufacture of food products and beverages in the EU in 2007. About 60% of the food we eat in the UK has been produced in the UK (Defra, 2010), with prices fluctuating annually according to supply, national and international pressures. Food prices for the consumer declined in real terms between 1998 and mid-2007 but then rose rapidly to a peak in

February 2009 (Defra, 2010). This rise in food prices between the two years included in this study (2006 and 2008) was matched for most crops by a rise in crop value (mean £/tonne). For example, the value of wheat used for milling rose from £77/tonne in 2006 to £152/tonne in 2008. As such a dramatic increase in crop value would impact on the comparison of ozone effects between the two years. To allow meaningful comparison, we have used the mean yield value in £/tonne between the years 1996 and 2009 and the peak value to calculate the losses for each crop (see Chapter 2).

Over 50% of the UK land area dedicated to crop production is sown with wheat or barley each year (Figure 1.1). Oilseed rape accounts for 12.6% of the land area, and other crops such as potato, maize, sugar beet and oats account for about 2-3% of the land area each. The crops included in this study account for 89.8% (2006) and 90.8% (2008) of the UK land area dedicated to crop production. As described in Chapter 2, choice of crops was restricted to the availability of ozone response functions.

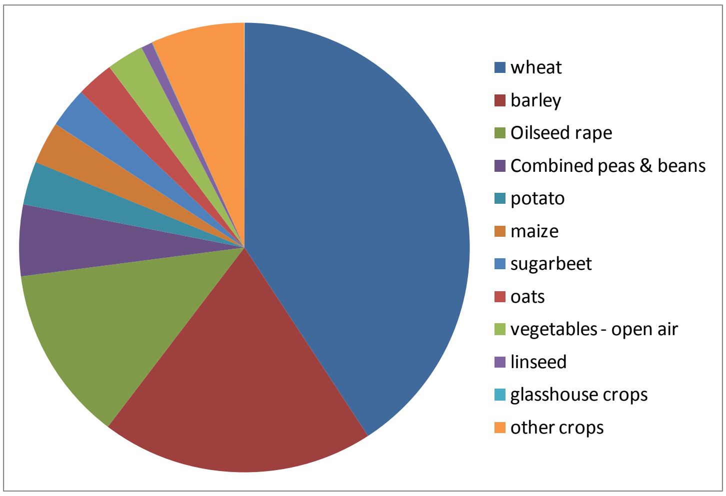

Figure 1.1 Proportion of UK crop production area sown with each crop in 2006 (Source: http://www.defra.gov.uk/statistics/foodfarm/).

1.4 Effects of ozone on crops

Ozone is absorbed into plants via the stomatal pores on the leaf surface. These pores open and close according to climatic conditions, soil moisture content and plant growth stage, with the stomata being most widely open under warm, humid conditions with adequate soil moisture available. Modelling the impacts of climate, soil and plant factors on the opening and closing of stomata allows the amount of ozone entering the plant (i.e. the flux of ozone to the plant) to be estimated and related to the impacts of ozone.

Once inside the plant, a proportion of the absorbed ozone is detoxified by the plant's natural defence mechanisms; the reaction products of the remaining ozone cause damage to cell membranes and impact on photosynthesis. Effects of ozone are cumulative, the greater the amount absorbed over a time period, the greater the effect. Over the life cycle of a crop, ozone reduces vegetative growth including premature dieback of leaves, reduces root development and decreases the amount of photosynthate reaching the seeds leading to seed abortion and reduced seed weight.

Many crops are sensitive to ozone within the range of concentrations experienced in the UK. Effects have been detected by exposing crops growing in the field in open-top chambers (Figure 1.2) 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. Data from the open top chamber experiments have been collated and analysed for crop sensitivity to ozone (Mills et al., 2007). Wheat, peas and beans were found to be amongst the most sensitive group of crops, with potato, oilseed rape and sugar beet being moderately sensitive and maize and barley being moderately tolerant and tolerant respectively. Since then, as part of work package 5 of this contract, this database has been updated with recently published papers, and barley has been reclassified as moderately tolerant to ozone (see contract report and European crop loss assessment currently being prepared). 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).

Several crop species respond to ozone episodes by developing visible injury on the leaves. Such injury appears first on the upper surface of older leaves as pinhead sized cream or bronze-coloured lesions. (Figure 1.3 (a)). After prolonged exposure to ozone episodes, the lesions join to cover large areas of both leaf surface (Figure 1.3 (b)) and the leaves are abscised from the plant. Development of visible injury does not necessarily mean that the seed yield will be reduced for crops such as wheat as some recovery can occur if there are no further episodes. Ozone injury development is, however, a much bigger problem for the horticultural industry where crop value is dependent upon the visual appearance of the foliage. Crops such as lettuce (including "ready-to-eat" salad leaves), spinach, spring onion and several herbs such as coriander and basil can develop ozone injury symptoms at the concentrations experienced during ozone episodes in the UK.

Figure 1.2 Exposure of wheat to ozone in Open-top chambers placed over the crop as it emerged. Source: H Pleijel, Sweden.

Figure 1.3 Ozone damage to lettuce on a commercial farm in Greece (a) hydroponically-grown indoor crop and (b) outdoor crop. Photos courtesy of D. Velissariou.

1.5 Quantifying the impacts of ozone on crops in the UK

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 derived for the development of the LRTAP Convention's Gothenburg Protocol to abate the effects of acidification, eutrophication and ground level ozone were based on AOT40, the accumulation of hourly mean concentrations above a threshold of 40 ppb. 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 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).

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

The flux-based critical levels for grain yield in wheat and tuber yield in potato and their associated response functions were used in this study to quantify ozone impacts in the UK. Two further flux-based analyses were conducted in this study: oilseed rape seed yield and impacts on the clover content of pasture. For wheat, potato, oilseed rape, sugar beet, maize, barley, peas and beans an impact analysis has been conducted using AOT40-based response functions that have been updated from the original Mills et al. (2007) study. We have also included an impact study for ozone effects on salad leaf crops by quantifying the frequency of ozone episodes and estimating the effects on market value of associated visible injury.

1.6 Mapping ozone flux and concentration

Chemical transport models are used to estimate the temporal distribution of ozone in the UK. These fall broadly into two groups dependant on approach used: Lagrangian and Eulerian. In simple terms, Lagrangian models calculate ozone distribution from the trajectories of a large number of individual parcels of air whereas Eulerian models use a fixed three dimensional frame of reference and compute the temporal changes in concentration within each grid cell from the physical and chemical compositions. Both approaches have advantages and disadvantages, with several variants in use (Monks et al., 2007). The LRTAP Convention uses the Eulerian approach within the EMEP model for mapping ozone concentrations and fluxes across Europe, and a UK version of the EMEP model (EMEP4UK) has been developed. When reviewing options for modelling ozone formation and impacts on ecosystems and health in the UK, Monks et al. (2007) recommended that Defra should consider moving towards using Eularian models. A further report comparing modelled predictions of hourly mean ozone concentrations has been prepared for the Defra Air Quality Modelling Review Steering Group (Carslaw, 2011). For this study, a Langragian model developed by AEA was used as this model is currently in use for policy work related to the health impacts of ozone and its use facilitates cross referencing between predictions for effects on health and ecosystems. Thus, to model spatial and temporal changes in ozone flux across the UK, the AEA Ozone Source Receptor-Surface Ozone Flux model (OSRM-SOFM) was used in combination with the SEI ozone deposition to vegetation (DO_3SE) model. It has been noted, however, that the OSRM-SOFM model tends to underestimate ozone concentration and flux in the dry years such as 2006 (Abbott and Cooke, 2010). Ozone concentration and AOT40 maps have been created using the UK ozone monitoring sites data.

1.7 Selection of years for study

Two contrasting ozone and climate years were selected to assess ozone impacts on crop production in the UK: 2006 and 2008. 2008 was selected as an example of a typical current year. The spring daily maximum temperature in 2008 was between 12 and 16 °C over most of England, Wales and Northern Ireland excepting the mountainous areas and NE England (Figure 1.4), and rainfall totals were in the range 100-300 mm in these regions (Figure 1.5). Mean daily maximum temperatures in 2008 were generally lower in the crop growing areas of Scotland (10 – 14 °C), with rainfall totals in the range 100 - 400 mm. In the summer of 2008, mean daily maximum temperatures were in the range 14 – 20 °C in Wales, SW England, N England, Scotland and Northern Ireland with rainfall totals in the range 200 – 800 mm. Mean daily maximum temperatures were warmer in the rest of England, ranging from 18 – 22 °C with lower rainfalls in the range 100 to 300mm. 2006 was selected to represent climatic conditions that would become a more frequent occurrence in an increasingly warmer climate in the coming decades. Spring maximum temperatures and rainfall totals in the UK were similar in 2006 to 2008 but temperatures were a few degrees warmer in the summer, ranging from 18 – 24 °C over most of the crop growing areas of the UK with less rainfall (mainly <200mm).

The ozone concentrations associated with these climatic conditions are described in detail in Section 3.2. In summary, the ozone concentrations were similar in the spring of both years but differed in distribution with the highest concentrations in 2006 being in E Anglia, SW England and northern Scotland whilst in 2008 the highest concentrations were in NE England and N Scotland. The biggest contrast between the two years was in the summer, with ozone concentrations continuing to be high in East Anglia and moderate in the rest of England and E Wales in 2006, but being low across most of the UK in the summer of 2008.

1.8 Structure of this report

This introduction is followed by a chapter describing the methodology used. An analysis of the impacts at the UK scale including quantification of the certainty of the data is presented in Chapter 3, and individual chapters follow for the crops, grouped by cereals (Chapter 4), oilseed rape (Chapter 5), root crops (Chapter 6), legumes (Chapter 7), salad leaf crops (Chapter 8) and pasture (Chapter 9). In the final chapter, an overview of the main conclusions is presented together with policy and research recommendations. At the start of each chapter is a text box summarising the main conclusions.

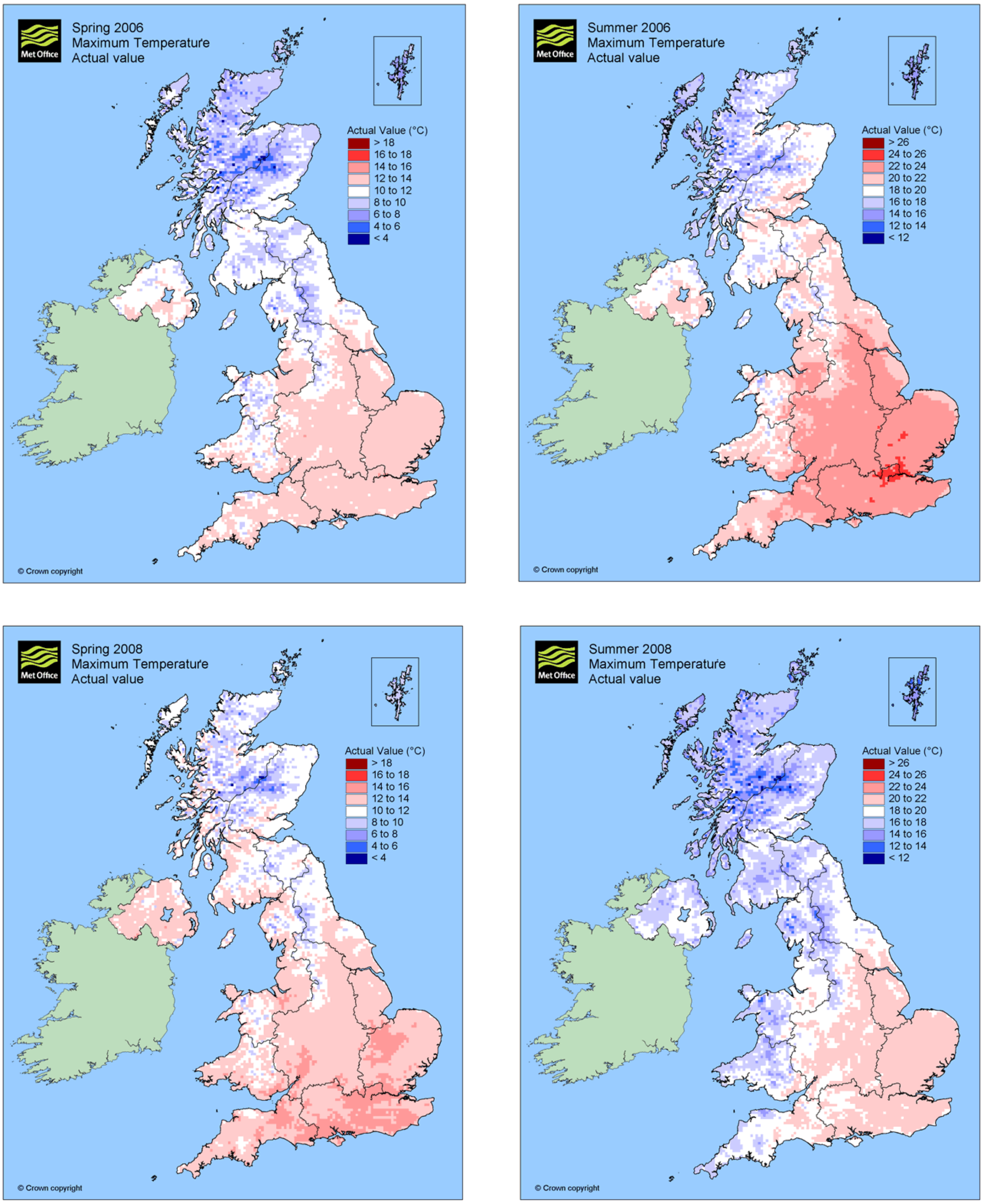

Figure 1.4 Mean daily maximum temperature for the UK in the spring and summer of 2006 and 2008. Source: http://www.metoffice.gov.uk/climate/uk/

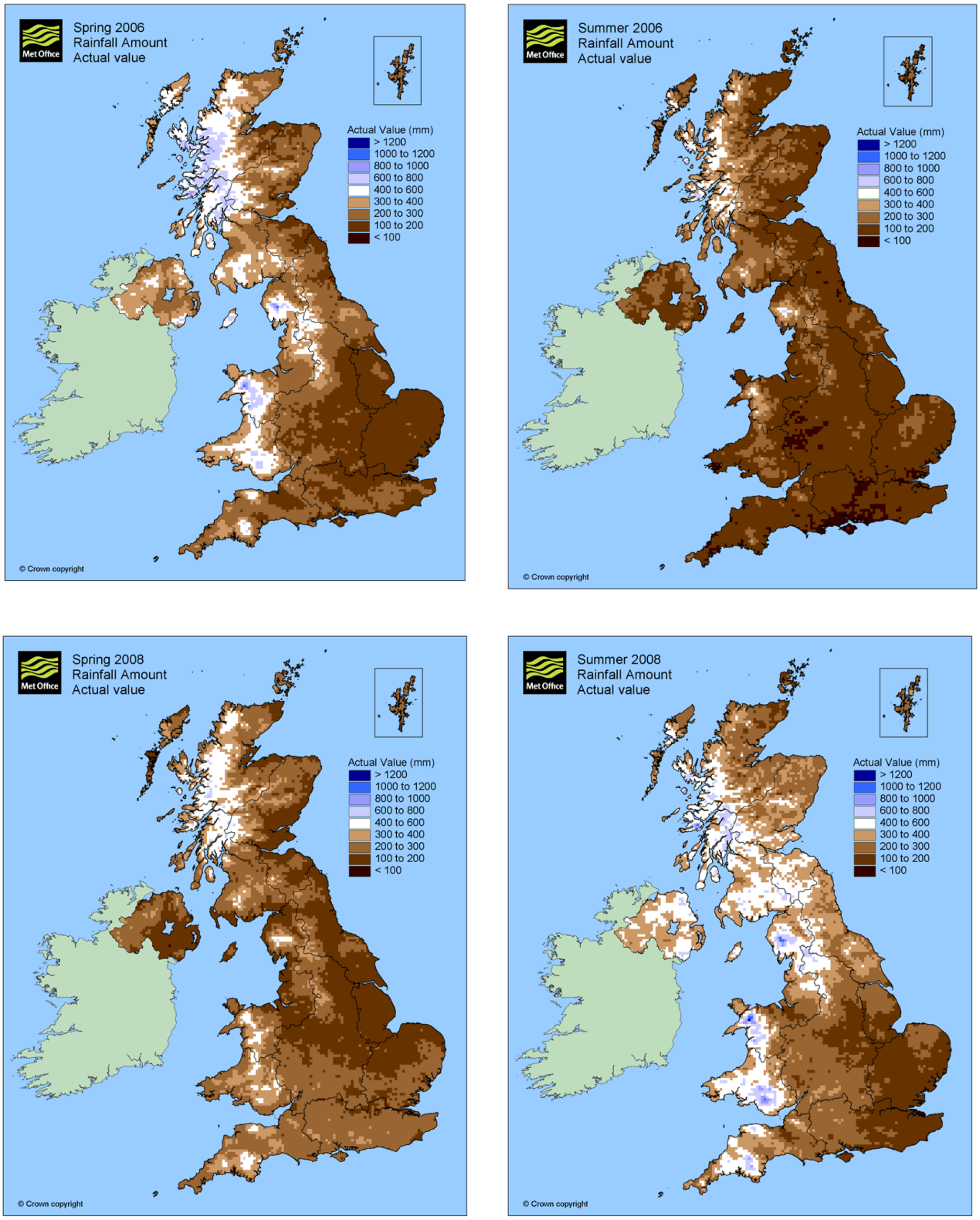

Figure 1.5 Total rainfall (mm) for the UK in the spring and summer of 2006 and 2008. Source: http://www.metoffice.gov.uk/climate/uk/

2. Methods

Summary: Methods used

To calculate the impacts of ozone on crop production in the UK, several sources of information were drawn together. These included crop distribution and production data, crop values (£/t), ozone concentration fields, modelled ozone flux and response functions for effects on yield.

Two years were selected for the study: 2006 - a relatively high ozone year with dry conditions considered typical of 2020, and a cooler wetter year, 2008 - more typical of a current UK growing season. Here, we provide an overview of the methodology used and sources of information.

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2.1 Mapping of crop distribution and productivity

Maps were generated for Great Britain using the 10 km grid obtained from Ordnance Survey through DIGIMAP (University of Edinburgh). The data was provided as an ESRI shape file and imported into ArcGIS. In addition, a 10km grid for Northern Ireland was created in ESRI ArcGIS 9.2 using the Hawth's Toolbox add-in sampling tools. The grid was created to adjoin the existing GB grid and thus cover the whole of the UK.

2.1.1 Sources of crop data

Crop statistics on extent and yield for 14 agricultural classes across the UK were obtained from a variety of sources for the base years of 2006 and 2008:

- Wheat – Areas and yields were obtained from Eurostat for NUTS3 areas. The data was for 2006 and 2008 and was accessed on 15-02-2011 12:51:28.
- Barley – Areas and yields were obtained from Eurostat for NUTS3 areas. The data was for 2006 and 2008 and was accessed on 15-02-2011 12:51:28.
- Maize Forage & Grain – Area of Maize in the UK for 2006 and 2008 obtained from Defra (Census of Agriculture). Average yield of 10 t/ha was chosen based on industry review where maximum achievable yield is 15 t/ha.
- Sugar Beet – Areas were obtained from Eurostat for NUTS3 areas. The data was for 2006 and 2008 and was accessed on 15-02-2011 12:51:28. National yield data was obtained from Defra.
- Oilseed-Rape – Areas and yields were obtained from Eurostat for NUTS3 areas. The data was for 2006 and 2008 and was accessed on 15-02-2011 12:51:28.
- Potatoes – Areas were obtained from Eurostat for NUTS3 areas. The data was for 2006 and 2008 and was accessed on 15-02-2011 12:51:28. The national average yields per hectare for 2006 and 2008 were obtained from the UK Potato Council for potato main crops. These were applied to the NUTS3 estimates of area. (http://www.potato.org.uk/media_files/MIS_reports/production&pricesaug2010.pdf)
- Pulses – The data on area grown and yields for peas and beans were obtained from Defra (Basic Horticultural Statistics database). The area under production for 2005/6 was applied to the 2006 calculations and 2007/8 applied for 2008 estimates. The data was obtained for the national total area of production for the UK.

- Horticulture – Areas were obtained from Eurostat for NUTS3 areas. The data was for 2006 and 2008 and was accessed on 15-02-2011 12:51:28.
- Lettuce & Salad - The area and yield of production for 2006 and 2008 was obtained from Defra production data. These data were for the UK and disaggregated to regions proportionally using the methodology described below.

2.1.2 Land Cover Datasets

(a) LRTAP Convention Harmonised Land Cover Dataset

The Long-Range Transboundary Air Pollution (LRTAP) Convention's harmonised land cover map (formerly the SEI European Land Cover Map, 2006 Revision) is a digital spatial dataset designed for environmental modelling applications requiring continental scale land cover information. The dataset has been compiled for use by modellers for assessing the impacts of air pollutants on European ecosystems and agriculture. The information is being used by the United Nations Economic Commission for Europe (UN-ECE) and the European Monitoring and Evaluation Programme (EMEP) in assessing tropospheric ozone impacts.

The data has been compiled from a mixture of existing digital and paper sources including the European Environment Agency (EEA) Corine Land Cover 2000, SEI Land European Cover Map (2002 Revision), FAO Soil Map of the World, EEA European Biogeographical regions (2005).

The data have been modelled and combined to generate classes differentiating between various European Nature Information System (EUNIS) codes (http://eunis.eea.europa.eu/). The dataset contains information down to EUNIS level 3 for specific habitat types.

The LRTAP Convention data was used to identify the extent of agricultural land (EUNIS code - I1: Arable land and market gardens) and pasture (EUNIS code - E2: Mesic grasslands) in the UK. Additional data from the IGBP was then used to differentiate crop distribution.

(b) Global Land Cover Map 2000

The IGBP Global Land Cover agricultural data was used to differentiate types of agricultural land. Firstly, the agricultural classification information was extracted from them full GLC classification. From this subset a thiessen polygon map was generated of the dominant agricultural classes across the UK. This was overlaid with the original agricultural polygon boundaries to identify the most likely agricultural class for all locations in the UK. 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 those 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.

2.1.3 Generation of crop area and yield values on a 10 km grid Square

The workflow for generating the final crop area and yield values by 10 km grid square can be seen in Figure 2.1. Production of NUTS3 region specific crop production estimates required the disaggregation of some national data to NUTS3 borders. Data on production were only available from EUROSTAT at the UK scale for Maize, Oats and Lettuce. Lettuce was allocated to NUTS3 regions as a fixed percentage of horticulture calculated from national totals. The actual level of horticulture by NUTS3 region from Eurostat was then used to disaggregate this fixed percentage. For maize and oats the regional distribution was estimated as a fixed percentage (calculated from the UK national totals) of NUTS3 specific cereals.

The adjustment to the area and yield of crops was undertaken to ensure crops that are under-reported in the mapping process are adequately represented. The total area reported from the mapping process was calculated and compared to the regional specific statistics. From this, adjustment factors were generated to match the reported statistics. This process ensures the grid totals by region matched the reported statistics.

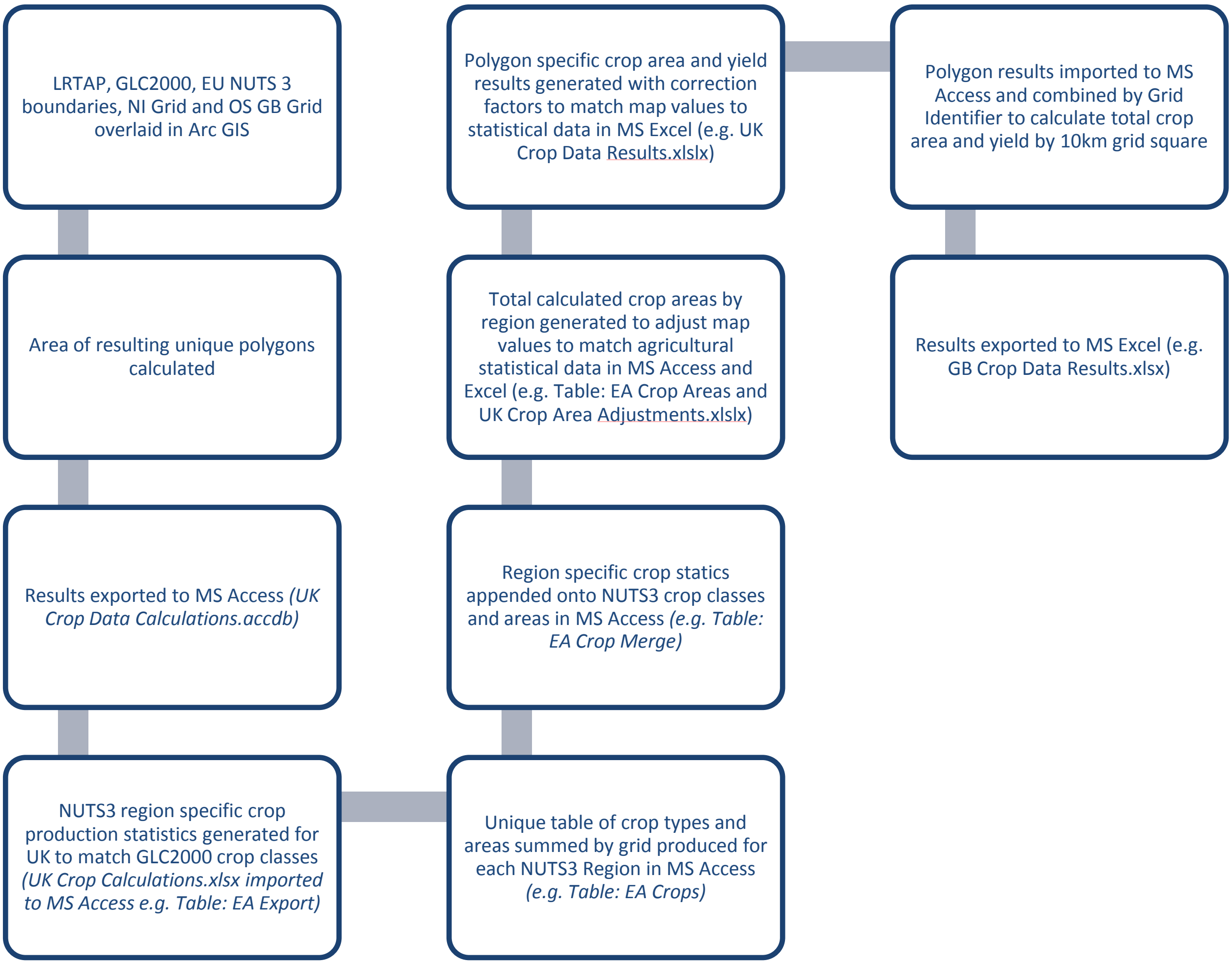


Figure 2.1 Flow chart of procedure for generation of crop statistics

2.1.4 Definition of areas of pasture

The extent of pasture was identified from the LRTAP Harmonised Land Cover map as EUNIS habitat type E2 Mesic Grassland "lowland and montane mesotrophic and eutrophic pastures and hay meadows of the boreal, nemoral, warm-temperate humid and Mediterranean zones".

2.2 Ozone concentration mapping

Ozone concentration-based statistics were calculated from data from the UK air quality monitoring sites, based on non-overlapping fixed 8 hour periods, then mapped to a 1 km OS grid square using basic Kriging in the Surfer mapping software. The 10 km x 10 km maps are calculated by averaging all values in each 10 x 10 km grid square (excluding grid cells with water). For this study, ozone was calculated as either the AOT40[2] or number of ozone episodes within a fixed time period.

The following three-month time periods were used to accumulate AOT40. Each was selected to represent the main vegetative and, where appropriate, seed development periods using UK-specific information (Francis, 2009):

- 1 April to 30 June (oil seed rape, winter barley, early pasture)
- 15 April to 15 July (winter wheat)

[2] AOT40 is the sum of the differences in the hourly mean ozone concentration (in ppb) and 40 ppb when the concentration exceeds 40 ppb during daylight hours and accumulated over a stated time period.

- 1 May to 31 July (peas and beans, Modelling and Mapping Manual wheat timing)
- 15 May to 15 August (potato)
- 1 June to 31 August (sugar beet, maize)
- 1 July to 30 September (late pasture)

The frequency of occurrence of ozone episodes was split into three-month periods representing early (1 April to 30 June) and late (1 July to 30 September) growing season (see Section 8.2 for further details).

2.3 Ozone flux modelling

The Surface Ozone Flux Model (SOFM) and Ozone Source Receptor Model (OSRM) have been used to calculate accumulated flux over threshold values throughout the UK at 10 km x10 km resolution for four key crops: wheat, oilseed rape, potato and pasture (based on the clover component).

The OSRM calculates hourly ozone concentrations at receptor locations throughout the United Kingdom. The SOFM evaluates the components of resistance that control the rate of deposition of ozone to vegetation. The SOFM postprocessor then combines the OSRM output (or measured ozone concentrations) with the SOFM resistance values to provide estimates of the accumulated flux of ozone deposited from the atmosphere to surface vegetation during the growing season. The accumulated flux metrics correspond to the metrics specified in the Summer 2010 version of the LRTAP Convention Modelling and Mapping Manual.

2.3.1 Model framework

Figure 2.2 shows the basic model framework and the route of the transfer of data between the model components.

The three main components of the model are:

- Ozone Source Receptor Model (OSRM)
- Surface Ozone Flux Model (SOFM)
- Post-processor for flux calculations

SOFM and OSRM both use the same meteorological data.

2.3.2 Model components

Ozone Source Receptor Model (OSRM)

The OSRM has been developed in parallel with this work and is not the subject of this report. However, the interfaces between the OSRM and the other components will be referred to throughout the report. OSRM calculates the average ozone concentration throughout the boundary layer at selected receptor locations in the UK for each hour of the year. Concentrations are calculated from the photochemical formation of ozone along 4-day trajectories carrying precursor emissions and surface losses occurring from deposition and reactions with locally emitted oxides of nitrogen. Details of the OSRM are given in Hayman et al. (2010).

Surface Ozone Flux Model (SOFM)

The SOFM may be represented by the resistance analogue model shown in Figure 2.3.

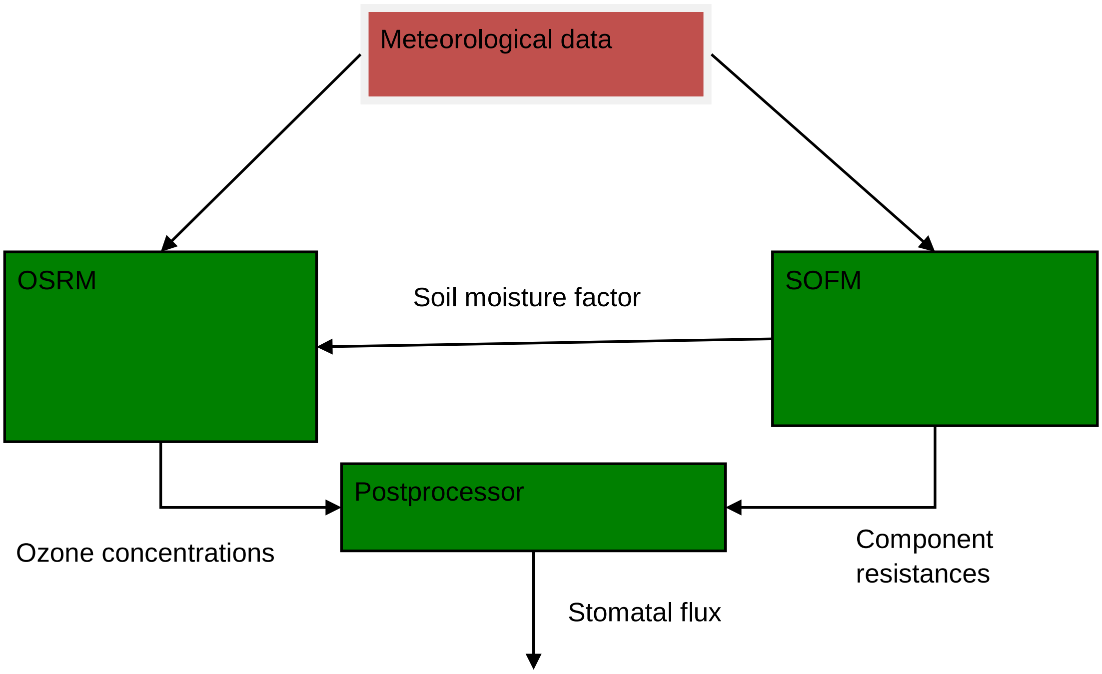


Figure 2.2 Framework of program modules

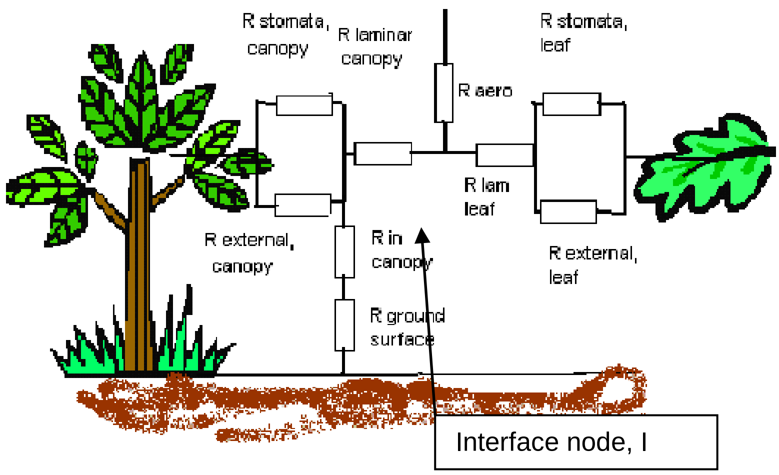


Figure 2.3 Resistance analogue of ozone transfer between the atmospheric surface layer and terrestrial ecosystems

The purpose of the SOFM is to calculate the values of component resistances to ozone flux between a reference height and the bulk canopy, the upper canopy leaves or flag leaves and the ground. The individual leaf on the right hand side of Figure 2.3 represents the uppermost canopy leaf potato and the flag leaf for wheat. The whole plant on the left hand side represents the vegetative canopy as a whole. The surface area of the individual upper canopy leaf or flag leaf is very small so that it has little effect on the ozone concentrations and so the ozone concentrations in the canopy are dominated by the fluxes to the canopy and to the ground. However, the yield loss in crops is related to the ozone flux to the upper canopy leaf or the flag leaf. It is therefore necessary to calculate the ozone flux to the whole canopy in order to determine the flux to the most sensitive leaves.

The component resistances are:

- Aerodynamic resistance from a specified reference height to the canopy displacement height
- Stomatal resistance of the bulk canopy
- The external resistance to external plant tissue in the canopy
- The quasi-laminar resistance to the canopy
- The in-canopy air resistance below the displacement height
- The ground surface resistance
- Stomatal resistance to the upper canopy/flag leaf
- The external resistance to external plant tissue of the leaf
- The quasi-laminar resistance to the leaf.

The Modelling and Mapping Manual (LTRAP Convention, 2010) describes the methods to calculate the stomatal resistance, external resistance and quasi-laminar resistance to the upper canopy leaf: these methods and recommended parameters have been implemented within the surface ozone flux model wheat, potato and pasture (clover).

Methods to calculate the bulk canopy resistances are not specified in the Modelling and Mapping Manual. The methods currently used in the SOFM have been developed from those reported by Emberson et al. (2000) and used in the DO_3SE model. The developments have involved extensive detailed discussions between AEA and Dr Emberson at SEI.

The stomatal conductances are calculated using a multiplicative algorithm with the following formulation:

$$g_{sto} = g_{\max} \times \lfloor \min(f_{phen}, f_{O_3}) \rfloor \times f_{light} \times \lfloor \max\left(f_{\min}, (f_{temp} \times f_{VPD} \times f_{SWP}\right) \rfloor$$

where g_{sto} is the stomatal conductance at specified conditions; g_{max} is the species specific maximum stomatal conductance.

The factors f_{phen}, f_{O3}, f_{light}, f_{temp}, f_{VPD} and f_{SWP} are in the range 0-1. They take account of the effect of plant phenology, ozone-induced senescence, light levels, temperature, water vapour pressure deficit and soil water pressure.

Appendix 1 of Abbott and Cooke (2011) describes how SOFM calculates the components of resistance and the factors f_{phen}, f_{light}, f_{temp}, f_{VPD} and f_{SWP}. SOFM calculates these values for each hour at gridded locations at 1 degree latitude and longitude resolution throughout the UK. The factor f_{O3} is not calculated in SOFM: it is applied in the postprocessor.

The current model calculates bulk canopy and leaf level resistances for:

- Wheat
- Potato
- Pasture, clover
- Oilseed rape

The model assumes that potato and oilseed rape crops in the UK are irrigated to prevent loss of yield in dry periods. The Modelling and Mapping Manual provides alternative methods for the calculation of f_{phen} for potato based on accumulated temperature or fixed dates: SOFM uses the fixed date method.

The Modelling and Mapping Manual specifies a method to calculate f_{phen} for wheat based on accumulated temperature. Appendix 1 of the report to CEH by Abbott and Cooke (2011) describes how we adapted the method for use in SOFM.

Recent developments in SOFM and OSRM to accommodate new formulations developed for the DO_3SE model at SEI York have been described in the report to Defra by Abbott and Cooke (2010). These have been further adapted to allow calculation of POD_Y using the Modelling and Mapping Manual.

2.3.3 Flux post-processor

The purpose of the flux post-processor is to calculate the flux of ozone to the stomata of the upper canopy leaf for potato and the flag leaf for winter wheat and oilseed rape and clover from the outputs of the OSRM and SOFM models. It is described in detail in Appendix 2 of Abbott and Cooke (2011).

The postprocessor calculates the ozone concentration at the interface node I (Figure 2.3) from the average boundary layer height concentration calculated by OSRM and the bulk canopy resistances. It calculates the ozone senescence factor, f_{O3} for wheat and potato and adjusts the stomatal resistance to the upper canopy/flag leaves where f_{O3} is less than f_{phen}. It then calculates the ozone flux through the leaf stomata using the concentration at the interface node at the top of the canopy and the components of resistance.

The program calculates phytotoxic ozone dose (POD_Y) as the accumulated sum of the stomatal flux over specified thresholds for wheat, potato, clover and oilseed rape for periods specified in the Modelling and Mapping Manual:

—— mmol m^{-2} projected leaf area

where Y is the threshold flux, nmol m^{-2} s^{-1}.

The sum is calculated as the sum of hourly fluxes over daylight hours in the accumulation period. Table 2.2 shows the values of the threshold flux and accumulation period specified in the ICP Modelling and Mapping Manual and used in this study, Table 2.3 shows the parameterisations used for each species and Figure 2.4 shows the parameterisation of the flux model for wheat based on stomatal conductance measurements.

Table 2.2 Threshold fluxes and accumulation periods

Crop	Threshold flux	Accumulation period
Wheat	6 nmol m^{-2} s^{-1} on a projected leaf area basis	Accumulated where f_{phen}>0
Potatoes	6 nmol m^{-2} s^{-1} on a projected leaf area basis	70 days starting at plant emergence. Emergence occurs on day 146.
Clover	1.0 nmol m^{-2} s^{-1} on a projected leaf area basis	Early pasture:1 April to 30 June Late pasture:1 July to 30 September
Oilseed rape	6 nmol m^{-2} s^{-1} on a projected leaf area basis	1 April to 30 June

Table 2.3 Parameterisations used in the OSRM-SOFM flux modelling

		Wheat	Potatoes	Clover	Rape
Canopy factors	G_{max}, mmol $m^{-2}s^{-1}$	500	750	270	490
	F_{min}	0.01	0.01	0.01	0.02
	$F_{phen\ a}$	0.1	0.2	1	0.52
	$F_{phen\ 1}$, days	0	20	0	48
	$F_{phen\ 4}$, days	45	45	0	61
	$F_{phen\ e}$	0.1	0.2	1	0.85
	Light-a	0.0105	0.005	0.009	0.0027
	T_{min}, ^oC	12	13	8	5
	T_{opt}, ^oC	26	28	24	22
	T_{max}, ^oC	40	39	39	39
	VPD_{max}, kPa	1.2	2.1	2.8	1.5
	VPD_{min}, kPa	3.2	3.5	4.5	3.5
	SWP_{max}, MPa	PAW 0.5	-999	-0.49	-999
	SWP_{min}, MPa	n/a	-999	-1.5	-999
	Root depth, m	0.75	0.75	0.75	0.75
	Height, m	1	2	0.2	1
	Start of growing season (50^0N), day	119	146	1	91
	end of growing season, 50^oN, day	211	266	365	199
	LAI_{min}	0	0	2	0
	LAI_{max}	3.5	4.2	3.5	3.5
	Ls, day	70	35	140	70
	Le, day	22	65	135	22
	ground resistance	200	200	1000	200
	albedo	0.2	0.2	0.2	0.2
Leaf factors	g_{max} mmol $m^{-2}s^{-1}$	500	750	390	490
	f_{min}	0.01	0.01	0.4	0.02
	$f_{phen\ a}$	0.3	0.4	Use Fphen, accumulate separately for early and late pasture	Use Fphen
	$f_{phen\ e}$	0.7	0.2		
	f_{phen1}, (50^0N)	20/16*	20		
	f_{phen4} (50^0N)	8/5*	50		
	Start of growing season, (50^0N), day	154/157*	146		
	End of growing season , (50^0N), day	210/200*	216		
	Light-a	0.0105	0.005	0.008	0.0027
	Sig VPD	8	10	n/a	n/a
	L, m	0.02	0.04	0.05	0.02

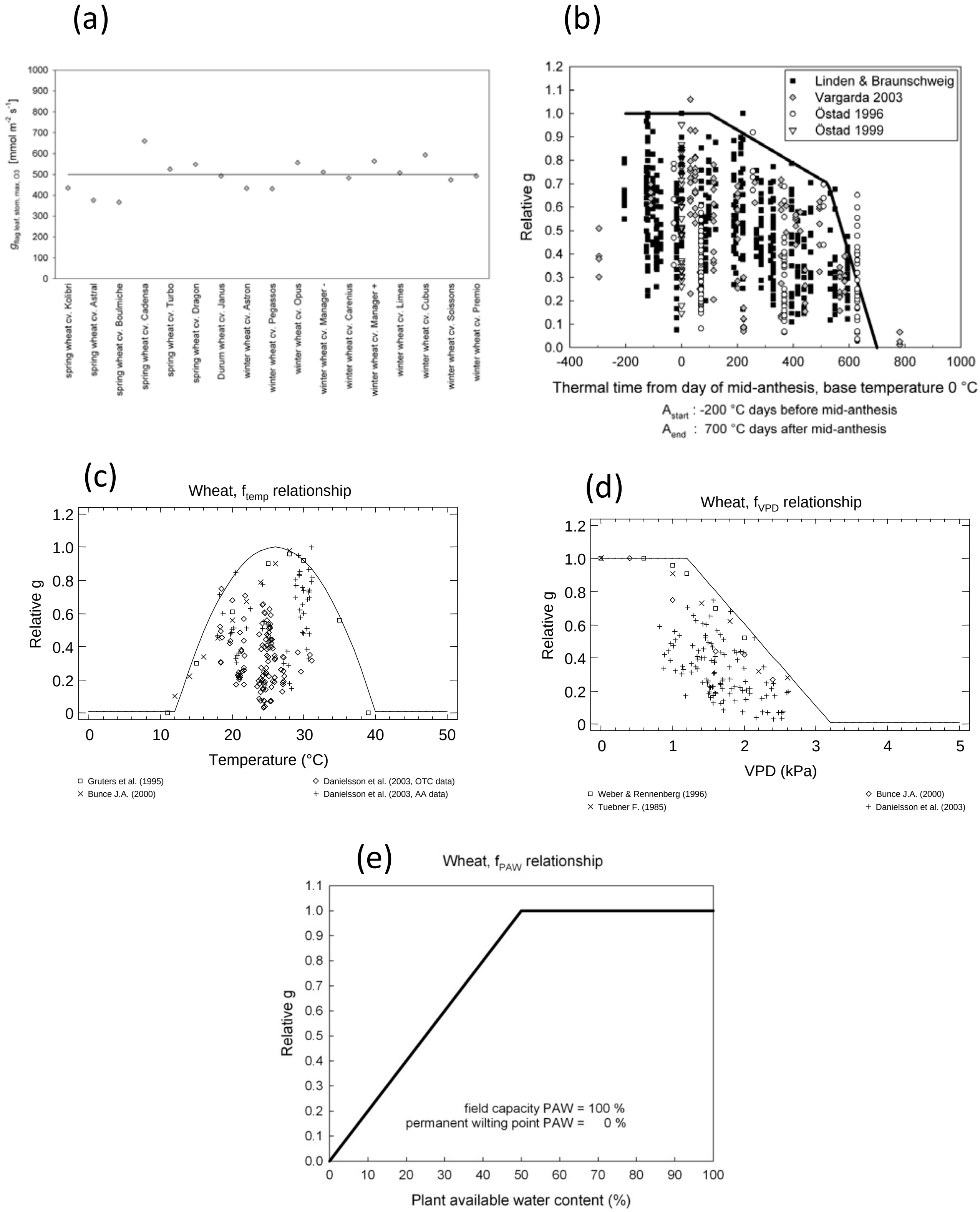


Figure 2.4 Flux parameterisation for wheat: (a) derivation of g_{max}, the maximum stomatal conductance, (b) f_{phen}, the effect of phenology on relative stomatal conductance(g), (c) f_{temp}, the effect of temperature on relative g; (d) f_{VPD}, the effect of vapour pressure deficit on relative g; (e) f_{PAW}, the effect of plant available water in the soil on relative g.

2.4 Crop response functions

At the 23rd Task Force meeting of the ICP Vegetation (February, 2010), all available knowledge on flux-effect relationships for crops was reviewed and new critical levels were set for those crops for which sufficiently robust data and response relationships existed. The crops selected for inclusion of flux-based critical levels in the LRTAP Convention's Modelling and Mapping Manual were wheat, potato and tomato. Because of their widespread growth in this country, wheat and potato were selected for use in this study. A response function was also presented at the Task Force meeting for oilseed rape. This wasn't considered sufficiently robust for international use because the data was only from one experiment conducted in one country (Belgium). We have, however, used this response function in this study since the climatic conditions in Belgium are not dissimilar to those in the UK. The flux-based yield-response functions are included in Table 2.4; the functions used are presented graphically in the relevant chapters.

In order to cover a greater range of crops grown within the UK it was necessary to also use concentration-based response relationships, accepting that these are less biologically relevant than those based on the flux of ozone into the leaf. The AOT40-based response function for wheat was calculated using original data for the AOT40 and is that used to derive the concentration-based critical level for agricultural crops (Mills et al., 2007). For the other functions (Table 2.4), AOT40 has been calculated from the 7h mean values reported in papers using the conversion function included in Mills et al. (2007). There is some uncertainty in using this approach, however, as 7h means below 29 ppb are all assumed to have an AOT40 of 0 ppm h, but may have included some concentrations above 40 ppb that would contribute to AOT40. The response functions shown in Table 2.3 are those derived as part of work package 5 of this contract and include new data from papers published since the Mills et al. (2007) study.

For each crop, the yield was calculated for each treatment relative to that of the lowest treatment (Relative Yield, RY). This data was then combined for all experiments and linear regression was used to derive the response function. Where the regression provided a relative yield at zero AOT40 or POD_6 of less than 1, the response function was forced through 1. This approach was taken to standardise economic loss calculations.

Table 2.4 The dose response relationships used in this study; OSR = oilseed rape

	Parameter	Relative yield function	r2	p	No. of cultivars	Data source	O3 data derived from
wheat	POD6	RY=1-0.038*POD6	0.84	<0.001	5	LRTAP Convention (2010)	modelled flux
wheat	AOT40	RY=1-0.0161*AOT40	0.89	<0.001	9	LRTAP Convention (2010)	measured AOT40
potato	POD6	RY=1.-0.013*POD6	0.76	<0.001	1	LRTAP Convention (2010)	modelled flux
potato	AOT40	RY=1-0.0105*AOT40	0.16	0.017	11	ICP Vegetation (2011)	AOT40 converted from 7h mean
OSR	POD6	RY=1.-0.0111*POD6	0.19	0.02	1	Vandermeiren, pers. comm.	modelled flux
OSR	AOT40	RY=1-0.0128*AOT40	0.95	0.041	6	ICP Vegetation (2011)	AOT40 converted from 7h mean
barley	AOT40	RY=1-0.0063*AOT40	0.013	0.065	6	ICP Vegetation (2011)	AOT40 converted from 7h mean
maize	AOT40	RY=1-0.0065*AOT40	0.68	<0.001	6	ICP Vegetation (2011)	AOT40 converted from 7h mean
sugarbeet	AOT40	RY=1-0.0089*AOT40	0.26	0.003	4	ICP Vegetation (2011)	AOT40 converted from 7h mean
peas and beans	AOT40	RY=1-0.0193*AOT40	0.14	<0.001	9	ICP Vegetation (2011)	AOT40 converted from 7h mean

2.5 Economic valuation

Crop prices are highly volatile, with values peaking in the mid-1990s and again in 2008 and 2009. For many crops, there has been a two-fold range in value over the period 1996 to 2009 (see Table 2.5 and figures provided for each crop in the relevant sections), making choice of crop value critical to the economic losses predicted in this study. To standardise across crops, the mean crop value (per tonne or per hectare) over the period 1996-2009 has been used for the main calculations and in the maps presented for economic losses. For each crop, there is also an evaluation of crop losses for the mean, first and third quartiles, minimum and maximum crop values over this time period.

2.6 Stages in analysis

Figure 2.5 illustrates the stages in the analysis conducted. All data was taken into an MS Access database allowing the various data types to be brought together on a 10 x 10 km grid square for the UK. For each crop, the following maps were generated:

1. Crop distribution. The 10 x 10 km squares for which the crop is present is shown in all of the maps. Different cut-off values (e.g. >100 ha or 1% of the grid square for wheat) are used for each crop dependant on the intensity of the crop production across the UK.

2. Crop production data on a tonne/grid square.

3. Ozone flux, AOT40 or counts of episodes.

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 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) for illustration, but summed values for the UK include crop losses for all squares, including those with the area of production below the relevant cut-off value.

Table 2.5 Annual mean crop values for the period 1996 – 2009; OSR = oilseed rape. Sources: http://www.defra.gov.uk/statistics/foodfarm/ and http://www.britishleafysalads.co.uk/know/faq.shtml

	crop value (£/tonne)				
	Mean	**Min**	**Max**	**Q1**	**Q3**
wheat (milling)	94	71	152	76.3	107.0
wheat (feed)	84	63	127	69.0	96.5
potato (mean of early & main crop)	124	69	175	100.0	146.6
OSR (£/tonne volume)	231	138	314	205.8	258.1
sugarbeet	29	24	34	27.5	30.8
maize (only 2007 prices available)	679	n.a.	n.a	n.a.	n.a.
barley (malting)	95	72	153	78.3	115.3
barley (feed)	79	58	118	68.3	85.3
comb.peas and beans (mean of both)	156	93	228	143.3	172.2
Salad leaf crops (£/ha) in 2008	9000	n.a	n.a	n.a	n.a

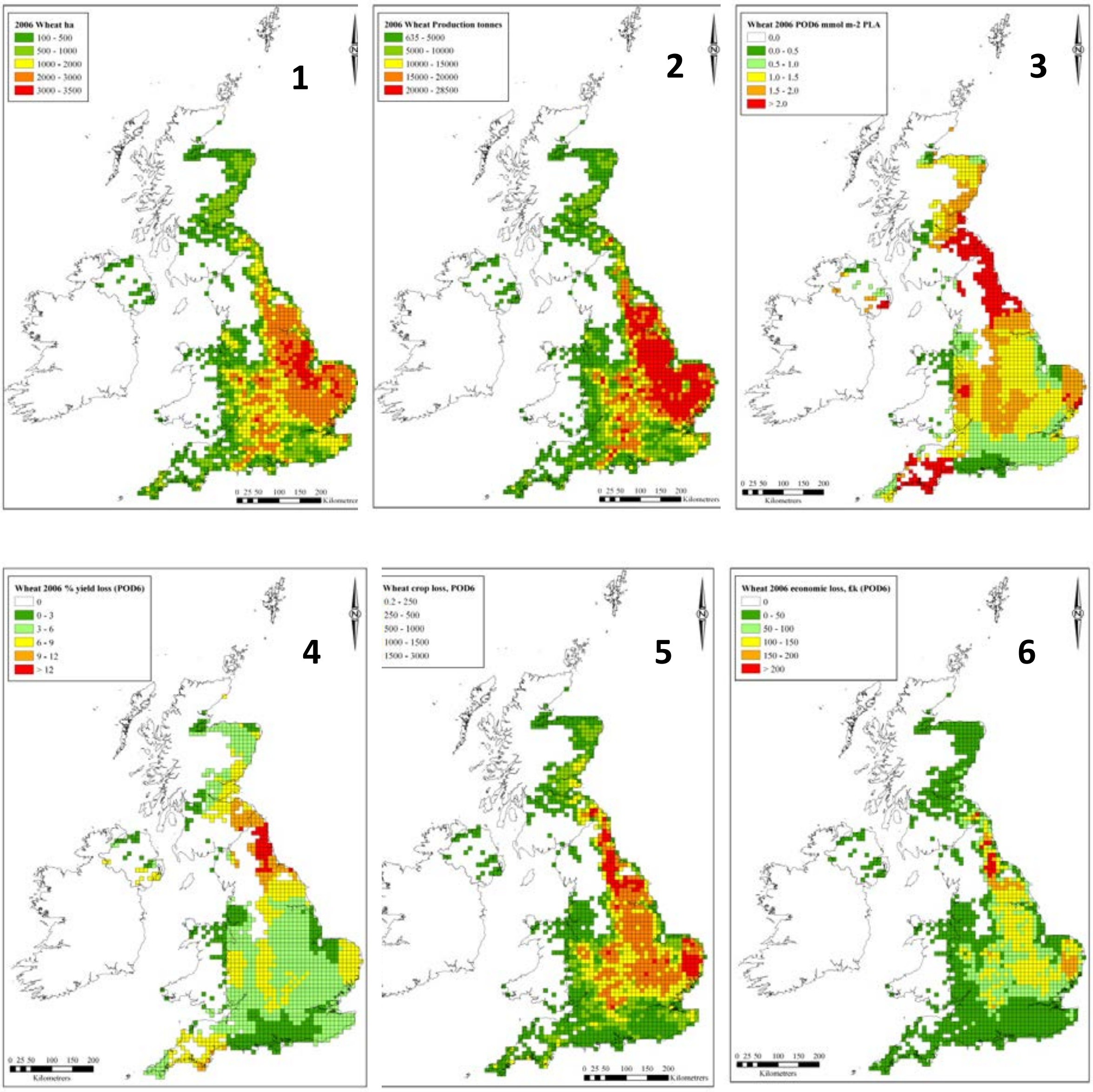


Figure 2.5 Using a POD_6-based assessment for wheat in 2006 as an example, the stages in the analysis of economic losses due to ozone (see text for details)

2.7 Indicative certainty

In any analysis of this type there are many sources of uncertainty in the quantification of economic losses. To aid interpretation of the maps and numbers produced, the degree of certainty of the data has been estimated using a simple low, medium and high scoring system. The quantifiable and unquantifiable sources of uncertainty in the data are discussed in Section 3.5.

3 Crop losses at the UK-scale

Summary: Crop losses in the UK

- The ozone concentrations were similar in the spring of both 2006 and 2008 but differed in distribution with the highest concentrations being in the crop growing areas of East Anglia and Cornwall in 2006 and in the NE of England in 2008. Ozone concentrations continued to be high in the summer of 2006 but were relatively low across most of the UK in the summer of 2008.

- The flux-based methodology takes into account the influence of climate and soil water availability on the uptake of ozone by the leaves of plants and is biologically more meaningful than the AOT40-based methodology which is based only on the ozone concentration in the air above the crop. Currently, flux models are only available for wheat, potato and oilseed rape; the AOT40-based approach had to be used for the other important UK crops included here: barley, maize, sugar beet, peas and beans, and salad leaf crops.

- Based on AOT40, the agricultural crops studied decreased in sensitivity to ozone as follows: pea and bean > wheat > potato and oilseed rape > sugar beet > maize and barley.

- For the eight crops included in this study, **the total economic losses were predicted to be £205 million in 2006 and £183 million in 2008**, based on the mean crop value representing an average of **9.1 and 6.6 % losses** respectively.

- This study has shown that **ozone pollution impacts almost as much on crop yield in the UK in a typical year as in a more extreme year**. Even though the ozone concentrations were lower overall in 2008, the uptake of ozone was greater because the climatic and soil conditions were more suitable for uptake than in 2006.

- Using corrections for flux model underestimates and peak crop value, the potential economic losses due to ozone are predicted to be **£359 million in 2006 and £253 million in 2008**, representing an average of **10.1% and 6.7% yield loss** for the two years respectively.

- Based on the mean crop value, **losses** predicted with the flux-based methodology **were highest for wheat**, resulting in £77.6 million of lost yield in 2006 and £91.2 million in 2008 (Table 3.2 and Figure 3.3). These losses represented 5.6% of economic value in both 2006 and 2008.

- Predicted losses for other crops were in the range £6 - 30 million in 2006 and £0.3 - 33 million in 2008. For potato, maize, peas and beans and sugar beet, monetary losses were predicted to be 2 to 4 times higher in 2006 than in 2008 using the AOT40-based methodology.

- Several uncertainties have been identified in this approach, including the under-estimates of ozone flux using the OSRM-SOFM model, the lack of flux-effect relationships for several important UK crops, the volatility of crop value, application of response functions using data for cultivars grown in the 1980s and 1990s but not grown now, and difficulty of accurately mapping crop distribution and production on a 10 x 10km grid.

- The overall indicative certainty for the results presented here was: “high” for wheat”, “medium” for potato, oilseed rape and sugar beet, and “low” for maize, barley, peas and beans, and salad leaf crops.

3.2 Ozone concentrations in 2006 and 2008

Although the climatic conditions differed between the two years, the ozone concentrations in the early part of the growing season (April-June, Table 3.1) were quite similar with the 24 hour mean concentration across all of the UK grid squares averaging at 33.0 ppb in 2006 and 31.1 ppb in 2008. The AOT40 values were also similar for the first half of the growing season, but were substantially lower in the second half of the growing season in 2008 than in 2006 (0.79 and 3 ppm h respectively). Similarly, the number of eight day periods in which the ozone concentration rose above 60 ppb was substantially lower in July to September in 2008 than in 2006.

Even though the mean ozone concentrations in April to June 2006 were similar to those for the same time period in 2008, the distribution of ozone was different between the two years (Figure 3.1). In 2006, the highest ozone concentrations were found in England in East Anglia, Cornwall and south Devon, whilst in 2008, the highest ozone concentrations were in the coastal areas of Yorkshire. In both years, ozone concentrations were moderate and occasionally high in Wales and the northern areas of Scotland. The biggest contrast between the two years was in the ozone concentrations found during July to September. In 2006 concentrations remained high in East Anglia and much of central England and eastern Wales, with AOT40 values exceeding 4 ppm h, whilst in 2008 concentrations were substantially lower throughout the UK with AOT40 only rising above 1.5 ppm h in East Anglia.

Table 3.1 Ozone metrics for 2006 and 2008 calculated from the 10 x 10 km grid square values shown in Figure 3.1.

	2006		2008	
	April-June	July-Sept	April-June	July-Sept
24h mean				
Q1	28.6	22.3	28.2	19.6
Q3	36.5	28.1	33.9	26.0
Median	31.8	25.5	30.4	21.8
Mean	33.0	25.3	31.1	23.1
Mean daily max				
Q1	40.4	32.9	40.1	32.4
Q3	46.0	37.6	47.6	37.0
Median	42.3	35.6	45.7	34.5
Mean	43.4	35.3	45.8	34.9
AOT40				
Q1	2.68	1.27	3.84	0.43
Q3	5.54	4.32	5.38	1.08
Median	4.13	2.78	4.68	0.64
Mean	4.31	3.00	4.65	0.79
No of episodes (O3 conc >60 ppb on 1 day in 8)				
Q1	3.0	2.1	1.9	0.5
Q3	4.0	5.1	3.6	1.7
Median	3.5	3.2	2.8	0.8
Mean	3.7	3.5	2.8	1.1

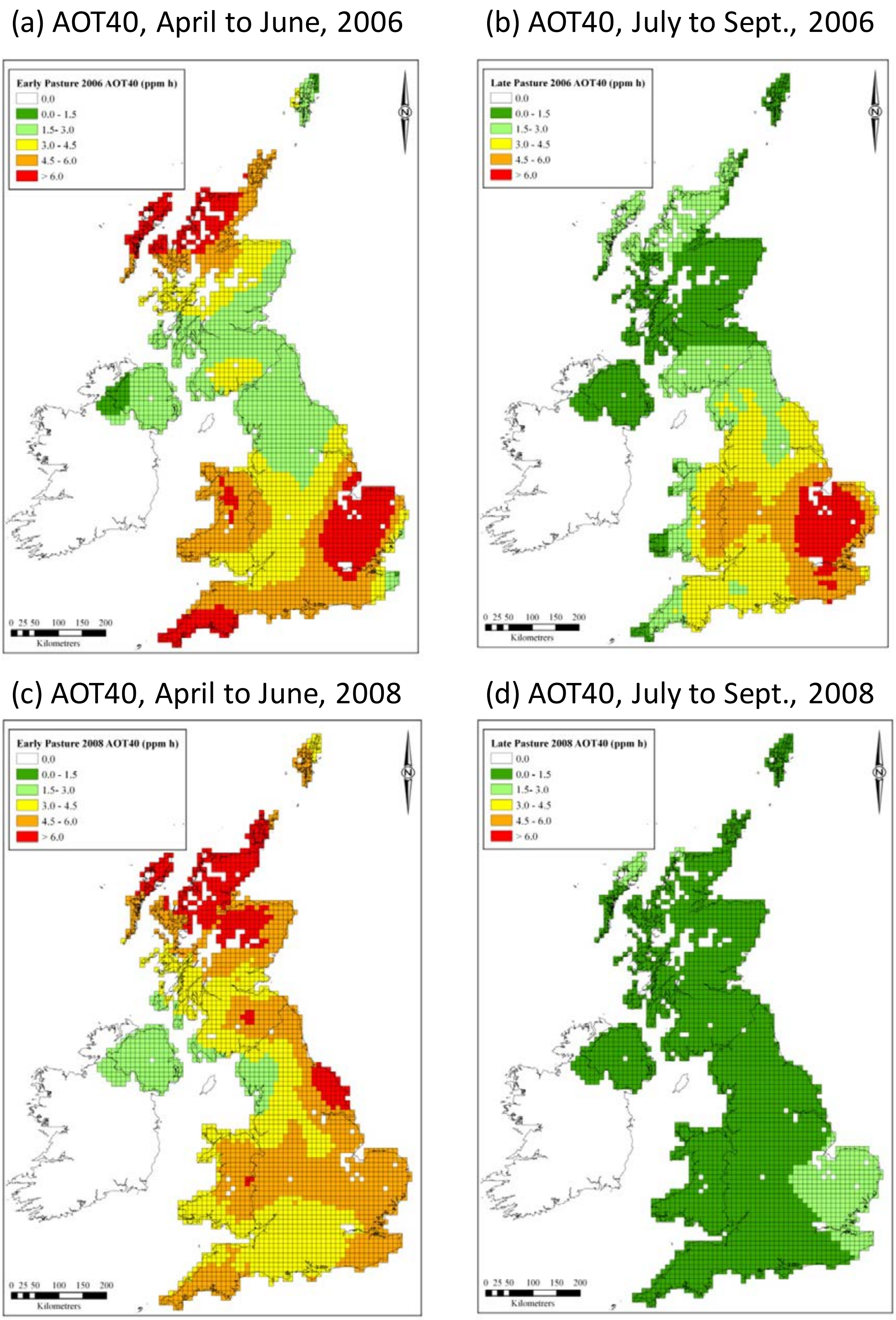


Figure 3.1 Ozone concentrations in the UK in 2006 and 2008 presented as the AOT40 values in ppm h for early (April to June) and late (July to September) growing seasons

3.3 Relative sensitivity of UK crops

The yield-response functions for all of the crops included in this study are provided in Table 2.4 and presented graphically in the corresponding chapters. In Figure 3.2, the slope of the linear regressions are plotted together to illustrate the relative sensitivity of the crops being studied. Using the flux-based methodology, wheat is clearly more sensitive than potato and oilseed rape with the slope being approximately 3 times steeper. The accumulated fluxes are influenced by the species-specific maximum stomatal conductance which are similar for wheat and oilseed rape (500 and 490 mmol m^{-2} s^{-1} respectively), but higher for potato (750 mmol m^{-2} s^{-1}). Thus, for a given set of climatic conditions and a specified ozone concentration, potato would take up more ozone than wheat or oilseed rape. . For the AOT40-based functions, peas and beans are the most sensitive with wheat being second in sensitivity, potato, oilseed rape and sugar beet having medium sensitivity and maize and barley being the least sensitive of the crops studied.

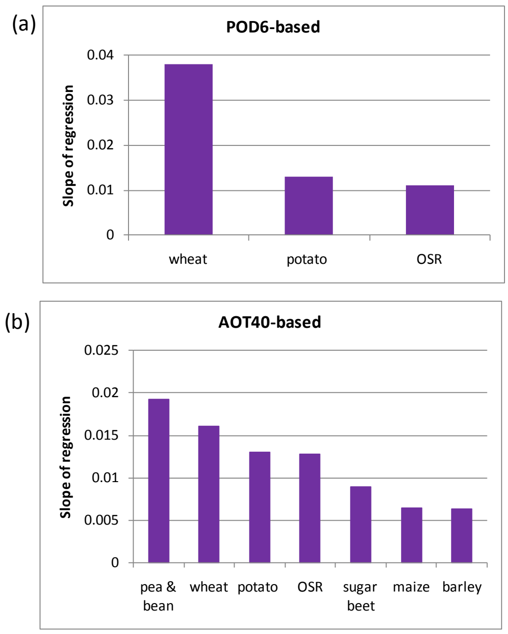


Figure 3.2 The relative sensitivity of the crops used in this study based on the slope of the regression functions (a) Ozone flux-based (POD_6) and (b) AOT40-based functions

3.4 Crop losses resulting from ozone pollution

In Table 3.2, we provide an overview of the hectares grown, production and total value of each crop in 2006 and 2008 together with the lost value and economic losses predicted in this study. As discussed in the next section, crop value (£/tonne) varies substantially from year to year which has a major influence on the economic losses predicted in this study. Furthermore, the OSRM-SOFM model underestimated ozone flux, especially in 2006. Table 3.3 provides the total crop losses for each year based on the data method described here together with the potential losses taking under/over estimates of ozone flux by OSRM-SOFM and the maximum crop value into account.

Table 3.2. Summary of expected losses in economic value in the UK due to ozone in 2006 and 2008

	Wheat		Potato		Oilseed Rape		Maize	Barley	Sugar beet	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**	**30.43***	**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**	**n.a.**
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**	**n.a.**
% economic loss	**5.64**	**9.15**	**0.04**	**2.78**	**7.22**	**6.57**	**1.03**	**3.08**	**1.97**	**9.73**	**n.a.**
Certainty of estimates	High	Medium	Medium	Low	Medium	Low	Low	Low	Medium	Low	Low

* 2007 prices available only

** 2008 prices available only

Table 3.3 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

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	9.1	6.6
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	10.1	6.7

For the eight crops included in this study, the total economic losses were predicted to be £205 million in 2006 and £183 million in 2008, based on the mean crop value, representing 9.1 and 6.6% of the total UK value in 2006 and 2008 respectively. The potential losses using corrections for flux model underestimates and peak crop value are predicted to be £359 million in 2006 and £252 million in 2008. It should be noted that the % values and economic losses do not appear to tally in this table. This is because in each year the relative proportion of losses per crop varies dependant on the timing of crop growth in relation to ozone exposure and climatic conditions, with a knock-on effect on the total dependant on the contribution each crop makes to the total crop value.

Based on the mean crop value, losses predicted with the flux-based methodology were highest for wheat, resulting in £77.6 million of lost yield in 2006 and £91.2 million in 2008 (Table 3.2 and Figure 3.3). Predictions using the AOT40-based methodology were significantly higher at £169 million in 2006 and £148 million in 2008. These losses represented 5.6 and 12.3% of economic value in 2006 and 5.6 and 9.2% of economic value in 2008 for the flux- and AOT40-based methodology respectively. Using the maximum crop value in the last 14 years, yield losses were approximately 50% higher, reaching £115.2 million and £135.4 million for wheat in 2006 and 2007 respectively (flux-based method). It can be argued that with increasing pressure on food supplies, the future crop value is likely to equal and possibly exceed the highest recorded value from 1997 to 2009, and that these higher crop losses should be those used to quantify ozone impacts.

For the agricultural crops studied, the next most affected crop was oilseed rape with similar predictions of ca. £25 million in 2006 and £32 million in 2008. Potato was predicted to be more affected in 2006 than 2008, with flux-based losses of £9.9 million and £0.3 million in the two years. Predicted losses for other crops were in the range £6-30 million in 2006 and £1-60 million in 2008. For potato, maize, peas and beans and sugar beet, monetary losses were predicted to be 2 to 4 times higher in 2006 than in 2008 using the AOT40-based methodology.

The clover component of pasture is very sensitive to ozone. In Chapter 9, the spatial distribution of potential effects is presented, but for the reasons explained there it was not possible to quantify the economic losses associated with ozone-induced reductions in pasture quality.

3.5 Unit values

To facilitate comparison with studies on air pollution impacts on ecosystem services (e.g. by Jones et al., 2011), the unit cost per ppm h (AOT40) and mmol m^{-2} (POD_6) of ozone are provided in Table 3.4 together with the growing period specific mean AOT40 and POD_6 values for the areas where each crop is grown for 2006 and 2008. It first is noteworthy that the mean AOT40 values varied from 1.47 (sugar beet, 2008) to 6.29 (sugar beet, 2006) with earlier growing crops experiencing relatively similar AOT40 values for the two years, whilst later growing crops experienced substantially higher AOT40s in 2006 than 2008. The differences between the years for mean ozone flux were crop-specific, with the largest difference being for potato where ozone flux was more than 5 times higher in 2006 than in 2008.

For AOT40, the unit values calculated from the total value lost in the UK divided by the mean AOT40 for the crop growing areas were as expected relatively similar, with values being the highest for wheat at ca. £35 million per ppm h of AOT40, similar for potato, oilseed rape and maize (ca. 10, 6.3 and 6.8 respectively) and lowest for barley sugar beet and peas and bean (ca. 3.5, 2.8 and 0.8 respectively). Unit values based on ozone flux were more variable reflecting the spatial differences in flux between the two years in relation to the amount of crop grown in each grid square.

Table 3.4. The unit cost in value (£ million) per unit flux (mmol m^{-2} POD_6) or unit ppm h (AOT40) calculated from the total value lost in the UK divided by the mean AOT40 or POD6 for the crop specific time intervals and crop-specific growing areas.

	wheat	Potato	Oilseed rape	Maize	Barley	Sugar beet	peas and beans
2006							
Total lost value (£ million)	77.63	9.91	24.95	n.a	n.a	n.a	n.a
mean POD6 (mmol m-2)	1.23	1.08	4.58	n.a	n.a	n.a	n.a
unit cost/mmol m-2 POD6	63.34	9.19	5.44	n.a	n.a	n.a	n.a
2008							
Total lost value (£ million)	91.24	0.30	32.87	n.a	n.a	n.a	n.a
mean POD6 (mmol m-2)	0.99	0.20	5.09	n.a	n.a	n.a	n.a
unit cost/mmol m-2 POD6	92.45	1.46	6.46	n.a	n.a	n.a	n.a
2006							
Total lost value (£ million)	169.97	50.47	24.92	30.43	13.31	17.45	5.93
mean AOT40 (ppm h)	4.84	4.93	4.18	4.81	4.25	6.49	6.14
unit cost/ppmh AOT40	35.10	10.23	5.96	6.33	3.13	2.69	0.97
2008							
Total lost value (£ million)	148.07	22.51	29.90	8.33	17.65	4.37	3.02
mean AOT40 (ppm h)	4.14	2.26	4.51	1.19	4.53	1.47	3.94
unit cost/ppmh AOT40	35.75	9.95	6.63	7.02	3.90	2.97	0.77

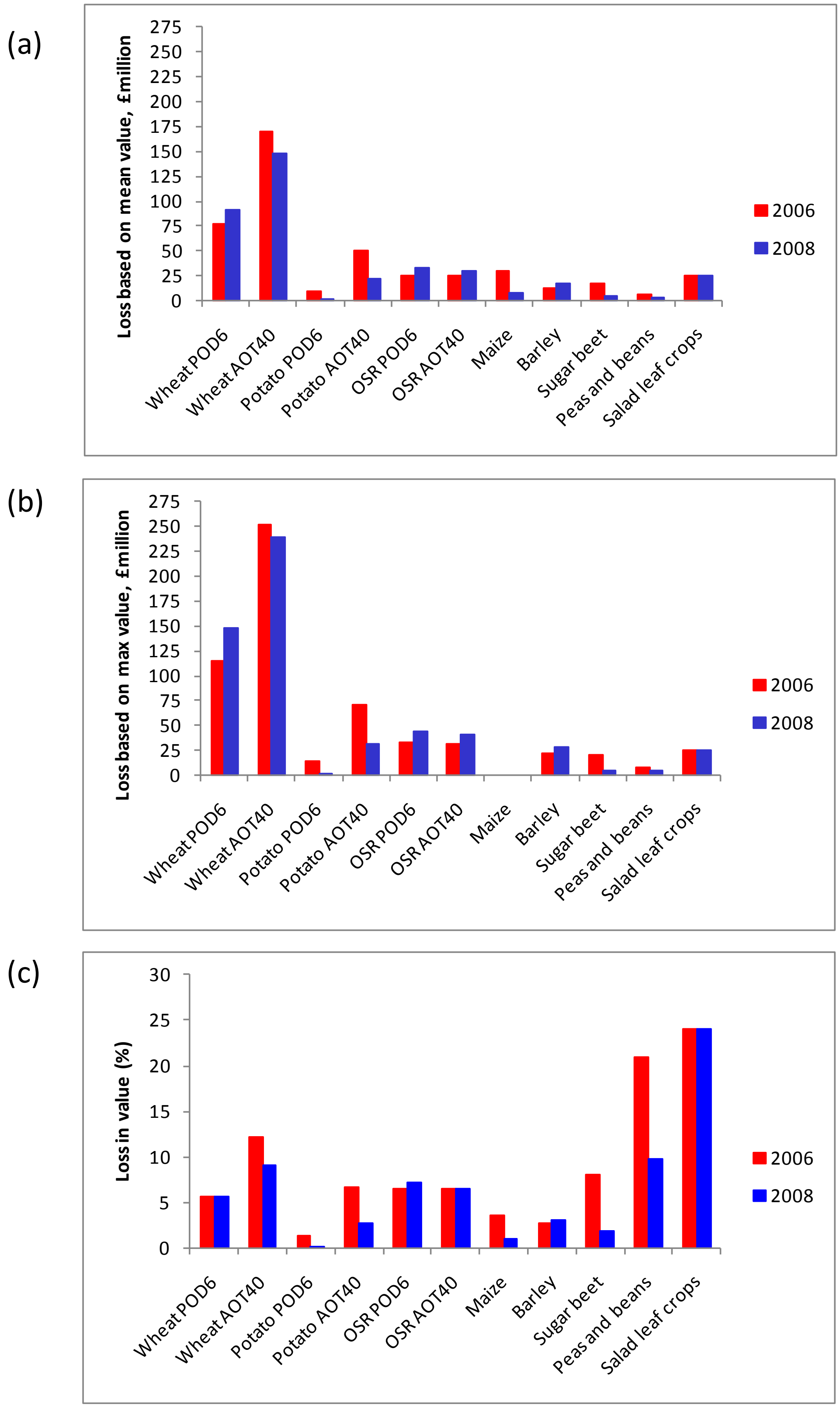


Figure 3.3 Economic losses based on (a) mean crop value and (b) maximum crop value and (c) % yield loss for 2006 and 2008; OSR = oilseed rape. Note: 2008 values for salad crops were not available; 2006 values used as indicators of losses.

3.6 Indicative certainty

In Table 3.2, the bottom row provides an indication of the certainty of the numbers provided. The most certainty is associated with wheat yield loss predictions ("high" for flux and "medium" for AOT40), those for potato and oilseed rape based on POD_6 and sugar beet based on AOT40 have "medium" certainty, and the other crops have the least certainty. These values are provided from a qualitative assessment of the impact of quantifiable factors on the data provided.

Those influencing factors that can be quantified are provided in Table 3.5. The strength of the regression varies from crop to crop, with the function for barley being the least reliable ($r^2 = 0.013$, $p = 0.065$) and those for wheat being the most reliable ($r^2 = 0.84$ and 0.89, $p < 0.01$ for both methods). The two functions for wheat and that for potato were approved for use for the derivation of critical levels and are included in the LRTAP Convention's Modelling and Mapping Manual. Most of the other functions have been derived from the ICP Vegetation (2011) database and was an update of the data collation reported in Mills et al. (2007). As the published data primarily reports effects based on the 7h mean ozone metric, then the data needed to be converted to AOT40 for use in this study. This introduces some error into the functions as the conversion function does not take into account the hourly variation in ozone concentrations that contribute to AOT40. A further source of error results from forcing the response function through a relative yield of 1 at zero AOT40; for several of the functions the unforced linear regression predicted a relative yield of between 0.85 and 0.95 at zero AOT40. Greater certainty was awarded to the flux-based functions as the flux method is more biologically meaningful than the AOT40-based method. Overall, only the wheat POD_6 function was awarded "high" certainty score. The response functions for wheat (AOT40) and potato (POD_6), oilseed rape (POD_6) and sugar beet (AOT40) were given a "medium" certainty score and the other functions were given a "low" certainty score.

Table 3.5 (b) provides the indicative certainty associated with the spatial data used in the project. Crop distribution data from Eurostat and distributed into the 10 x 10 km grid squares matched that from the Defra statistics for wheat and barley, but there was some variation for other crops. The range of crop price values provides the largest quantifiable source of uncertainty in this study, with, for example, the value for wheat ranging from £71 per tonne to £152 per tonne over the 1996 to 2009 period. Use of the mean crop value significantly underestimates the potential economic value of the yield loss as described above. With the exception of the sugar beet price which does not vary so much, the volatility of crop prices resulted in a low indicative certainty score for all of the crops.

Data was not available for validation of the ozone concentration maps and thus uncertainty caused by the interpolation of concentrations between measuring sites could not be quantified. AEA calculated the ozone flux at specific locations and compared values with those modelled using the OSRM-SOFM model for the same sites (data is summarised in Table 3.6 and presented graphically in the individual chapters). For potato the OSRM-SOFM model produced lower values of POD_6, by a factor of around 2 (for both 2006 and 2008) relative to predictions derived from measured ozone concentrations. For wheat and oilseed rape, the OSRM-SOFM model produced similar values of POD_6 in 2008 compared with values derived using measured ozone concentrations, but the model -derived values were a factor of approximately 1.5 lower than derived from measured concentrations for 2006. The two methods produced similar values of POD_1 for late clover in 2006, but OSRM-derived values for 2008 are higher (by a factor of approximately 1.3) relative to predictions derived from measured concentrations. These differences arise because the OSRM-SOFM tends to under-estimate peak ozone concentrations in years where these are particularly high (such as in the summer of 2006) and over-estimate ozone concentrations in years where ozone concentrations are low. Such under- and over-estimations will have significantly impacted on the crop loss quantifications presented here (see individual chapters) and are a major source of uncertainty in the data.

There are further unquantified uncertainties associated with the estimation of the f factors in the SOFM or DO_3SE models from meteorological data. For example, the f_{swp}, f_{PAW} factors for soil water content rely on modelled estimates of the soil water content and f_{light} relies on modelled radiation. This uncertainty would arise irrespective of the model used to predict ozone flux.

To give some indication of the overall certainty in the data, the certainty class for each effect was added together and presented as a percentage of the maximum score for each crop and ozone metric combination (Table 3.7). Values above 75% were given the overall certainty of "high", those between 50 and 75% were given a certainty value of "medium", and those below 50% were classified as “low certainty”. The certainty of the results will also have been influenced by several currently unquantifiable factors. These include extrapolation of ozone effects from field-based open-top chambers to the open field environment; use of AOT40-based response functions rather than those based on the flux of ozone into the leaf (POD_6) for several crops; relative sensitivity of UK cultivars compared to those included in the experiments; and impacts on crop quality as well as quantity etc.

Table 3.6 The relationship between the phytotoxic ozone dose calculated using OSRM-SOFM (x) with that from measured ozone and met data (y) at selected sites in the UK

Crop	Parameter	2006	2008
wheat	POD_6	y = 1.501x	y = 0.978x
potato	POD_6	y = 2.213x	y = 1.797x
Oilseed rape	POD_6	y = 1.516x	y = 1.093x
Early clover	POD_1	y = 1.153x	y = 1.004x
Late clover	POD_1	y = 0.939x	y = 0.739x

Table 3.7 Overview of levels of certainty applied to the data; OSR = oilseed rape. See Table 3.5 (next page) for details.

Crop	O3 parameter	Dose response function	Crop distribution data	Price variation	Flux model	Total	Certainty (% of max score)	Overall Class
wheat	POD6	3	3	1	2	9	75.0	High
wheat	AOT40	2	3	1	n.a.	6	50.0	Medium
potato	POD6	3	2	1	1	7	58.3	Medium
potato	AOT40	1	2	1	n.a.	4	33.3	Low
OSR	POD6	1	3	1	2	7	58.3	Medium
OSR	AOT40	1	3	1	n.a.	5	41.7	Low
barley	AOT40	1	3	1	n.a.	5	41.7	Low
maize	AOT40	1	1	1	n.a.	3	25.0	Low
sugar beet	AOT40	1	3	2	n.a.	6	50.0	Medium
peas and beans	AOT40	1	3	1	n.a.	5	41.7	Low
Lettuce	counts>60	1	1	1	n.a.	3	25.0	Low

Table 3.5. Derivation of indicative certainty for (a) the response functions and (b) the spatial data used. Note: certainty is scored as 3 (high), 2 (medium) and 1 (low).

(a)

Crop	O3 parameter	r2	p	variation at 5% yield loss, +/- %	Data source	O3 data derived from	Response function forced through RY =1	Certainty score
wheat	POD6	0.84	<0.001	1.8	LRTAP Convention (2010)	modelled flux	no	3
wheat	AOT40	0.89	<0.001	1.6	LRTAP Convention (2010)	measured AOT40	no	2
potato	POD6	0.76	<0.001	3.8	LRTAP Convention (2010)	modelled flux	no	3
potato	AOT40	0.16	0.017	4.3	ICP Vegetation (2011)	AOT40 converted from 7h mean	yes	1
oilseed rape	POD6	0.19	0.02	21.7	Vandermeieren, pers. comm.	modelled flux	yes	1
oilseed rape	AOT40	0.95	0.041	7.5	ICP Vegetation (2011)	AOT40 converted from 7h mean	yes	1
barley	AOT40	0.013	0.065	5	ICP Vegetation (2011)	AOT40 converted from 7h mean	yes	1
maize	AOT40	0.68	<0.001	4.8	ICP Vegetation (2011)	AOT40 converted from 7h mean	yes	1
sugar beet	AOT40	0.26	0.003	3.8	ICP Vegetation (2011)	AOT40 converted from 7h mean	yes	1
peas and beans	AOT40	0.14	<0.001	7	ICP Vegetation (2011)	AOT40 converted from 7h mean	yes	1

(b)

	Crop distribution data used		Defra UK statistics			Price variation, £/t					Flux model validation**/ use of AOT40 uncertainty		
Crop	2006	2008	2006	2008	Indicative Certainty	Mean	Min	Max	(max-min)/mean	Indicative Certainty	2006	2008	Indicative Certainty
wheat	1.83	2.08	1.83	2.08	3	£94	£71	£152	0.86	1	1.50	**0.98**	**2**
potato	0.14	0.143	0.044	0.064	2	£124	£69	£175	0.86	1	**2.23**	1.80	1
oilseed rape	0.5	0.6	0.58	0.6	3	£231	£138	£314	0.76	1	**1.52**	1.09	2
barley	0.88	1.01	0.88	1.03	3	£95	£72	£153	0.85	1	n.a.	n.a.	
maize	0.125	0.119	n.a.	n.a	1	£679	n.a.	n.a.	n.a.	1	n.a.	n.a.	
sugar beet	0.13	0.12	0.13	0.12	3	£29	£24	£34	0.34	2	n.a.	n.a.	
peas and beans***	0.045	0.049	0.04	0.05	3	£156	£93	£228	0.87	1	n.a.	n.a.	
lettuce	0				1	£9000*	n.a.	n.a.	n.a.	1	n.a.	n.a.	

* £/ha

** slope of PODy calculated using measured vs modelled O3 conc

*** Data used in this study is for combined peans and beans only, other pulses may be included in the Defra statistics

4. Economic losses for cereals

Summary: Cereals

- Wheat is sensitive to ozone whilst barley and maize are moderately tolerant.
- Losses in value were predicted to be £77.6, £30.4 and £13.3 million in 2006 and £91.2, £8.3 and £17.7 million in 2008 for wheat, maize and barley respectively using the best available methods and mean crop prices for the period 1996 – 2009.
- These losses represented 5.6, 3.6 and 2.7% of the economic value of the crop in 2006 and 5.6, 1.0 and 3.1% of the economic value in 2008 for wheat, maize and barley respectively.
- There were differences between the two years in the geographical areas most at risk of economic losses. For example the highest losses for wheat were predicted in the NE in 2006 where climatic conditions were cooler and wetter than in central England and East Anglia and were more conducive to ozone uptake. In contrast, in 2008, the greatest predicted impacts were in central England and East Anglia with lower impacts predicted for the NE.
- For wheat, predicted losses were ca. 2 x higher when AOT40 was used as the dose metric rather than the more biologically relevant flux metric (POD_6).
- The potential economic loss for wheat in the higher ozone year of 2006 taking into account under estimations within the OSRM-SOFM model and using the maximum crop value of £140/tonne was £172 million representing 8.4% of the UK wheat yield.

4.1 Introduction

In this study, we have investigated the effects of ozone on three cereals: wheat, barley and maize. Together, these cereals are grown on ca. 50% of the UK land area dedicated to crops. Unfortunately ozone response functions were not available for the other cereals grown in the UK (oats, rye and triticiale), but these are only grown on ca. 5% of the cereal-growing areas. Overall, wheat is the most important agricultural crop in the UK and is grown on approximately 2 million ha each year. Wheat grain is milled for flour for use in bread, biscuit and cake making as well as for animal feed and industrial uses (including bio-ethanol and starch production, Francis, 2009). Importantly, the analysis conducted for wheat has the highest degree of certainty of all of the crops included in this study. Analyses conducted for maize and barley have a low amount of certainty.

The response of wheat to ozone was studied extensively in Europe and the USA during the 1980s and 1990s. When the data were combined as part of the development of critical levels, response functions covering wheat grown in several countries were relatively robust, with r^2 values of greater than 0.8 and p values of less than 0.001. During the last two years, the dataset has been re-evaluated and a new response function using data from stomatal conductance measurements made on current cultivars of wheat has been derived (Grünhage et al., submitted). The function was further updated to include soil moisture represented as the plant available water (PAW). The AOT40-based function used here is that included in the LRTAP Convention's Modelling and Mapping Manual and reported in Mills et al. (2007). This study provides the first detailed analysis of country-specific maps of ozone index on wheat yield using both the flux-and the AOT40-based methodology.

Barley is the second most important crop in the UK by land area. It is used for malting (in the beer, whisky and malt industries) and animal feed (Francis, 2009). In contrast to wheat, barley is moderately tolerant of ozone (Figure 3.2), and thus lower economic impacts are predicted. Because of the lower sensitivity, fewer experiments have been conducted with barley and a flux model has not yet been derived for this crop. Thus, the analysis presented here is only based on AOT40.

Maize has been grown more extensively in the UK in the last decade. The crop is used as either a whole crop silage plant for animal feed or biogas feedstock, corn-cob maize silage, feed grain, or as a vegetable (Francis, 2009). In the UK, maize is sown between April to mid-May and harvested between September and November depending on use. Open-top chamber experiments were conducted extensively in the USA in the 1980s and 1990s and indicated that maize is moderately tolerant to ozone (Mills et al., 2007). No flux-response relationships are available for this crop.

Each cereal crop is considered separately in the following text, with a summary of the key findings for cereals presented in the text box at the beginning of this chapter.

4.2 Wheat

4.2.1 Methods used for wheat

The methods used for wheat followed those described in Chapter 2. The response functions used are presented in Figure 4.1 and the range in crop value is presented in Figure 4.2. The accumulation period for the flux-based method was from 200 °C days before anthesis to 700 °C days after anthesis with the timing of mid-anthesis being determined using a latitude model (LRTAP Convention, 2010). For the AOT40-based method, the accumulation period was 15 April to 15 July representing the main growing and grain fill period for winter wheat. This was chosen to be the most representative of the UK wheat crop, but is two weeks earlier than the timing window recommended in the LRTAP Convention's Modelling and Mapping Manual for Atlantic Central Europe.

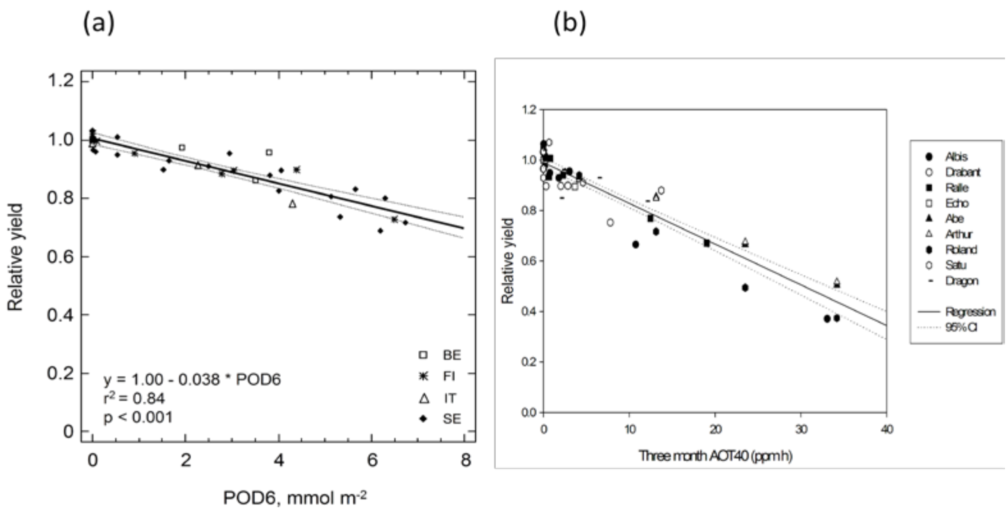


Figure 4.1 Response functions for the effects of ozone on wheat yield (a) using the flux-based methodology (POD_6) and (b) using AOT40. The response functions can be found in the LRTAP Convention's Modelling and Mapping Manual and in papers by Mills et al. (2007) and Grünhage et al. (submitted).

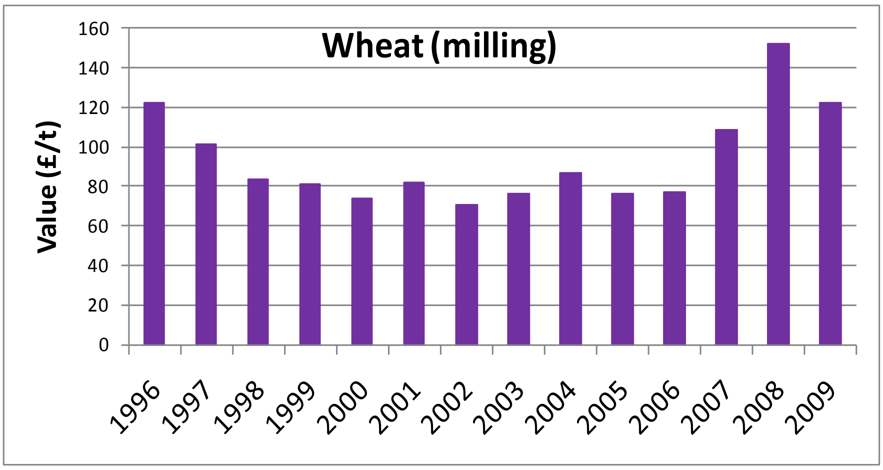


Figure 4.2 The value in £/tonne of the wheat crop in the UK for the years 1996 to 2009. Source: http://www.defra.gov.uk/statistics/foodfarm/

4.2.2 Flux-based analysis of economic losses for wheat

The maps presented in Figure 4.3 showed different spatial patterns for ozone impacts on wheat yield in 2006 and 2008. In the drier year of 2006, the largest percentage yield losses and economic impacts were predicted to be in North East England, particularly in coastal areas of Northumberland, Durham and Yorkshire. The main cereal growing areas in East Anglia were less impacted by ozone. This is likely to be because the low soil moisture content and high vapour pressure deficit in southern and eastern areas of the UK in 2006 were more limiting stomatal conductance and thus accumulated ozone fluxes were lower than might be expected for the AOT40s experienced in these areas (see Figure 4.4). This is illustrated in Figure 4.5 where the f_{phen}, f_{light}, f_{temp}, f_{vpd} and f_{paw} components of the flux model are shown for a single location (52.5 N 0.5W, a rural location between Peterborough and Corby) for 2006 and 2008. f_{paw} is less than 0.7 for over two thirds of the flux accumulation window and less than 0.5 for approximately the last third of the flux accumulation period. In 2008, F_{PAW} was only limiting stomatal conductance towards the end of the flux accumulation period and temperature was having a stronger negative impact on conductance at this location. Indeed, ozone impacts were predicted to be greater in central England in 2008 than in 2006 (Figure 4.3).

As the area with the highest ozone fluxes were not the areas of highest wheat production, the economic losses were lower than might be expected in 2006. In contrast in 2008, the highest percentage yield losses were predicted for central England and East Anglia where wheat production is at its highest for the UK. Thus, the total predicted wheat yield economic losses were higher for 2008 than for 2006 (£91.2 and 77.6 million respectively for the mean crop value, and £135.4 and 115.2million for peak wheat price, Table 4.1). Losses may have been greater in 2006 in areas where the wheat crop was irrigated to overcome the limiting effect of soil moisture on grain yield.

4.2.3 AOT40-based analysis of wheat loss

The AOT40-based analysis of crop losses shows a very different spatial pattern. This parameter accumulates ozone above a threshold concentration and does not take account of the influence of climate and soil water on the amount of ozone that is actually taken up by the plant. Thus, percentage yield losses predicted for 2006 were substantially larger and in different areas using AOT40 based methods than the flux-based methods, with highest impacts being predicted for East Anglia and much of the southern half of England and north-east Wales. As these are the areas with the highest production for wheat, then impacts on the economic value of the wheat yield were expected to be very high. Percentage yield losses were predicted to be markedly lower in 2008 than in 2006 in central and eastern England, but the area affected in 2008 extended up through north-east England and into east Scotland, in part making up for the lower impacts predicted further south. Overall, AOT40-based impacts on wheat yield were predicted to be higher in 2006 at losses of £170 million than in 2008 at £148 million (based on the mean value of the yield).

4.2.4 Comparison of POD_6 and AOT40-based results

The highest proportion of grid squares were predicted to have 4 to 6% yield loss using POD_6 as the ozone metric, whilst the highest proportion of grid squares were in the 8 to 10% (2008) and 10 – 12 % (2006) categories for AOT40 (Figure 4.6). This resulted in predicted losses that were 120% (2006) and 60% (2008) higher for AOT40 than for POD_6 when the effects were accumulated over the whole of the UK (Table 4.1). For POD_6, more than 70% of grid squares had economic losses of up to £75k, whereas for AOT40, economic losses were spread well along the low to mid range of values indicated in Figure 4.7. It is noticeable that, for both years, the proportion of grid squares in each category was relatively similar regardless of ozone metric.

These different results should be considered in the light of the performance of the flux model during validation (Figure 4.8). In 2008, the flux model reliably predicted the flux calculated using measured ozone and climate parameters, whereas in 2006 the flux model under estimated ozone flux by approximately 50%. When this effect was applied to the UK-wide predictions by simply multiplying the predicted losses by correction factors, then the estimated losses for 2006 increase accordingly to £116 million in 2006 and decline to £89million using the mean crop value. Even so, the losses did not reach those predicted using AOT40.

The impact of varying crop value on predictions using both ozone metrics is presented in Table 4.2. Predicted losses using POD_6 ranged from £55 to 115 million in 2006 and from 65 to 135 £million in 2008. The corresponding values for AOT40 were substantially larger at £121 to £252 million in 2006 and £105 to 219 million in 2008.

4.2.5 Key findings for wheat

- Economic loss estimates have high certainty for the flux-based method and medium certainty for the AOT40-based method.
- Using the flux-based index the greatest effects of ozone on wheat were likely in the north east in 2006 and central England and East Anglia in 2008.
- Using the spatial data and flux-based methodology economic impacts were predicted to be greater in 2008 (£91.2million) than in 2006 (£77.6 million), with similar losses as a percentage of the total value of UK production (5.6%).
- Losses predicted using the concentration-based approach (AOT40) were 120% (2006) and 60% (2008) higher for AOT40 than for POD_6 when the effects were accumulated over the whole of the UK, with the central and eastern England wheat growing areas being identified as being at the highest risk of losses in both years.

Table 4.1 Impacts of ozone on wheat yield in 2006 and 2008

Wheat	2006		2008	
	POD6	AOT40	POD6	AOT40
2006 million ha	**1.83**	**1.83**	**2.08**	**2.08**
2006 production, million t	14.73	14.73	17.22	17.22
2006 total value, £ million	1385	1385	1619	1619
2006 lost production, million t	0.83	1.81	0.97	1.58
Lost value at mean price, £million	**77.63**	**169.97**	**91.24**	**148.07**
Lost value at peak price, £million	**115.20**	**252.24**	**135.40**	**219.75**
% lost (calc from value)	**5.61**	**12.28**	**5.64**	**9.15**
with flux model correction				
correction factor (from Figure 4.7)	1.5006		0.9782	
Lost value at mean price, £million	**116.49**		**89.25**	
Lost value at peak price, £million	**172.87**		**132.45**	
% lost (calc from value)	**8.41**		**5.51**	
Certainty of estimates	High	Medium	High	Medium

Table 4.2 Impacts of crop value on predicted economic loss due to ozone

		Economic loss, £million			
	Value	**2006**		**2008**	
	£/t	**POD6**	**AOT40**	**POD6**	**AOT40**
Mean (milling)*	94	77.6	170.0	91.2	148.1
Mean	88.7	73.2	160.3	86.1	139.7
Min	67.0	55.3	121.1	65.0	105.5
Max	139.5	115.2	252.2	135.4	219.7
Q1	72.6	60.0	131.3	70.5	114.4
Q3	101.8	84.0	184.0	98.8	160.3
* used for crop loss calculations					

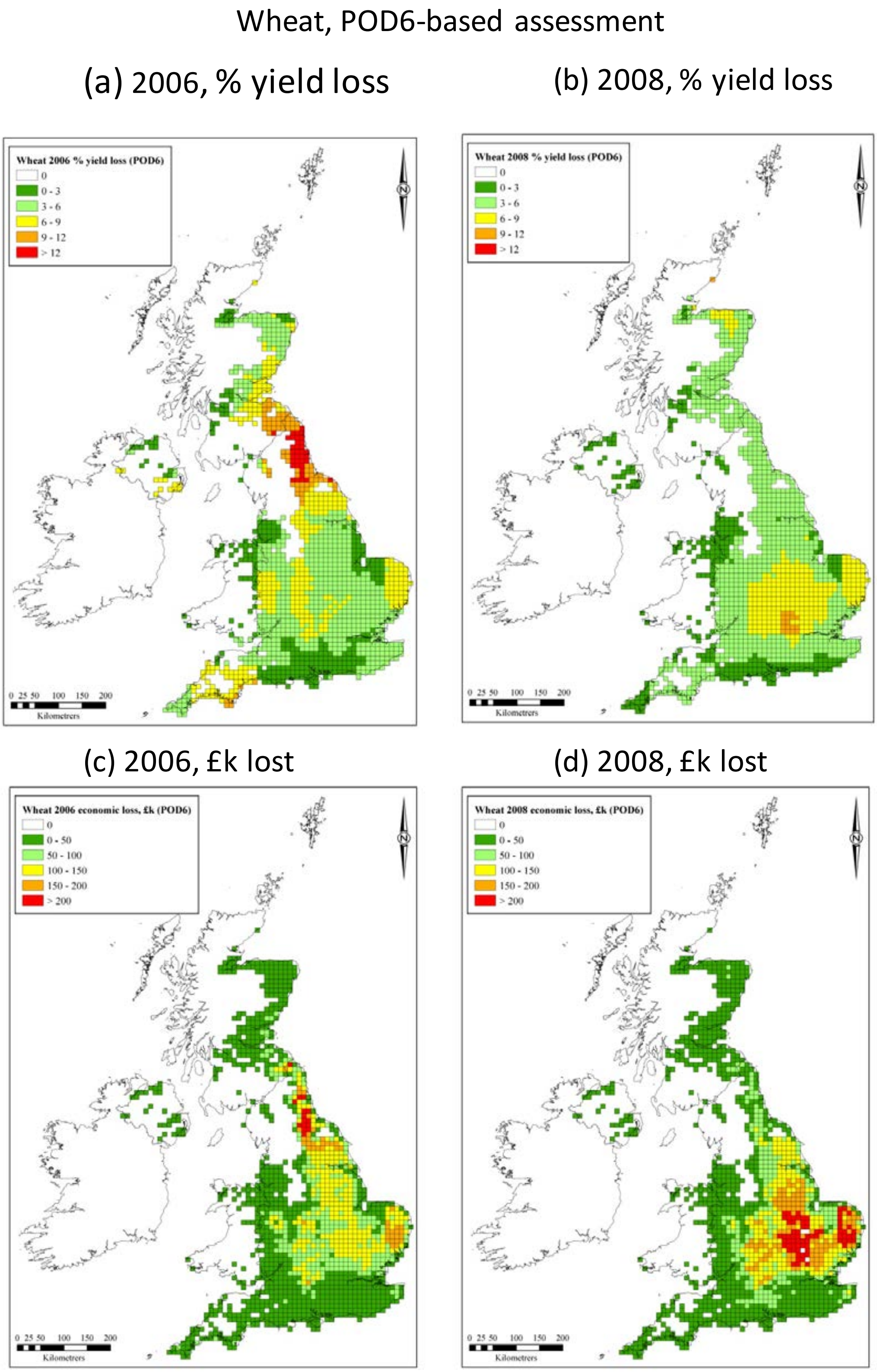


Figure 4.3 Spatial distribution of the impacts of ozone on wheat yield loss as predicted using POD_6 presented as a % of total yield and economic loss (£k) per grid square . Only those grid squares where wheat was grown on >100 ha (1%) of the grid square are shown.

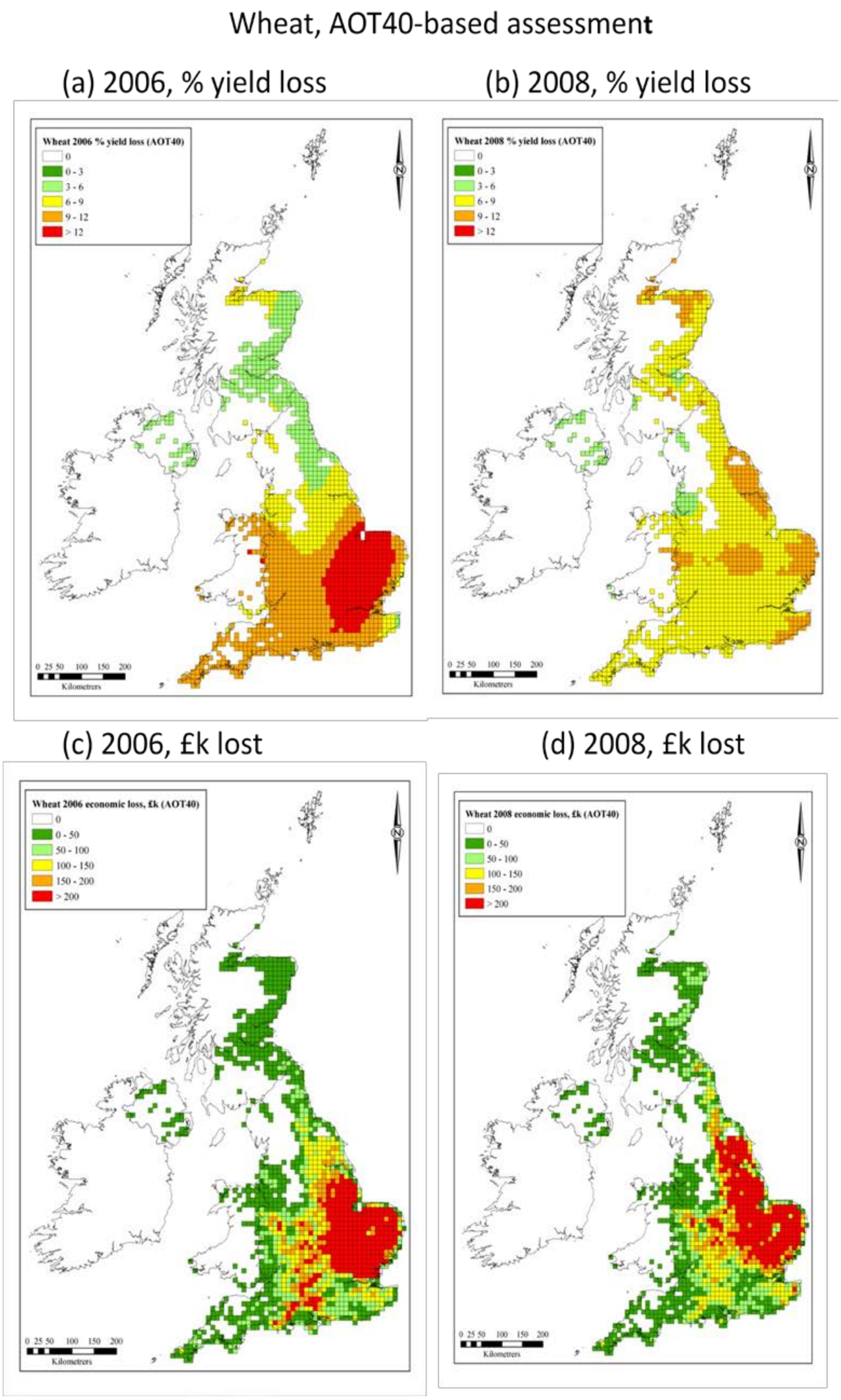
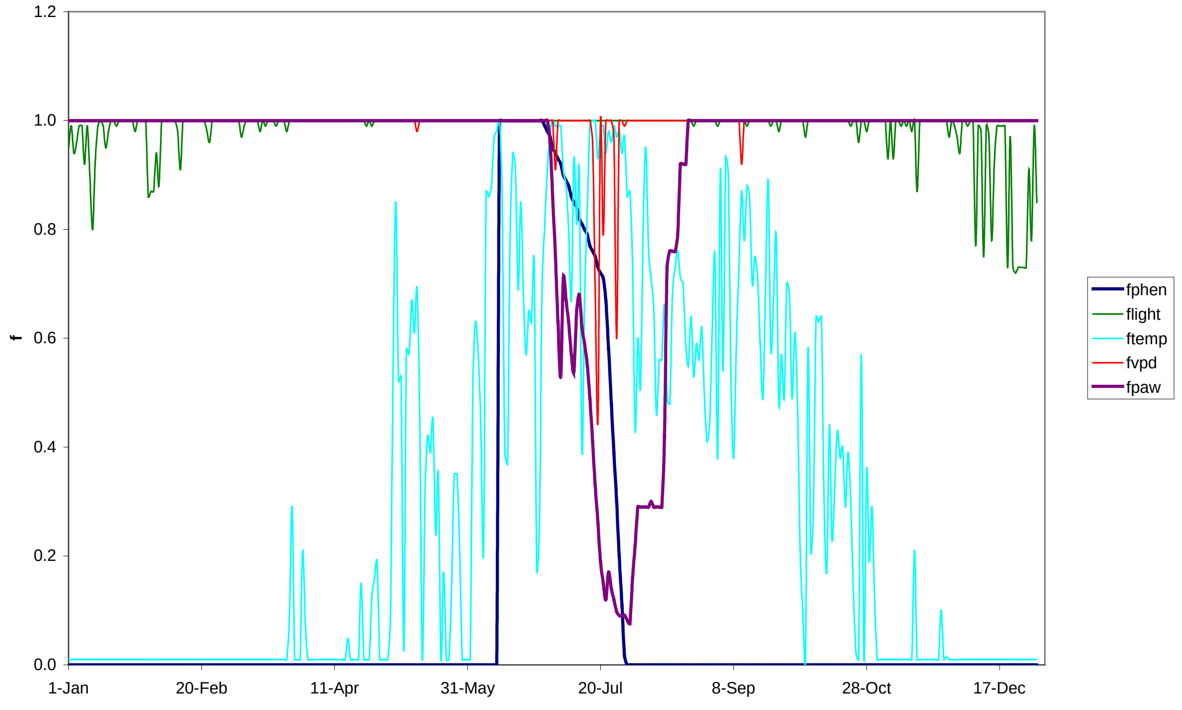


Figure 4.4 Spatial distribution of ozone impacts on wheat yield loss, as predicted using AOT40, presented as a % of total yield and economic loss (£k) per grid square. Only those grid squares where wheat was grown on >100 ha (1%) of the grid square are shown.



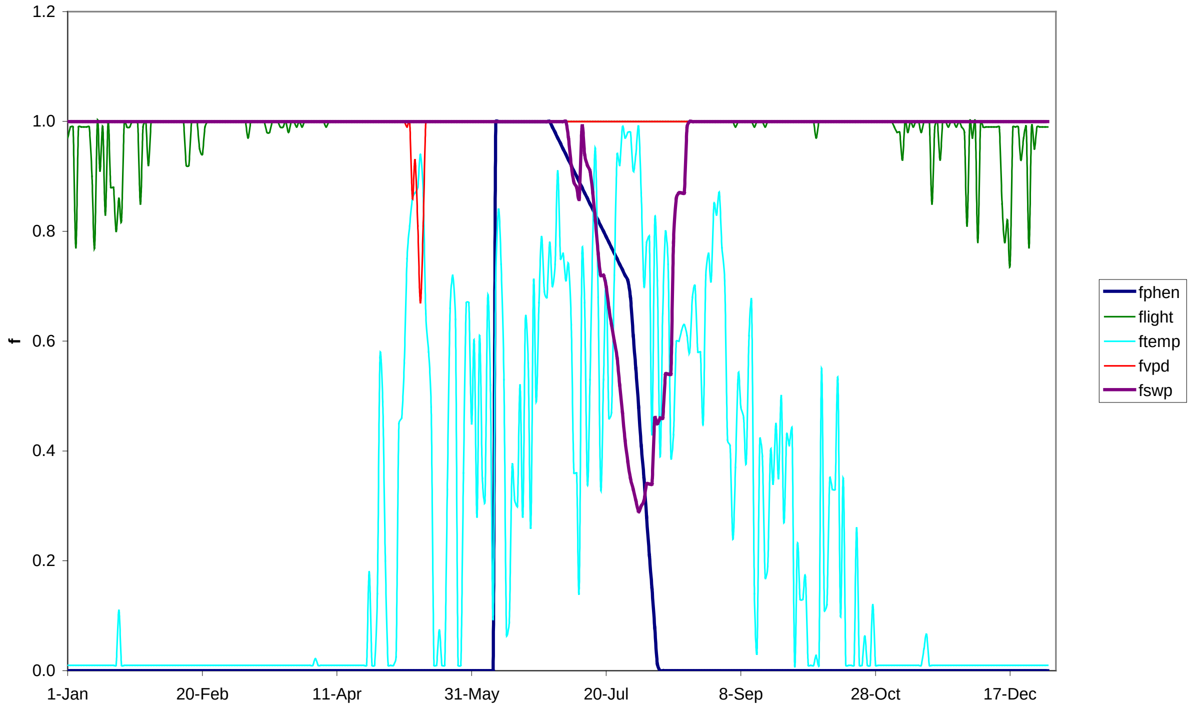


Figure 4.5 Variation in the f functions that contribute to the calculation of ozone flux to wheat at a rural site near Peterborough (52.5 N 0.5W) in 2006 and 2008. Ozone fluxes were accumulated during the time period when f_{phen} >1.

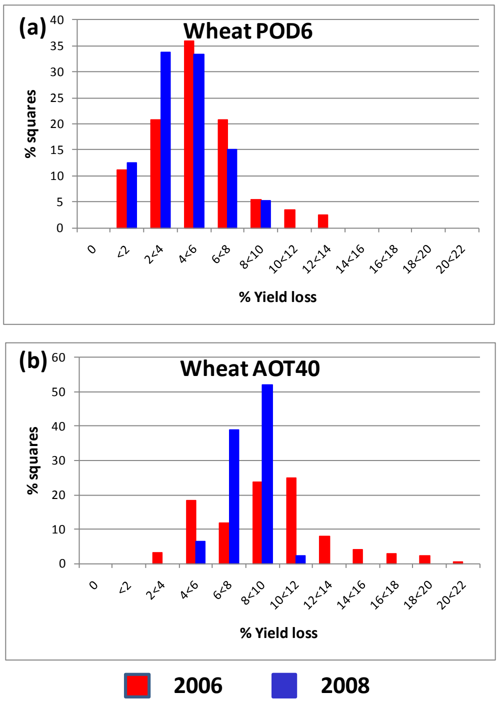


Figure 4.6 Frequency distribution of % yield loss for wheat the 10 x 10 km grid squares in Figure 4.3 and 4.4 using the POD_6 and AOT40 ozone metrics. Only data from the grid squares where wheat was grown on >100 ha (1%) of the grid square are shown

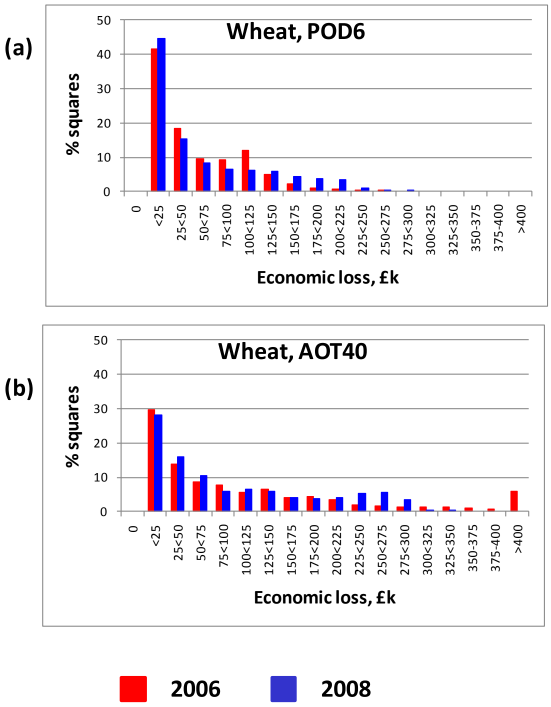


Figure 4.7 Frequency distribution of the economic losses (£k) for wheat for the 10 x 10 km grid squares in Figure 4.3 and 4.4 using the POD_6 and AOT40 ozone metrics. Only data from the grid squares where wheat was grown on >100 ha (1%) of the grid square are shown.

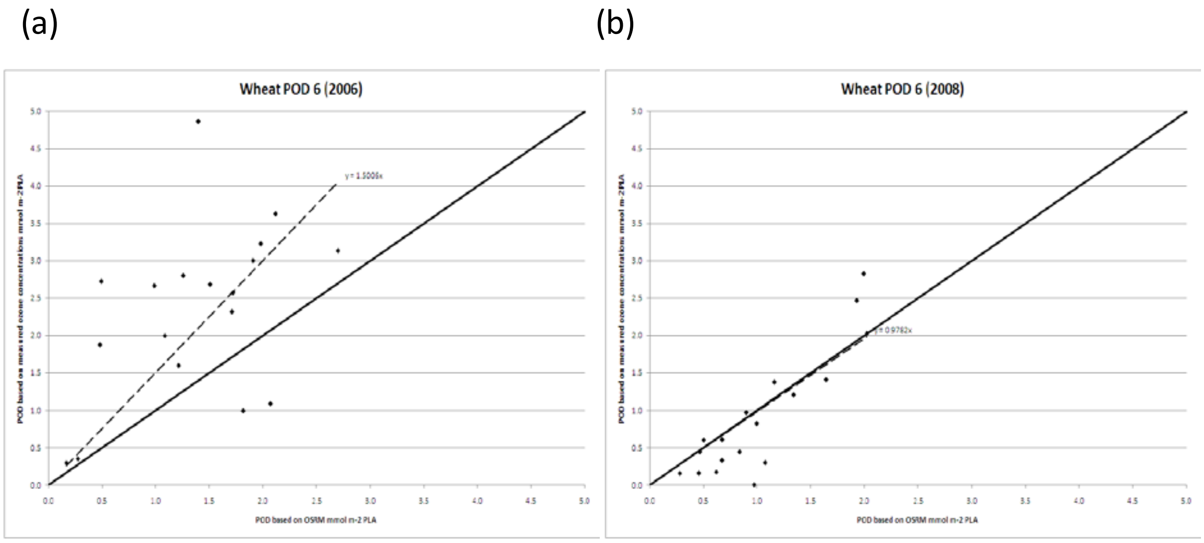


Figure 4.8 Comparison of predicted fluxes to wheat based on OSRM-SOFM predictions of ozone concentration and measured ozone concentrations at different sites in the UK in (a) 2006 and (b) 2008. The thick line indicates the 1:1 ratio.

4.3 Economic losses for barley

4.3.1 Methods used for barley

The method used for barley followed that described in Section 2. The only response function available was that using AOT40 (Figure 4.9) that was accumulated for the period 1 April to 30 June to coincide with the main growing and grain fill periods for winter barley. The yield response function has the most scatter of all of those used in this assessment and is only significant at the $p = 0.065$ level. Thus, the certainty level for this part of the analysis has been categorised as "low". Further sources of uncertainty come from the recent increase in crop value illustrated in Figure 4.10 which may not be fully represented by the mean price of £94.4/t used in this study.

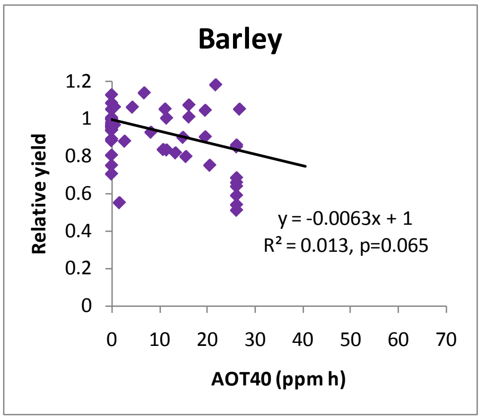


Figure 4.9 The AOT40-based response function for barley used in this study. The function is derived from an update of that in Mills et al. (2007) including more recently published data.

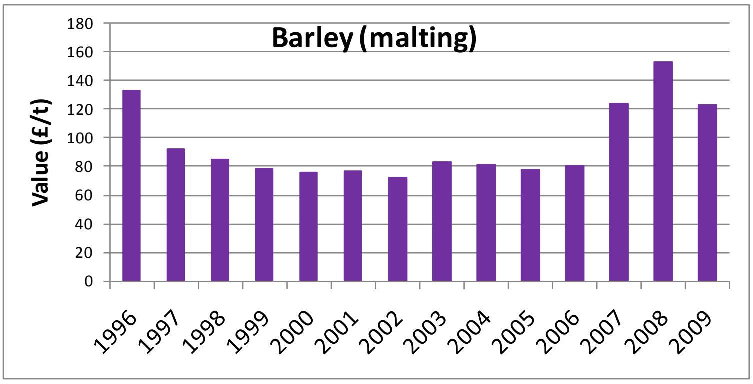


Figure 4.10 The value in £/t of the barley crop in the UK for the years 1996 to 2009.

Source: http://www.defra.gov.uk/statistics/foodfarm/

4.3.2 AOT40 based analysis of impacts for barley

As with wheat, the spatial distribution of predicted impacts varied between the two years but the overall impacts on percentage yield loss were lower than for wheat (Figure 4.11). The biggest percentage yield losses and associated lost value in 2006 were in East Anglia whereas in 2008, losses in the range of 3 to 6% were predicted for most of the east coast areas of the UK, including as far north as northern Scotland. As the Scottish counties of Tayside and Grampian are important growing areas for barley for use in the brewing and whisky industries, impacts in this area are economically important and contributed to the largest economic losses in 2008. In 2008, the percentage of grid squares was normally distributed around the 2-3 and 3-4% yield loss categories, whilst in 2006 most grid squares were in the 1-2% yield loss category (Figure 4.12a). The higher economic losses in 2008 were due to more grid squares in the £10 – 15k, £15 – 20k and £35 – 40k categories (Figure 4.12b).

Overall, economic losses for barley were 6 to 10 times lower than those for wheat (Tables 4.1 and 4.3), even though barley is grown on approximately one million ha, about half of the area dedicated to wheat growing. Using the mean price, the predicted losses were higher in 2008 than in 2006 (£17.7 million compared to £13.3 million) reflecting the higher AOT40s in the main growing areas in Scotland in 2008. These losses are equivalent to 2.7 and 3.1% loss in economic value for 2006 and 2008 respectively. Barley prices were relatively stable from the period 1997 to 2006, but increased sharply to peak in 2008 (Figure 4.9). Applying the full range of crop values over the 14 years, the economic losses for barley ranged from £10.1 to 21.4 million in 2006 to £13.4 to 28.4 million in 2008.. (Table 4.4).

4.3.3 Key findings

- Loss estimates for barley have a low degree of certainty because the only response function available, based on AOT40 had a large amount of scatter and was only significant at the $p=0.065$ level.
- 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 significant and represent ca. 3% of the total crop value in the UK based on mean crop prices.
- It is of particular note that high ozone concentrations during the main growing period for barley in eastern Scotland were likely to have caused economic losses of >£50k in twelve 10 x 10 km grid squares, and between £32.5k and £50k in a further 26 grid squares.

Table 4.3 Impacts of ozone on barley yield in 2006 and 2008

	2006	2008
Barley	**AOT40**	**AOT40**
Million ha grown	0.88	1.01
Production, million t	5.23	6.04
Total value, £ million	497	574
Lost production, million t	0.14	0.19
Lost value at mean price, £million	**13.31**	**17.65**
Lost value at peak price, £million	**21.43**	**28.42**
% economic loss	**2.68**	**3.08**
Certainty of estimates	Low	Low

Table 4.4 Impacts of crop value on the predicted economic loss due to ozone effects on barley

		Economic loss, £million	
		2006	**2008**
	£/t	**AOT40**	**AOT40**
Mean	95.4	13.31	17.65
Min	72.0	10.09	13.37
Max	153.0	21.43	28.42
Q1	78.3	10.96	14.53
Q3	115.3	16.14	21.41

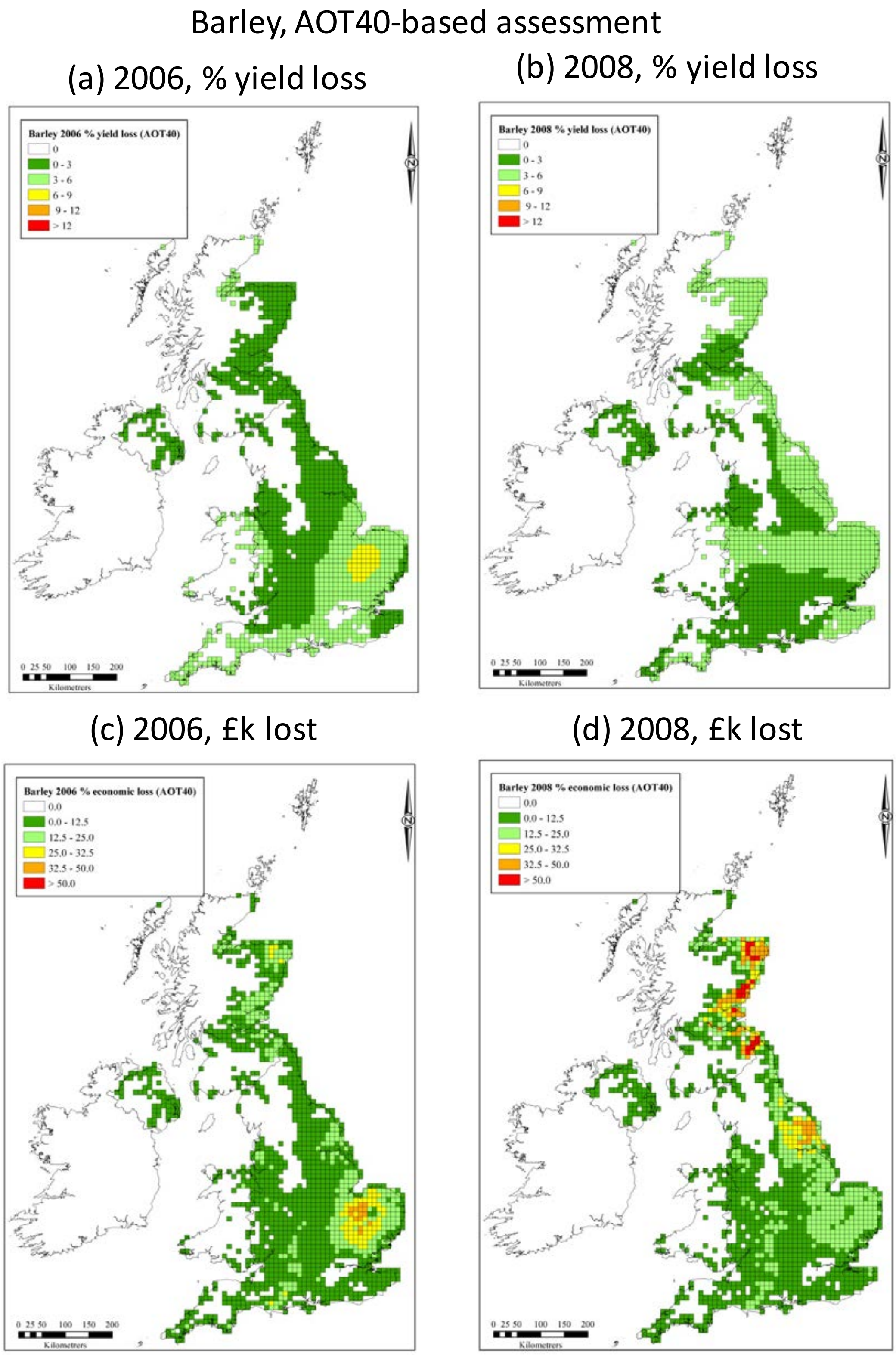


Figure 4.11 Spatial distribution of the ozone effects on barley yield loss as predicted using AOT40, presented as a % of total yield and economic loss (£k) per grid square. Only those grid squares where barley was grown on >100 ha (1%) of the grid square are shown

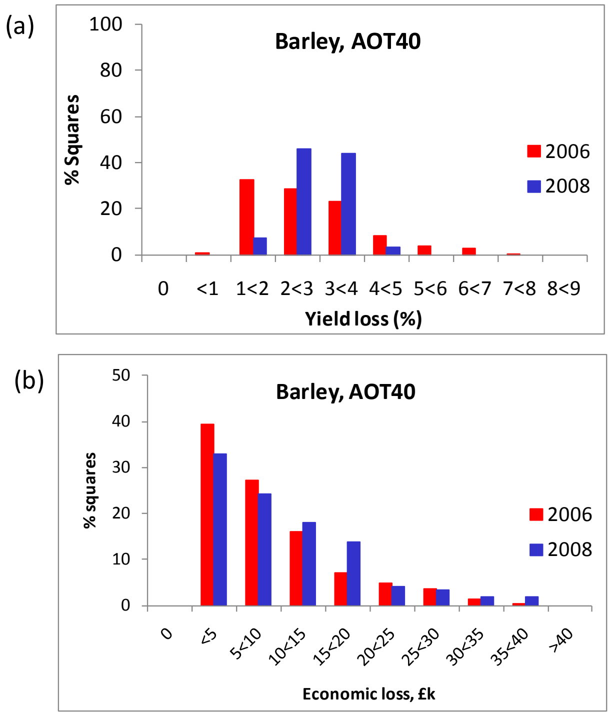


Figure 4.12 Frequency distribution of (a) % yield loss and (b) economic loss in £k for the 10 x 10km grid squares in Figure 4.10. Note: only data from the grid squares where barley was grown on >100 ha (1%) of the grid square are shown.

4.4 Economic losses for maize

4.4.1 Methods used for maize

The time period for accumulation of AOT40 was chosen to match the main growing and seed fill periods for maize and runs from 1 June to 31 August. The analysis was conducted as described in Chapter 2, using the response relationship shown in Figure 4.13. A time series of crop value was not available for this crop; the 2007 price of £679 per tonne was used in the economic analysis.

4.4.2 Economic impact assessment using AOT40

The maize growing areas of the UK experienced AOT40s in 2006 during the June, July, August accumulation period that were sufficient to induce yield losses of up to 9% (Figure 4.14 (a)). In contrast, in 2008, the cooler, wetter conditions during July and August resulted in significantly lower AOT40s (see Figure 3.1) and predicted percentage yield losses were substantially lower than in 2006 (Figure 4.14(b)). Economic losses of greater than £200k were predicted for grid squares in central England and East Anglia in 2006, but in 2008 predicted yield losses did not exceed £50k per grid square across the UK. The breakdown of proportion of squares in yield loss and economic loss categories further illustrates the large difference between the growing seasons. In 2006, the percentage of grid squares was normally distributed around the 3- 4% yield loss category, whilst in 2008, all of the grid squares where in the 0- 1 and 1- 2% categories (Figure 4.15 (a)). Similarly, economic losses of up to £350k per grid square were experienced in 2006, but all of the economic losses were less than £50k in 2008 (Figure 4.15 (b)).

This big difference in AOT40 between the years resulted in very large differences in the total economic losses (Table 4.5). In 2006, the lost value (using 2007 prices) was predicted to be £34.4 million in the UK whereas in 2008 the lost value was £8.3 million. This was equivalent to 3.6% of the total revenue for maize in 2006 and 1.0% in 2008.

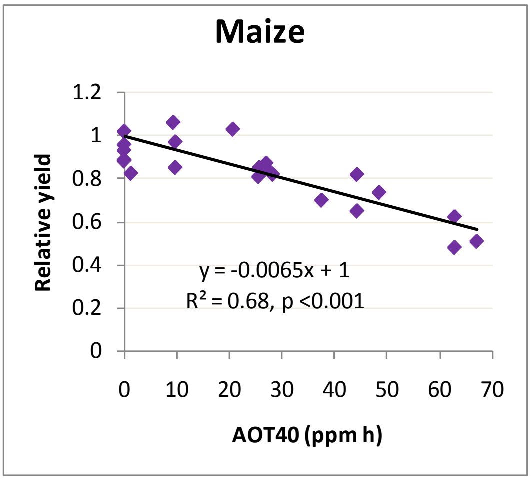


Figure 4.13 The response function for the effects of ozone on maize. This function was published in Mills et al. (2007) using data published up to 2004. No new data has become available since then.

4.4.3 Key findings for maize

- Maize is moderately tolerant to ozone and results provided here have a low degree of certainty.
- AOT40s during the main growing and grain fill period for maize (June-August) were higher in 2006 than 2008 resulting in 3.7 x higher economic losses (£30.4 million in 2006 compared to £8.3 million in 2008).
- The areas with the highest predicted losses were in central England and East Anglia.

Table 4.5 Impacts of ozone on maize yield in 2006 and 2008

	2006	2008
Maize	**AOT40**	**AOT40**
Million ha grown	0.13	0.12
Production, million t	1.25	1.19
Total value, £ million	849	808
Lost production, million t	0.05	0.01
Lost value at 2007 prices, £ million	**30.43**	**8.33**
% economic loss	3.58	**1.03**
Certainty of estimates	Low	Low

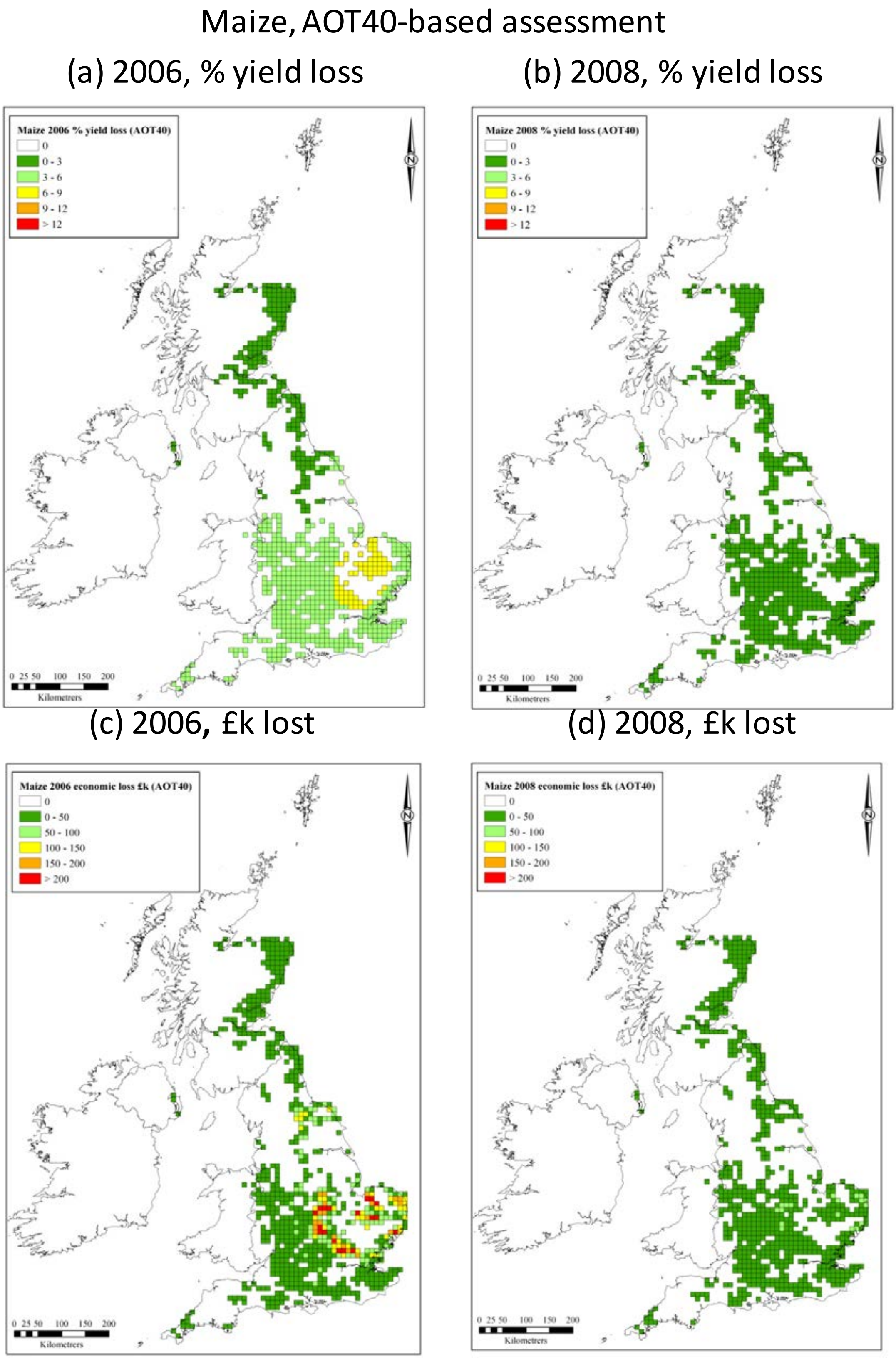


Figure 4.14 The spatial distribution of effects of ozone on maize yield loss in 2006 and 2008, presented as a % of total yield and economic loss (£k) per grid square. Only those grid squares where maize was grown on >50 ha (0.5%) of the grid square are shown.

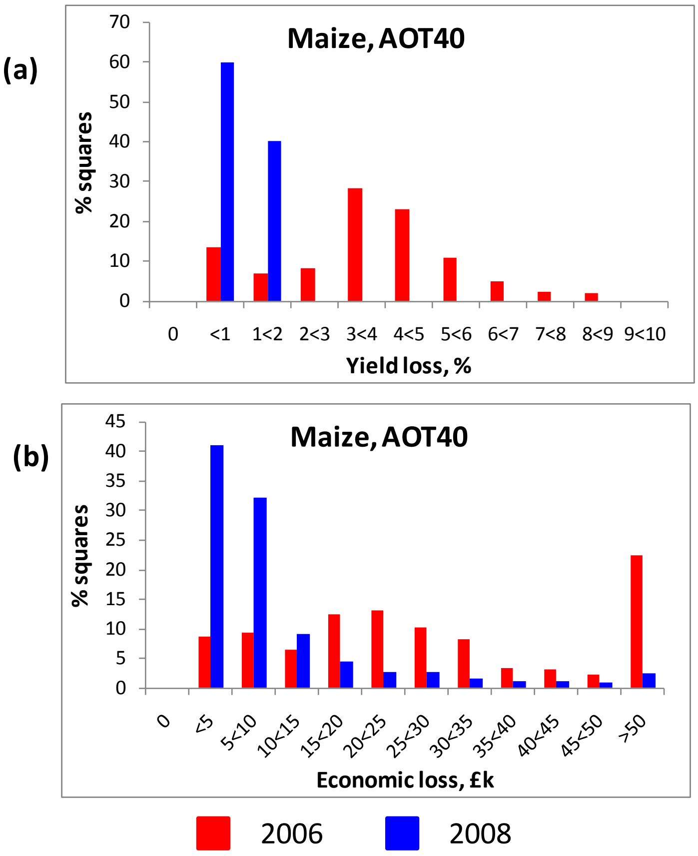


Figure 4.15 Frequency distribution for the effects of ozone on percentage yield loss and economic losses in maize for 2006 and 2008. Only those grid squares where maize was grown on >50 ha (0.5%) of grid squares are included.

5. Economic losses for oilseed rape

Summary: Oilseed rape

- Oilseed rape is moderately sensitive to ozone.
- During the main growing and seed fill stages, April to June, the highest ozone exposure (AOT40) and ozone flux (POD_6) occurred in the growing areas in East Anglia and central England in both years.
- Predicted impacts on economic value of the UK oilseed rape crop were very similar using both ozone metrics at £25 million in 2006 and £30-33million in 2008 representing 6.6 to 7.2% of the economic value.
- Using the recent peak in price (2008) and corrections for underestimations of ozone flux using the OSRM model, the highest economic losses predicted for the UK were £48.6 million for 2006.

5.1 Introduction

Oilseed rape is the UK's third most important crop by land area, being grown on approximately 0.6 million ha annually. The seed is crushed for oil, with the oil being used for vegetable oil, margarine production and biodiesel (Francis, 2009). Winter rape is sown in mid-August to mid-September and is harvested in late July to mid-August the following year, and Spring rape is sown in late March to mid-April and harvested in early September. Although an important crop in Europe, there have been only a few studies on the responses of oilseed rape to ozone. A recently completed study in Belgium exposed the spring oilseed rape cv Ability to three ozone exposure regimes in open-top chambers in 2007, 2008 and 2009, and investigated the effects on seed yield and oil quality (De Bock et al., 2011). We have used the POD_6-seed yield relationship from this study to investigate effects in the UK as this cultivar is on the UK HGCA list of recommended varieties. The relationship for AOT40 includes data from published experiments. Overall oilseed rape is regarded as moderately sensitive to ozone. The indicative certainty associated with the analysis for oilseed rape is "medium" for the POD_6 relationship and "low" for the AOT40-based assessments.

5.2 Methods for oilseed rape

The method used for oilseed rape matches that described in Chapter 2. Ozone flux was modelled using the parameterisations published by Op de Beeck et al. (2011), determined using stomatal conductance measurements collected in the Belgian study. Figure 5.1 illustrates the POD_6 and AOT40-response relationships used in this study and Figure 5.2 shows the range in crop value for rape oil in the UK from 1996 to 2009. The latter prices have fluctuated over the time period including a dip to the lowest value of £138 per tonne in 2005, and rising to a peak of £313 per tonne in 2008. The mean value used in this study was £231/tonne (volume). Ozone flux and AOT40 for oilseed rape were accumulated during the period 1 April to 30 June.

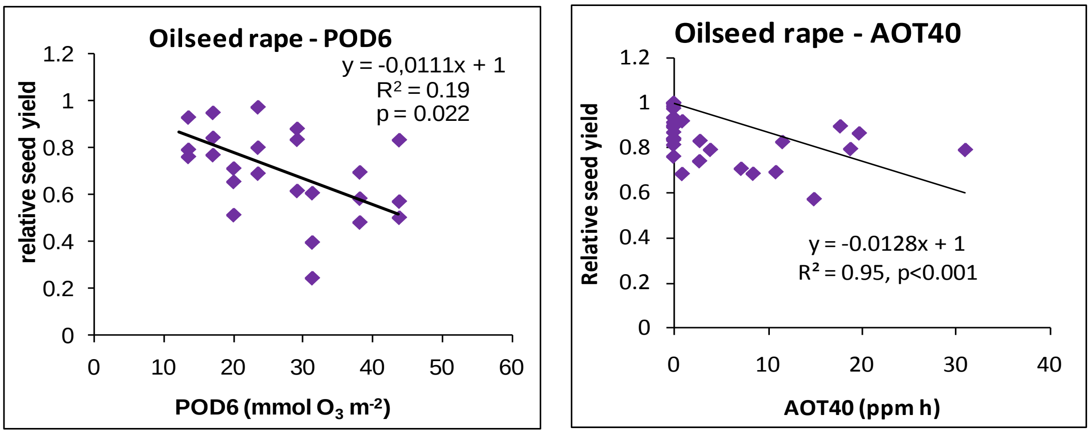


Figure 5.1 Response functions for the effects of ozone on seed yield of oilseed rape using (a) the flux-based methodology (POD_6) and (b) AOT40. The POD_6 relationship was provided by De Bock et al., 2011 and the AOT40 relationship is an update of that published by Mills et al. (2007) including more recently published data.

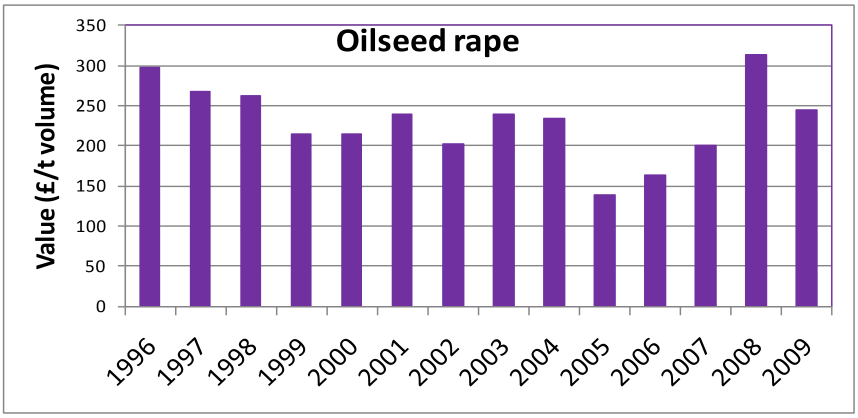


Figure 5.2 The value in £/t (by volume) of rape oil in the UK for the years 1996 to 2009

5.3 Flux-based analysis of economic losses for oilseed rape

Overall, the fluxes were similar in both years, with most of the growing area predicted to have greater than 3% yield loss (Figure 5.3). In some areas of Cornwall, Devon and Norfolk yield losses of over 9% were predicted. However, the biggest percentage yield losses were mainly predicted for areas where less oilseed rape was grown.

5.4 AOT40-based analysis of economic losses for oilseed rape

The AOT40-based analysis indicated that in 2006 the largest impacts would be expected in East Anglia (>12% yield loss), with yield losses predicted to be over 6% in southern England, parts of East Anglia and along the Welsh border (Figure 5.4). In 2008, no areas were identified as having > 12%

yield loss, but losses of over 6% were predicted for large areas of England and in parts of SE Scotland.

5.5 Comparison of POD_6 and AOT40-based assessments

The proportion of grid squares within each category was normally distributed for POD_6, peaking at 4 - 6% yield loss in 2006 and 6–8% in 2008, with the maximum predicted percentage yield loss being in the 10 – 12% category for each year (Figure 5.5). For AOT40, 25 to 30% of the grid squares were within each of the 2-4, 4-6, and 6-8% yield loss categories in 2006. There were also several grid squares for AOT40 in the high yield loss categories, with a total of 6% falling within the categories ranging from 10-16% yield loss. The POD_6-based assessment identified areas of Yorkshire in 2006 as being at risk of economic losses > £50k/grid square that were not identified in the AOT40-based assessment (Figures 5.3, 5.4 and 5.6). Overall, despite the spatial differences in areas identified as at risk, the total UK economic losses predicted by both methods were remarkably similar at £25 million in 2006 and £30-33 million in 2008, representing 6.6 to 7.2% of the total economic value of oilseed rape in the UK (Table 5.1). The total value of this estimate is affected by the volatility in rape oil prices, with the range in 2006 being from £14.2 million at the lowest crop value to 32.4 million at the highest crop value (Table 5.2).

A further source of uncertainty comes from the comparison of the modelled versus measured ozone flux. In 2006, the OSRM-SOFM – model underestimated ozone flux to oilseed rape by 52% (Figure 5.7a). The model fitted the flux calculated from measured data better in 2008 with only a 9% underestimation indicated for the test sites (Figure 5.7b). Taking this into account, economic losses could potentially have reached £49.1 million and £48.0 million in 2006 and 2008 respectively using peak prices representing 10.0 and 7.9% of total UK value of rape oil in 2006 and 2008 respectively (Table 5.1).

Table 5.1 Impacts of ozone on rapeseed oil yield in 2006 and 2008

	2006		2008	
Oilseed rape	**POD6**	**AOT40**	**POD6**	**AOT40**
Million ha grown	0.50		0.60	
Production, million t	1.64		1.97	
Total value, £ million	379		455	
Lost production, million t	0.11	0.11	0.14	0.13
Lost value at mean price, £ million	**24.95**	**24.92**	**32.87**	**29.90**
Lost value at peak price, £million	**32.41**	**32.26**	**43.96**	**40.82**
% economic loss	**6.59**	**6.58**	**7.22**	**6.57**
with flux model correction				
correction factor (from Figure 4.7)	1.5159		1.0914	
Lost value at mean price, £million	**37.83**		**35.87**	
Lost value at peak price, £million	**49.13**		**47.98**	
% lost (calc from value)	**9.98**		**7.88**	
Certainty of estimates	Medium	Low	Medium	Low

Table 5.2 Impacts of crop value (rape oil £/tonne volume) on predicted economic losses due to ozone.

		Economic loss, £million			
	Value	2006		2008	
	£/t vol.	POD6	AOT40	POD6	AOT40
Mean*	231.0	24.95	24.92	6.83	6.80
Min	138.3	14.26	14.19	3.17	3.14
Max	314.2	32.41	32.26	7.20	7.14
Q1	205.8	21.22	21.12	4.71	4.67
Q3	258.1	26.62	26.50	5.91	5.86
* used for crop loss calculations					

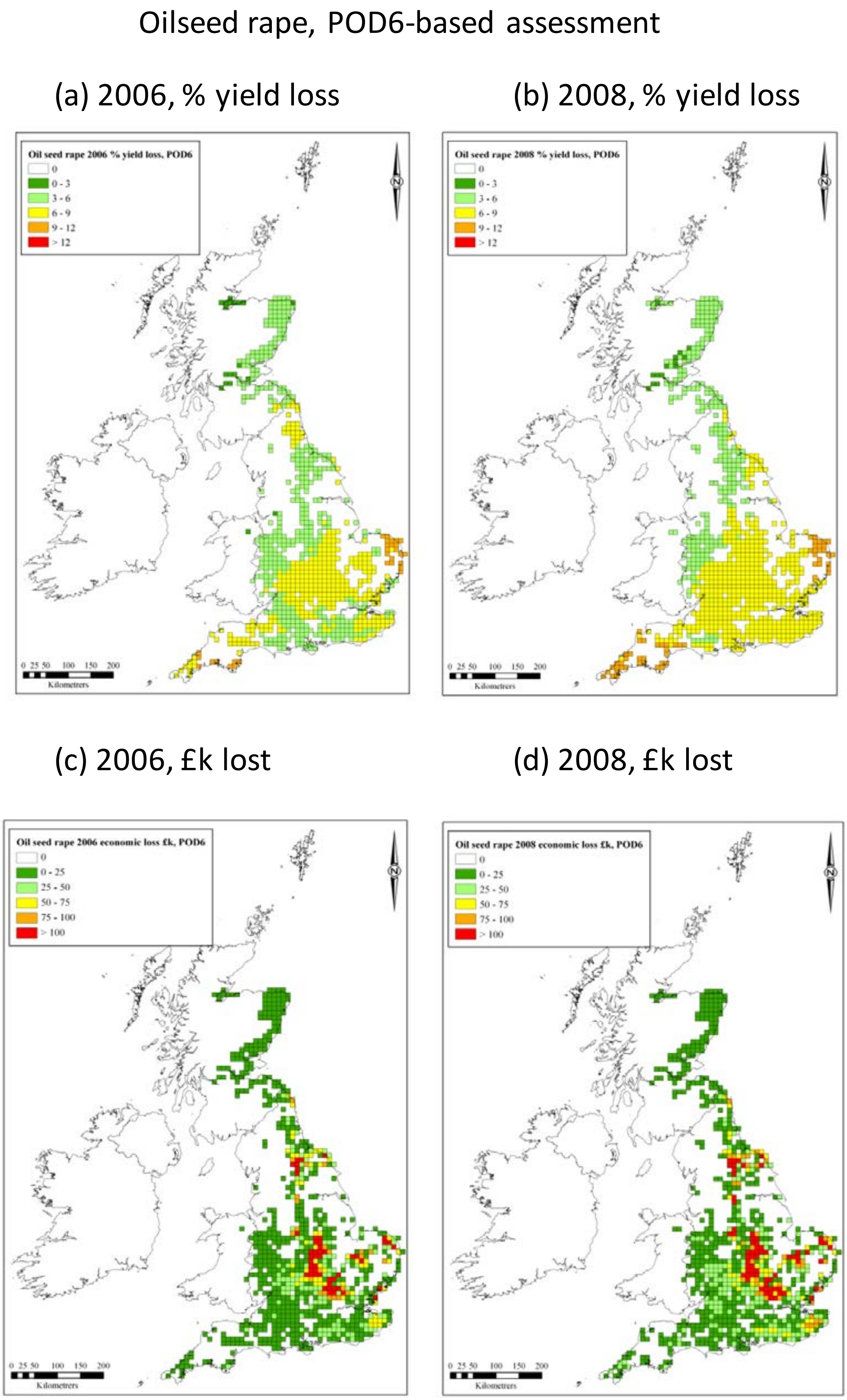


Figure 5.3 Spatial distribution of the impacts of ozone on oilseed rape loss as predicted using POD_6, presented as a % of total yield and economic loss (£k) per grid square. Only those grid squares where oilseed rape was grown on >100ha (1%) of the grid square are shown.

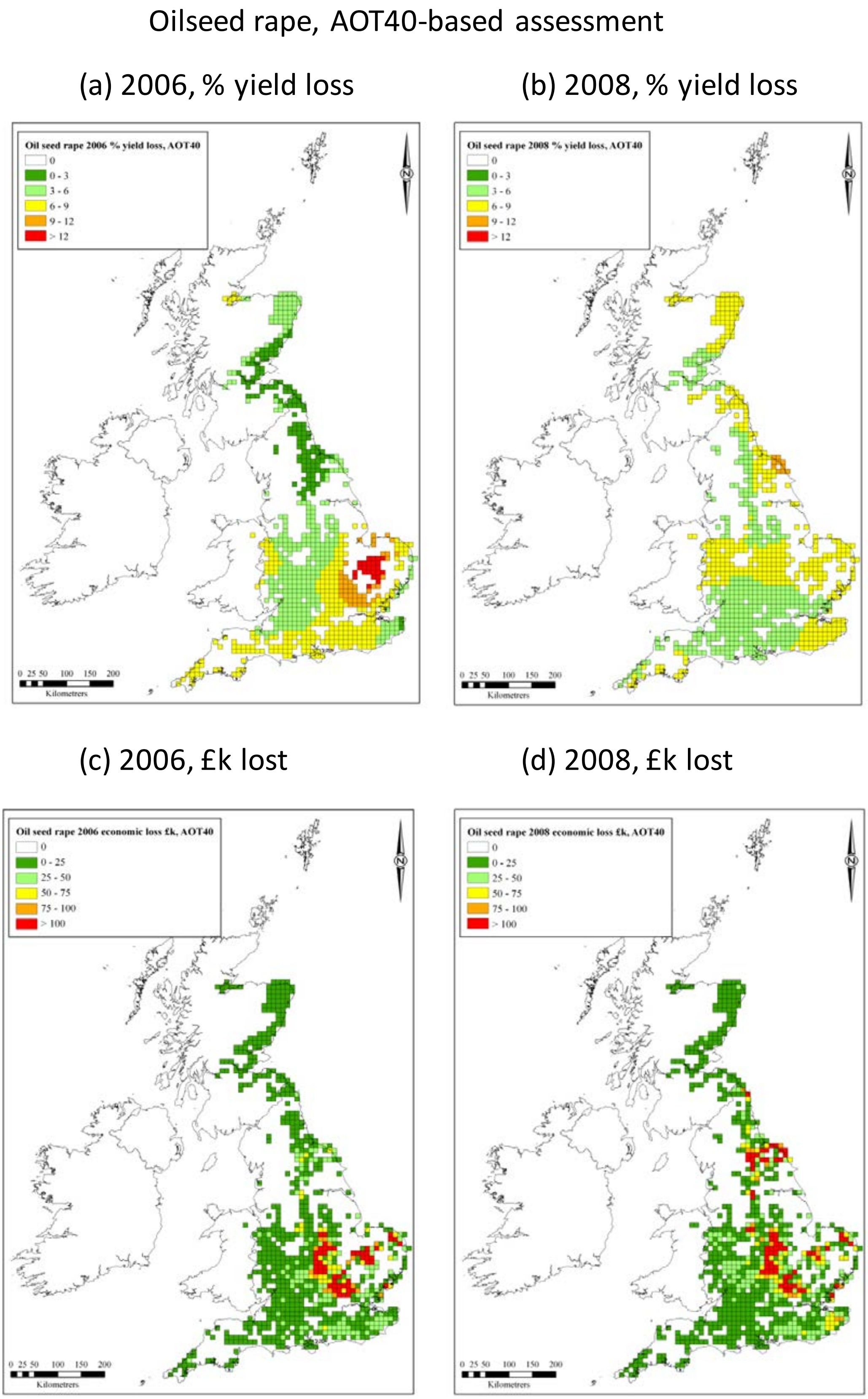


Figure 5.4 Spatial distribution of the impacts of ozone on the oilseed rape yield loss as predicted using AOT40, presented as a % of total yield and economic loss (£k) per grid square. Only those grid squares where oilseed rape was grown on >100ha (1%) of the grid square are shown.

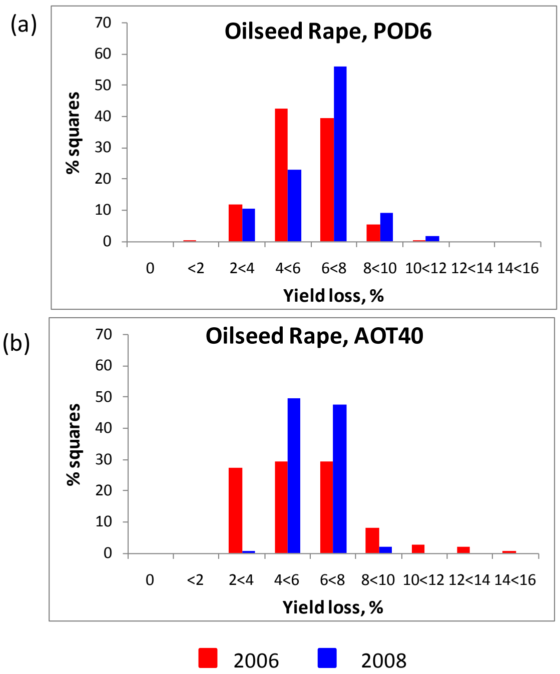


Figure 5.5 Frequency distribution of percentage yield loss for the 10 x 10 km grid squares in Figures 5.3 and 5.4 using the POD_6 and AOT40 ozone metrics

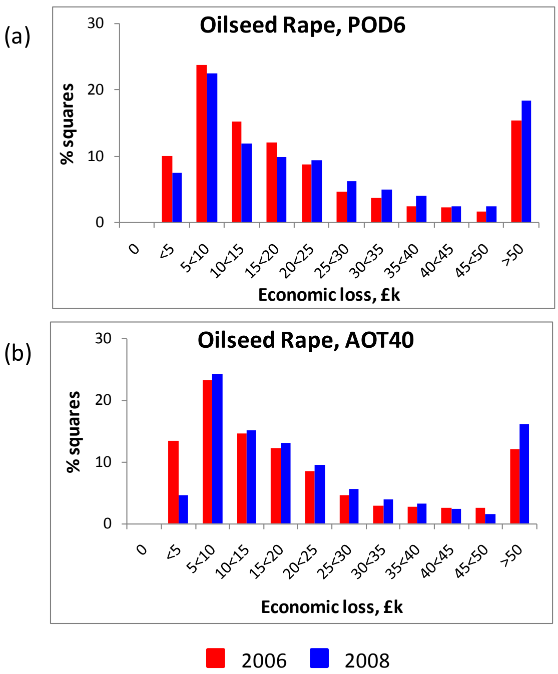


Figure 5.6 Frequency distribution of the economic losses (£k) for the 10 x 10 km grid squares in Figures 5.3 and 5.4 using the POD_6 and AOT40 and ozone metrics

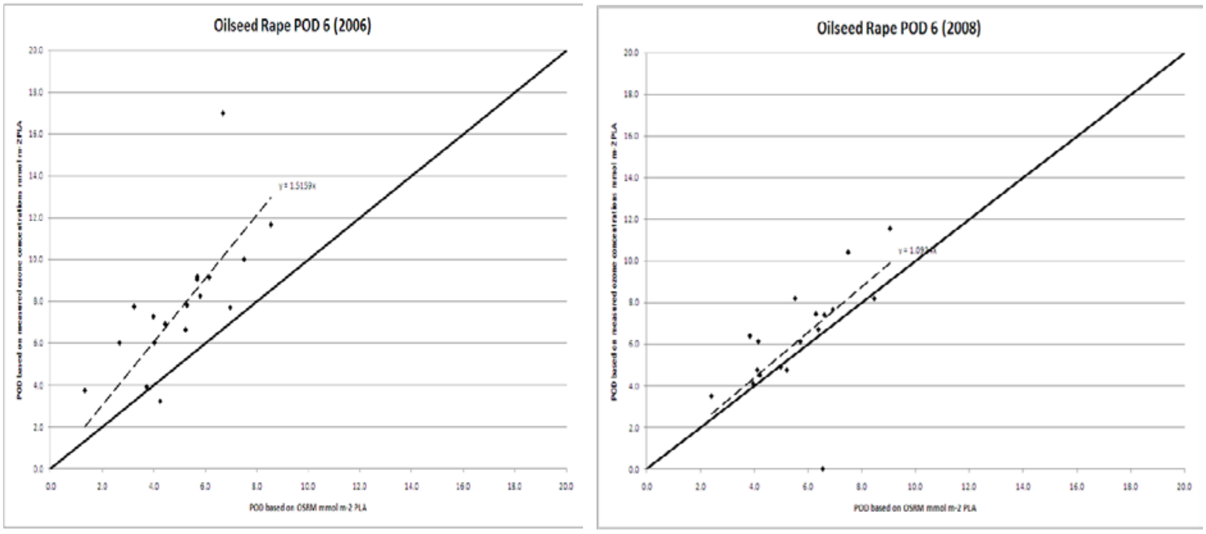


Figure 5.7 Predicted accumulated flux over threshold for oilseed rape at UK rural ozone monitoring sites for the years 2006 and 2008: comparison of predicted fluxes based on OSRM predictions of ozone concentration and measured ozone concentrations at different sites. The thick line indicates the 1:1 ratio.

6. Economic losses for root crops

Summary: Root crops

- Although both potato and sugar beet are moderately sensitive to ozone, significant economic losses are predicted for both crops when relatively high ozone concentrations occur during the late spring and summer months.
- Predictions for potato had "medium" indicative certainty using the flux-based methodology and "low" indicative certainty using AOT40, whereas those for sugar beet predicted using the AOT40 based methodology had "medium" indicative certainty.
- For potato, economic losses predicted using the flux-based methodology were substantially higher for 2006 than 2008 (£9.9 million compared to £0.8 million, using mean price). 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).
- The highest impacts for potato were in East Anglia, central England and Yorkshire, and for sugar beet were in East Anglia.
- 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.
- Comparing results for the two crops using AOT40-based methods, economic losses were higher for sugar beet in 2006 than for potato (8.2% compared to 6.7%), but in 2008 were lower for sugar beet than for potato (2.1% compared to 2.8%).

6.1 Introduction

Potato and sugar beet are grown on ca. 140 and 130 thousand hectares in the UK respectively. Analysis of published data for the two crops has revealed that potato is more sensitive to ozone than sugar beet, but less sensitive than legumes and wheat (Figure 3.2). A flux-effect relationship has been developed for potato (Pleijel et al., 2007) and has been used to set a critical level for effects on tuber yield (LRTAP Convention, 2010). Data from Belgium, Finland, Germany and Sweden contributed to the flux-effect relationship and thus it is suitable for application to the UK climatic and ozone conditions. An AOT40-based relationship also exists that has been updated in work package 5 of this contract allowing comparisons between the AOT40 and flux-based approaches to be included here.

Less research has been conducted on ozone impacts on sugar beet and only an AOT40-based relationship exists.

Potato tubers are mainly used for either human consumption, processing as a source of starch for the paper making industry and or as animal feed (Francis, 2009). Planted as earlies (January to February), second earlies (March) or main crops from late March to April, potatoes are harvested from June onwards with the main crops being harvested from late September. For this study, economic impacts on potato production were calculated as an average of the value of early and late potatoes. The potato growing area is quite extensive in the UK covering most regions including eastern Scotland and Northern Ireland.

Sugar beet roots are processed for the extraction of sugar and bio-ethanol with the residues being used as animal feed (Francis, 2009). This crop is sown in early March to mid- April and harvested at any time between September and February. Sugar beet production is mainly in the counties of central England, East Anglia, and parts of Lincolnshire and Yorkshire.

Each crop is considered separately within this chapter, with a summary of the key findings for root crops presented in the text box at the beginning of this chapter.

6.2 Economic losses for potato

6.2.1 Methods for potato

The method used for both crops followed that described in Chapter 2. The accumulation period used for flux accumulation was the default period provided in the LRTAP Convention's Modelling and Mapping Manual (2010), a fixed time period of 70 days starting at plant emergence which was assumed to be day 146. The start date was the average date of emergence of potato in the EU-funded CHIP project (De Temmerman et al., 2002) from which the flux-effect relationship was derived. Thus, the time period used for the flux method was from 26 May to 4 August. For the AOT40 approach a slightly longer time period of 15 May to 15 August was used. Within the OSRM-SOFM model it is assumed that potato is irrigated whenever soil water deficit is limiting. The response functions used for potato are provided in Figure 6.1. The flux-based relationship is much more robust than that for AOT40. The value of the potato crop in £ per tonne has fluctuated on a year to year basis over the period 1996 to 2009, with a gradual increasing trend (Figure 6.2).

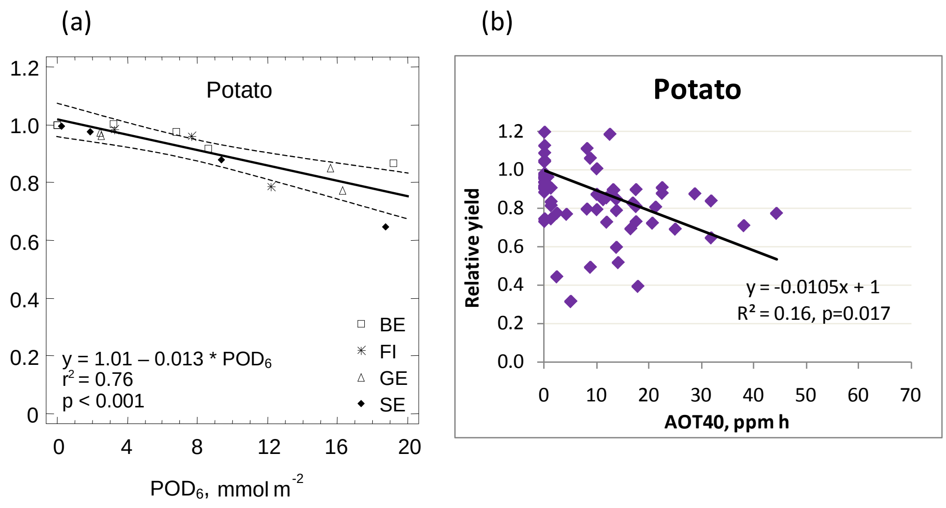


Figure 6.1 Response functions for the effects of ozone on potato tuber yield (a) using the flux-based methodology (POD_6) and (b) using AOT40. The flux-based response function

can be found in the LRTAP Convention's Modelling and Mapping Manual (2010) and in Pleijel et al. (2007).

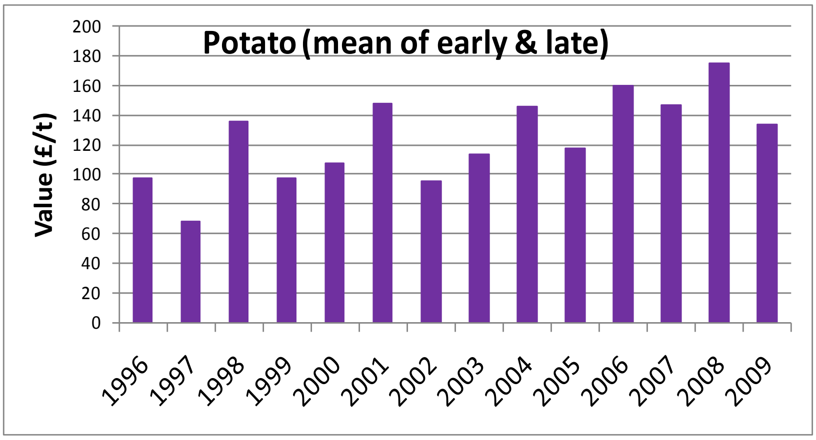


Figure 6.2 The value in £/t of the potato crop in the UK for the years 1996 to 2009. Source: http://www.defra.gov.uk/statistics/foodfarm/

6.2.2 Flux-based analysis of economic losses for potato

The lower sensitivity of potato to ozone is reflected in the percentage yield loss maps produced using the flux-based approach (Figure 6.3). In both years, percentage yield losses above 6% were not predicted, with effects of less than 3% only being evident in 2008. Nevertheless, in 2006 there were several grid squares in central England, East Anglia, and Yorkshire where economic losses greater than £50k were predicted per 10 x 10 km grid square (Figure 6.3 (c)), with losses of <12.5k predicted for some grid squares in Northern Ireland. In contrast, in 2008, the small area of East Anglia where effects were predicted (Figure 6.3 (b) resulted in losses of below £25k per 10 x 10 km grid square (Figure 6.3 (d)).

The f_{temp} function within the flux parameterisation for potato has a minimum temperature of 13° and an optimum of 28° C (Pleijel et al., 2007). The mean daily maximum temperature in the main growing areas for potato was approximately 4°C cooler in 2008 than in 2006 (Figure 1.4) which together with the lower ozone concentrations in the late spring-summer accumulation period for potato (Figure 3.1) will have reduced the total ozone flux in 2008. In both years, the rapid decline in f_{phen} in the second two thirds of the growing season will have limited ozone flux to the same extent.

Overall, economic losses for potato were predicted to be considerably higher in 2006 than 2008 using the POD_6 index. Based on the mean price value, losses were predicted to be £9.9 million in 2006 and £0.3 million in 2008, and at peak price, losses were predicted to be £14 million in 2006 and £0.35 million in 2008 (Table 6.1). Economic losses were predicted to be 1.3% and 0.04% of the total UK potato revenue value in 2006 and 2008 respectively. An indicative certainty of "medium" is associated with these figures (see Section 3.5).

6.2.3 AOT40-based analysis of economic losses for potato

Yield losses predicted using the AOT40-based method for 2006 were substantially higher than those predicted for 2008 (Figure 6.4 (a) and (b)), with losses of up >12%predicted for areas of East Anglia and up to 9% shown across much of central England, and up to 3% in some areas of N England, SE Scotland and Northern Ireland in 2006. Where the highest percentage yield losses coincided with the highest areas of production, economic losses of > £50k per grid square were predicted in 2006 (Figure 6.4(c)). In contrast, yield losses of below 6% were predicted for areas of East Anglia in 2008, and up to 3% in the rest of the UK crop growing areas (Figure 6.4(b)), Although economic losses of greater than £50k per grid square were predicted for parts of East Anglia, central England and Yorkshire, economic impacts were generally lower in other parts of the UK (Figure 6.4(d)). Using the mean crop prices, £50.5 million of lost production was predicted for 2006 and £22.5 million of lost production was predicted for 2008 using the AOT40-based method (Table 6.1). These values increased to £71.3 million and £31.9 million if the peak tuber price was used for 2006 and 2008 data respectively. Economic losses were predicted to be 6.7% and 2.8% of the total UK potato revenue value in 2006 and 2008 respectively (Table 6.1).

6.2.4 Comparison of flux-and AOT40-based analyses

Economic losses predicted using the AOT40-based methodology were substantially higher than those predicted using POD_6 for both years which gives an indication of the significance of the temperature limitation of ozone flux described above. Even with the correction for the underestimation of fluxes in both years using the OSRM-SOFM model (see Figure 6.5 and Table 6.1), the estimated effects using the flux-based methodology were still less than half of those predicted using AOT40 for 2006 and more than 50 times lower than those predicted using AOT40 for 2008.

These differences are shown in the proportion of grid squares in different yield loss categories, with AOT40-based estimates peaking at between 2 and 4% for 2008 whilst 94% were in the 0 yield loss category using the POD_6-based method (Figure 6.6). Similarly, economic losses were mainly in the lowest categories for POD_6, particularly in 2008, but extended up into the highest categories in both years when AOT40 was used as the ozone metric (Figure 6.7).

Taking into account the range in crop value (£/tonne of tubers) over the period 1996 to 2009, predicted economic losses ranged from £5.5 to 14 million in 2006 and from £0.14 to 0.35 million in 2008 using the POD_6-based method, and from £27.9 to 71.3 million in 2006 to £12.3 to 31.6 million in 2008 (Table 6.2).

6.2.5 Key findings for potato

- Even though potato is moderately sensitive to ozone, crop losses were predicted for both years.

- 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), most probably due to a combination of the lower ozone concentrations and greater temperature limitation of stomatal flux of ozone experienced in June and July, 2008.

- Using the AOT40-based methodology, predicted economic losses were twice as high in 2006 than in 2008, but were 5-75 fold higher than those predicted using POD_6-methodology.

- Overall, percentage yield losses were in the range 1.3 - 2.9% in 2006 and 0.04 – 0.07% in 2008, predicted using the flux-based methodology, with the range reflecting mean – maximum crop value and taking account of the underestimation of flux by the OSRM-SOFM model.

Table 6.1 Impacts of ozone on potato yield in 2006 and 2008

Potato	2006 POD6	2006 AOT40	2008 POD6	2008 AOT40
Million ha grown	0.14		0.14	
Production, million t	6.07		6.54	
Total value, £ million	753		811	
Lost production, million t	0.08	0.41	0.002	0.18
Lost value at mean price, £ million	**9.91**	**50.47**	**0.30**	**22.51**
Lost value at peak price, £million	**14.00**	**71.34**	**0.35**	**31.85**
% economic loss	**1.32**	**6.71**	**0.04**	**2.78**
with flux model correction				
correction factor (from Figure 4.7)	2.2133		1.7967	
Lost value at mean price, £million	**21.92**		**0.54**	
Lost value at peak price, £million	**30.99**		**0.63**	
% lost (calc from value)	**2.91**		**0.07**	
Certainty of estimates	Medium	Low	Medium	Low

Table 6.2 Impacts of potato crop value (£/t) on predicted economic loss due to ozone

	Value £/t	Economic loss, £million 2006 POD6	2006 AOT40	2008 POD6	2008 AOT40
Mean*	124.4	9.9	50.5	0.30	22.51
Min	68.5	5.5	27.9	0.137	12.3
Max	175.3	14.0	71.3	0.351	31.6
Q1	100.0	8.0	40.7	0.200	18.0
Q3	146.6	11.7	59.7	0.293	26.4

* used for crop loss calculations

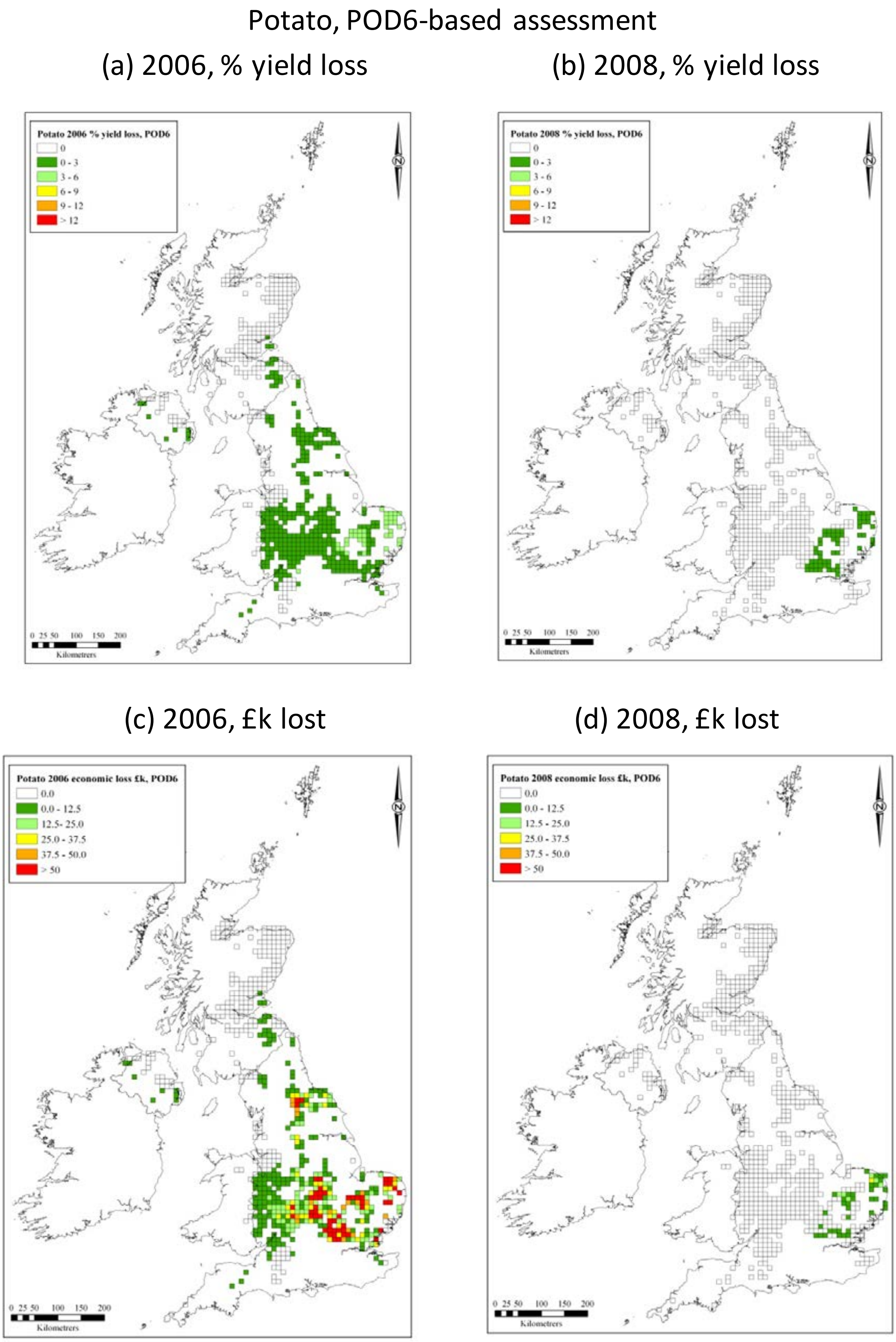


Figure 6.3 Spatial distribution of ozone impacts on potato yield loss, as predicted using ozone flux (POD_6), presented as a % of total yield and economic loss (£k) per grid square. Only those grid squares where potato was grown on >50 ha (0.5%) of the grid square are shown

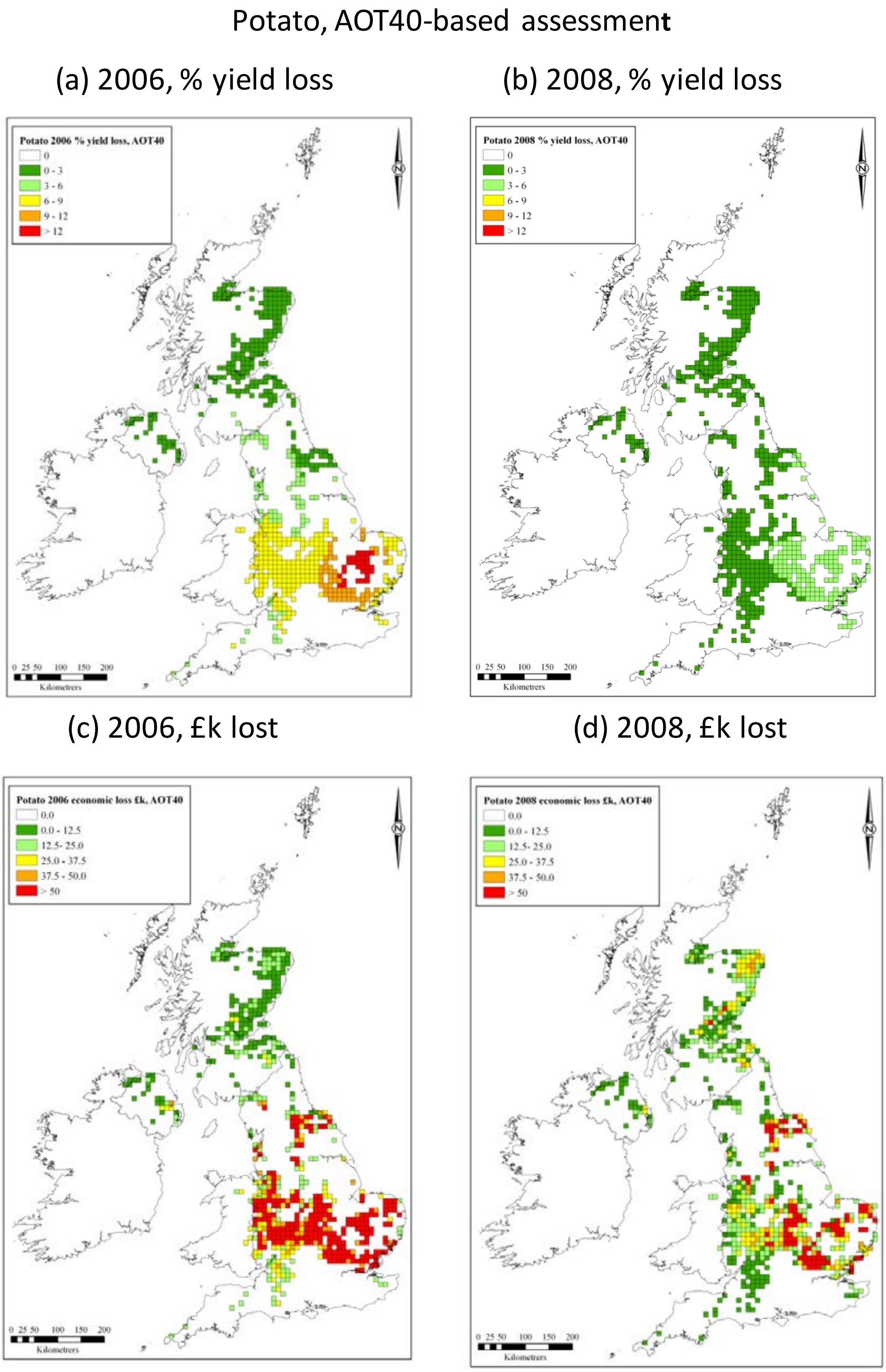


Figure 6.4 Spatial distribution of ozone impacts on potato yield loss, as predicted using AOT40,, presented as a % of total yield and economic loss (£k) per grid square. Only those grid squares where potato was grown on >50 ha (0.5%) of the grid square are shown.

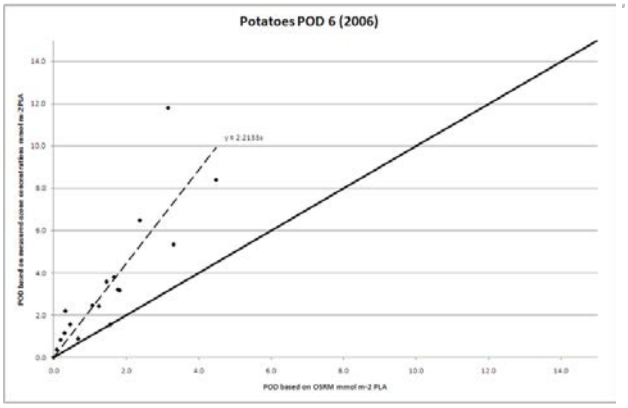


Figure 6.5 Comparison of predicted fluxes to wheat based on OSRM predictions of ozone concentration and measured ozone concentrations at different sites in the UK in (a) 2006 and (b) 2008. The thick line indicates the 1:1 ratio.

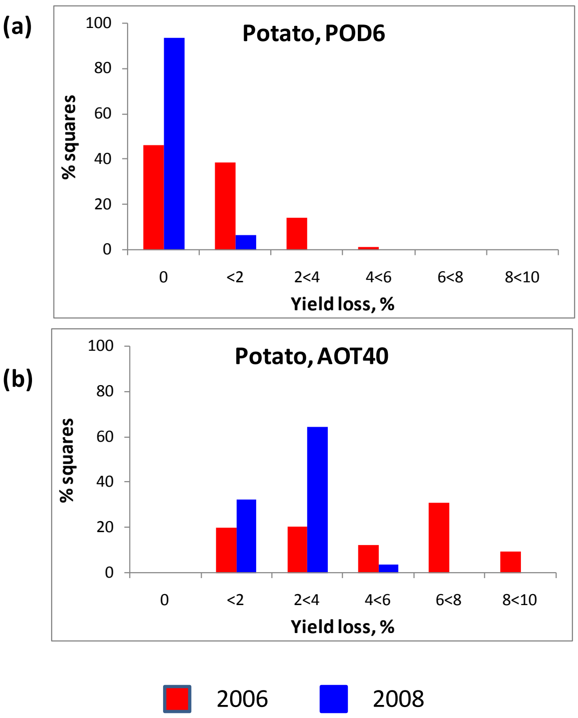


Figure 6.6 Frequency distribution of % yield loss for potato for the 10 x 10km grid squares in Figure 4.3 and 4.4 using the POD_6 and AOT40 ozone metrics. Only data from the grid squares where wheat was grown on >50 ha (0.5%) of the grid square are shown.

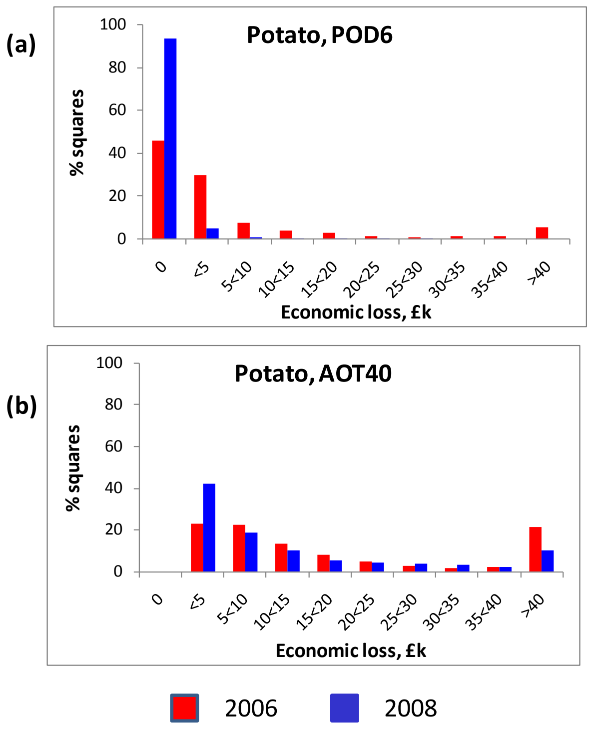


Figure 6.7 Frequency distribution of the economic losses (£k) for potato for the 10 x 10 km grid squares in Figure 6.3 and 6.4 using the POD_6 and AOT40 ozone metrics. Only data from the grid squares where wheat was grown on >50 ha (0.5%) of the grid square are shown.

6.3 An economic loss assessment for sugar beet

6.3.1 Methods for sugar beet

The method used for sugar beet followed that described in Chapter 2. The AOT40-based response function for effects on the weight of the root is shown in Figure 6.9 and includes data from open-top chamber experiments conducted in the USA, Belgium and Germany. Although sigificant at the p = 0.003 level, the relationship includes some scatter, some of which will have been introduced when the 7h mean was converted into AOT40. Over the time period 1996 to 2009 sugar beet prices have fluctuated between lows of £24/tonne in 2006 and 2007 and highs of £33-34/tonne in 1996 and 2004 (Figure 6.10).

6.3.2 AOT40-based analysis of economic losses for sugar beet

Although only moderately sensitive to ozone, the main growing period for sugar beet coincided with relatively high concentrations during the summer of 2006. Effects on yield loss exceeding 12% were predicted for some grid squares in East Anglia in 2006, with >6% predicted across the area (Figure 6.11). Consequently, yield losses in the main growing areas for sugar beet in 2006 were predicted to have had a large impact on the economic value, with losses exceeding £100k per grid square predicted over a large area. As shown in Figure 3.1, AOT40 values were lower in the summer of 2008 over the sugar beet growing areas and predicted effects on yield were much lower being less than 3% over the region, with economic losses exceeding £25k per 10 x 10 km grid square in only a small region of Essex and Suffolk. The difference between the two years is illustrated in the frequency distributions in Figure 6.12. In 2006, the percentage yield losses were normally distributed and peaked for the 4 – 6 % category, whereas in 2008, 66% of the grid squares in the sugar beet growing areas had < 2% yield losses with the remainder in the 2 – 4% category. As sugar beet production is most concentrated within regions of East Anglia, the predicted economic losses are well spread amongst the categories in Figure 6.12(b), with the highest percentage of grid squares (30%) being in the highest category of > £30k per grid square.

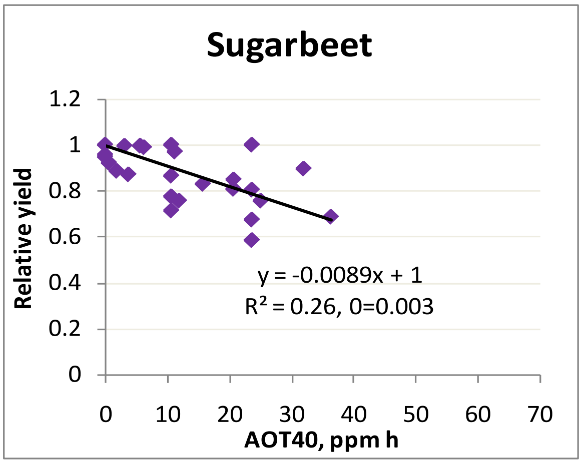


Figure 6.9 The AOT40-based response function for sugar beet used in this study. The function is derived from an update of that in Mills et al. (2007) to include data from De Temmerman et al. (2007).

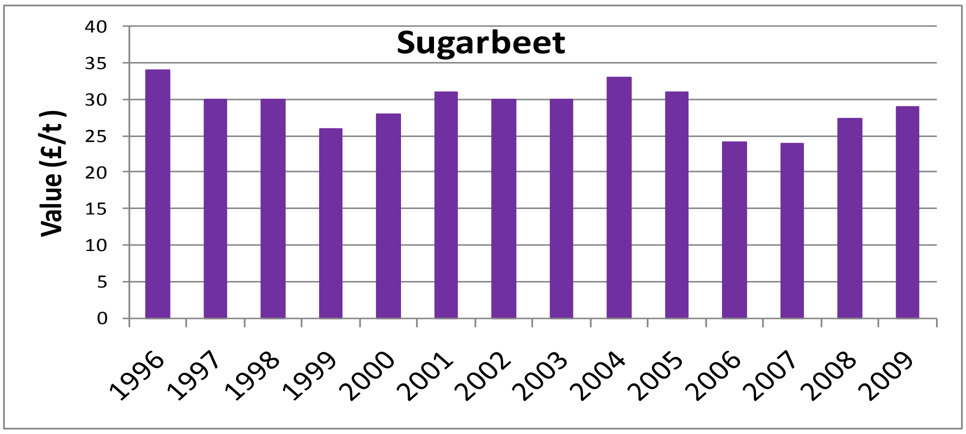


Figure 6.10 The value in £/t of the sugar beet crop in the UK for the years 1996 to 2009. Source: http://www.defra.gov.uk/statistics/foodfarm/

Overall, predicted losses were £17.5 million in 2006 and £4.4 million in 2008 based on the mean crop value (Table 6.3). Using the peak crop value of £34 per tonne, the predicted economic losses were £20.6 million and £5.1 million in 2006 and 2008 respectively. These mean losses represented 8.2% of the total economic value of sugar beet in the UK in 2006 and 2.0% of the value in 2008. The range of predicted economic losses for the UK in the highest ozone year, 2006, calculated using the minimum and maximum crop value between 1996 and 2009 was £14.4 to £20.5 million (Table 6.4). The indicative certainty of the predictions for sugar beet was medium.

6.3.4 Key findings for sugar beet

- Although sugar beet is moderately sensitive to ozone, significant losses in yield and economic value were predicted in the higher ozone year, 2006.
- Ozone concentrations were relatively high in the summer of 2006 in the main sugar beet growing area in East Anglia, resulting in losses of > £100k in many grid squares.
- Overall, losses based on mean crop value were predicted to be £17.5 million in 2006 and £4.4 million in 2008, representing 8.2 and 2.0% of the economic value in the UK in the two years respectively.

Table 6.3 Impacts of ozone on sugar beet yield in 2006 and 2008

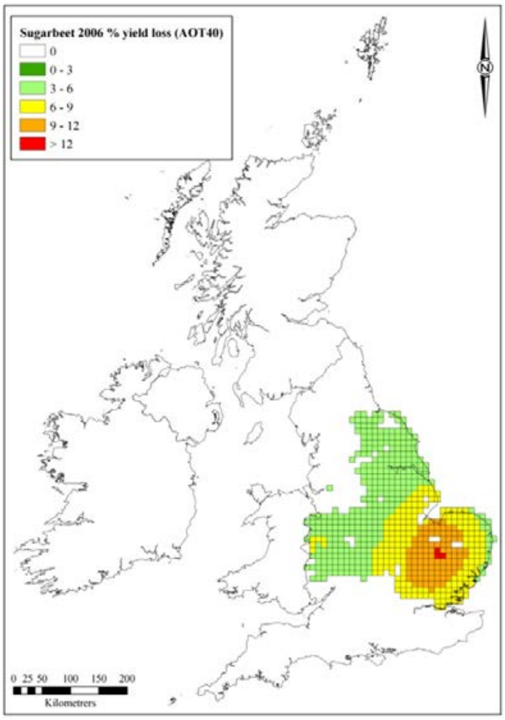
	2006	2008
Sugar beet	**AOT40**	**AOT40**
Million ha grown	0.13	0.12
Production, million t	7.37	7.63
Total value, £ million	214	221
Lost production, million t	0.60	0.15
Lost value at mean price, £ million	**17.45**	**4.37**
Lost value at peak price, £million	**20.46**	**5.12**
% economic loss	**8.17**	**1.97**
Certainty of estimates	Medium	Medium

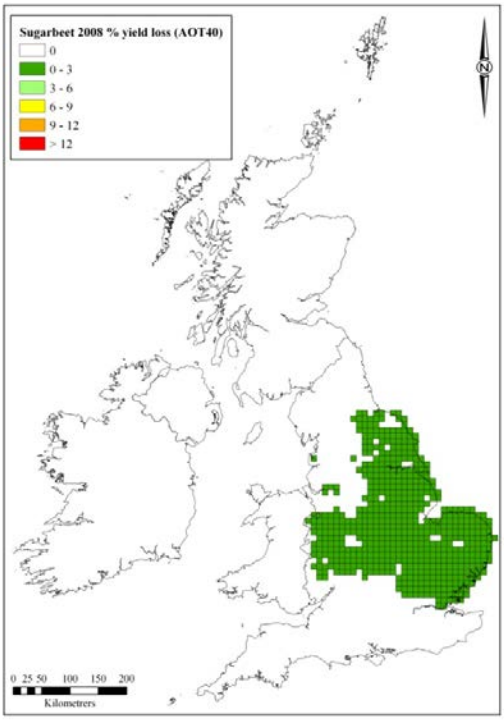
Table 6.4 Impacts of crop value (£/t) on the predicted economic loss due to ozone effects on sugar beet

		Economic loss, £million	
	Value	2006	2008
	£/t	AOT40	AOT40
Mean*	29.1	17.45	4.37
Min	24.0	14.40	3.60
Max	34.0	20.46	5.12
Q1	27.5	16.49	4.12
Q3	30.8	18.45	4.61

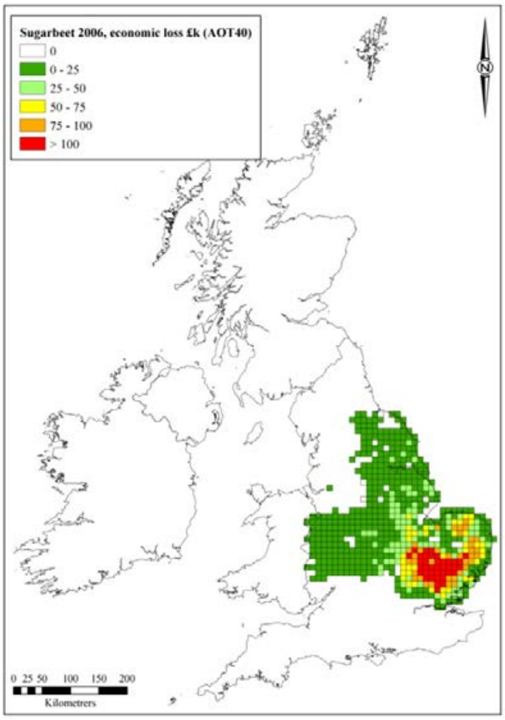
* used for crop loss calculations

Sugar beet, AOT40-based assessment





(c) 2006, £k lost



(d) 2008, £k lost

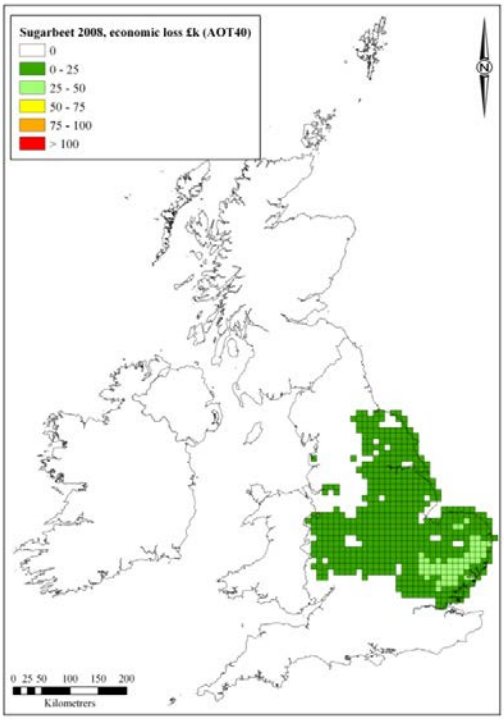


Figure 6.11 Spatial distribution of effects of ozone on sugar beet yield loss as predicted using AOT40, presented as a % of total yield and economic loss (£k) per grid square. Only those grid squares where sugar beet was grown on >10 ha (0.1% of the grid square) are shown.

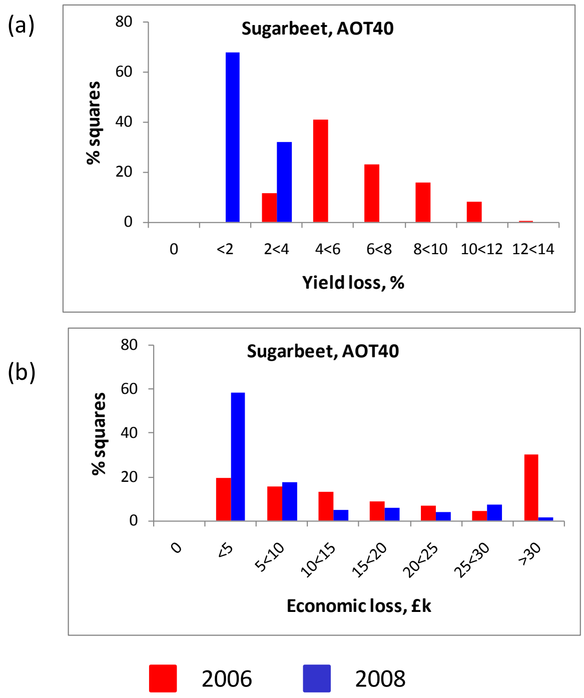


Figure 6.12 Frequency distribution for the effects of ozone on (a) percentage yield loss and (b) economic losses in sugarbeet for 2006 and 2008. Only those grid squares where sugar beet is grown on > 10 ha (0.1% of the grid squares) are shown.

7. Economic losses for legumes

Summary: Pea and bean

- Pea and bean are very sensitive to ozone, and were the most sensitive crop type included in this study.
- In 2006, 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.
- Although the AOT40s were lower during the growing period for pea and bean in 2008, losses of up to 9 - 12% were predicted in some parts of central England, East Anglia and Kent, with yield losses in the range 6 to 9% predicted for several other areas.
- The economic losses predicted for combined peas and beans were twice as high in 2006 than in 2008 at £5.9 million and £3.0 million respectively, based on the mean crop value (£/t).
- The range of predicted losses based on the minimum and maximum crop values was £3.5 to 8.7 million in 2006 and £1.9 to 4.3 million 2008.
- The percentage loss based on economic value was 20.9% in 2006 and 9.7% in 2008.
- Estimates for pea and bean have a "low" indicative certainty due in part to use of an AOT40–based function with high scatter.

7.1 Introduction

The Legume family is widely accepted to contain some of the most ozone-sensitive species that have been tested (Mills et al., 2007, Hayes et al., 2007a). These include clover species widely used as nitrogen fixers within pasture (see Chapter 8) as well as peas, beans and lentils. Within this study, peas and beans had the highest regression slopes for an AOT40-based response relationship (Figure 3.2(b)) and were thus the most sensitive to ozone included in the analysis. Both are grown in the UK as either an un-dried vegetable for human consumption or as a “combined” crop that is harvested when mature and dry for either human consumption or animal fodder (Francis, 2009). Sowing periods vary from late October to early December (winter field beans) through to February to March (spring field beans) and mid-February to late April (peas). Because of the lack of availability of production data for all pulses grown in the UK, this analysis focuses on “combined” peas and beans, i.e. those grown through to the dry seed stage. Due to the sensitivity of legumes to ozone, it is anticipated that the yield and economic losses described here would be mirrored for other legume species grown in the UK including the peas and beans grown to the moist seed stage for freezing, tinning or fresh consumption.

Despite the ozone sensitivity of legumes, no reliable flux-based response relationship currently exists. Colleagues in Spain collated flux-effect data for bean (*Phaseolus vulgaris*) from several sources for consideration for derivation of a critical level, but the data was considered too variable to meet the stringent criteria required for this purpose. Thus, for this study, analysis was restricted to AOT40-based methods.

7.2 Methods for legumes

The method used for legumes is described in Chapter 2. Species and varietal differences in sensitivity to ozone have contributed to the scatter shown in the AOT40-based response relationship (Figure 7.1). This has been redrawn using the data presented in Mills et al. (2007) together with new data published since then for experiments conducted in Italy (Gerosa et al., 2009) and the USA (Booker et al., 2009). The crop value used was the mean of that for combined peas and combined beans. Crop values were relatively stable at ca. £155 per tonne during the period 1999 – 2004, but dipped to < £100 /tonne in 2005 and 2006, rising again in subsequent years (Figure 7.2). As for most of the crops considered in this study, this variation in price was too great to enable the impact of ozone on the actual prices in 2006 and 2008 to be directly compared. The accumulation period used for combined peas and beans was 1 May to 31 July.

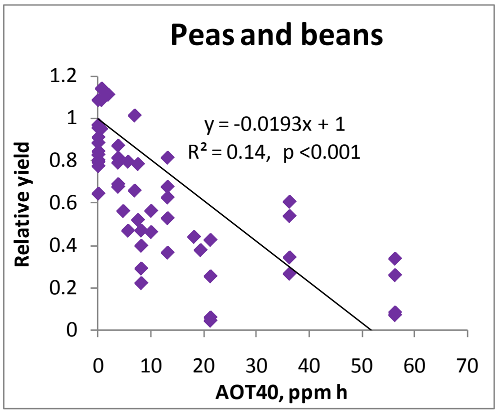


Figure 7.1 The AOT40-based response function for pea and bean used in this study. The function is derived from an update of that in Mills et al. (2007) including more recently published data from Gerosa et al. (2009) and Booker et al. (2009).

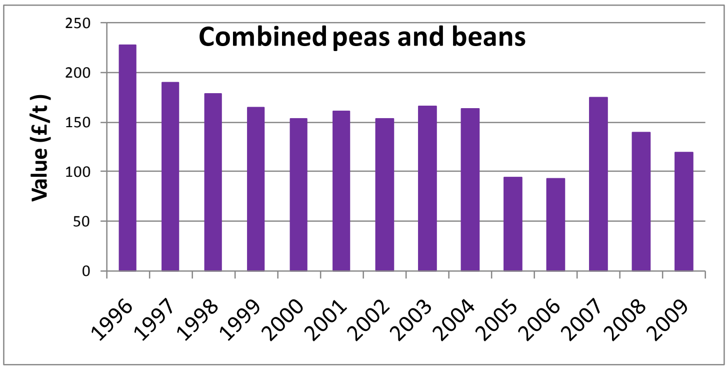


Figure 7.2 The mean value in £/t of combined pea and combined bean in the UK for the years 1996 to 2009.

7.3 AOT40-based analysis of effects on pea and bean

In 2006, 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. Economic impacts were greatest in central England and parts of East Anglia where the highest production area is for these crops (Figure 7.3 (b)), with losses greater than £20k per 10 x 10 km grid square predicted. Although the AOT40s were lower during the growing period for pea and bean in 2008, losses of up to 12% were predicted in parts of central England, East Anglia and Kent, with yield losses in the range 6 to 9% predicted for several other areas of England including the NE, as well as for parts of eastern Scotland. Economic impacts were predictably lower in 2008 than in 2006, with only a few grid squares in, for example Oxfordshire, Cambridgeshire and Northamptonshire, with losses exceeding £20k per 10 x 10 km grid square.

In 2006, the proportion of grid squares was normally distributed around the 10 - 15 and 15 - 20% yield loss categories (Figure 7.4 (a)), whilst in 2008 >80% of the grid squares where pea and bean are grown were in the 5 - 10% yield loss category. In both years, over 60% of the grid squares were in areas where production was relatively low and economic losses were in the range up to £5k per 10 x 10 km grid square (Figure 7.4 (b). However, in 2006, 47 (6.8%) of the grid squares were predicted to have had economic losses greater than £30k.

Overall, the economic losses predicted for combined peas and beans were twice as high in 2006 than in 2008 at £5.9 million and £3.0 million respectively, based on the mean crop value (£/t) (Table 7.1). The range of predicted losses based on the minimum and maximum crop values was £3.5 to 8.7 million in 2006 and £1.9 to 4.3 million 2008 (Table 7.2). The percentage loss based on economic value was 20.9% in 2006 and 9.7% in 2008. These figures have a "low" indicative certainty.

Table 7.1 Impacts of ozone on combined pea and bean yield in 2006 and 2008

	2006	2008
Peas and beans	**AOT40**	**AOT40**
Million ha grown	0.05	0.05
Production, million t	0.18	0.20
Total value, £ million	28	31
Lost production, million t	0.04	0.02
Lost value at mean price, £ million	**5.93**	**3.02**
Lost value at peak price, £million	**8.68**	**4.33**
% economic loss	**20.93**	**9.73**
Certainty of estimates	Low	Low

Table 7.2 Impacts of crop value on the predicted economic losses for combined pea and bean

		Economic loss, £million	
		2006	**2008**
	£/t	**AOT40**	**AOT40**
Mean	155.6	5.93	3.02
Min	93.2	3.5	1.9
Max	228.3	8.68	4.33
Q1	143.3	5.4	2.9
Q3	172.2	6.5	3.4

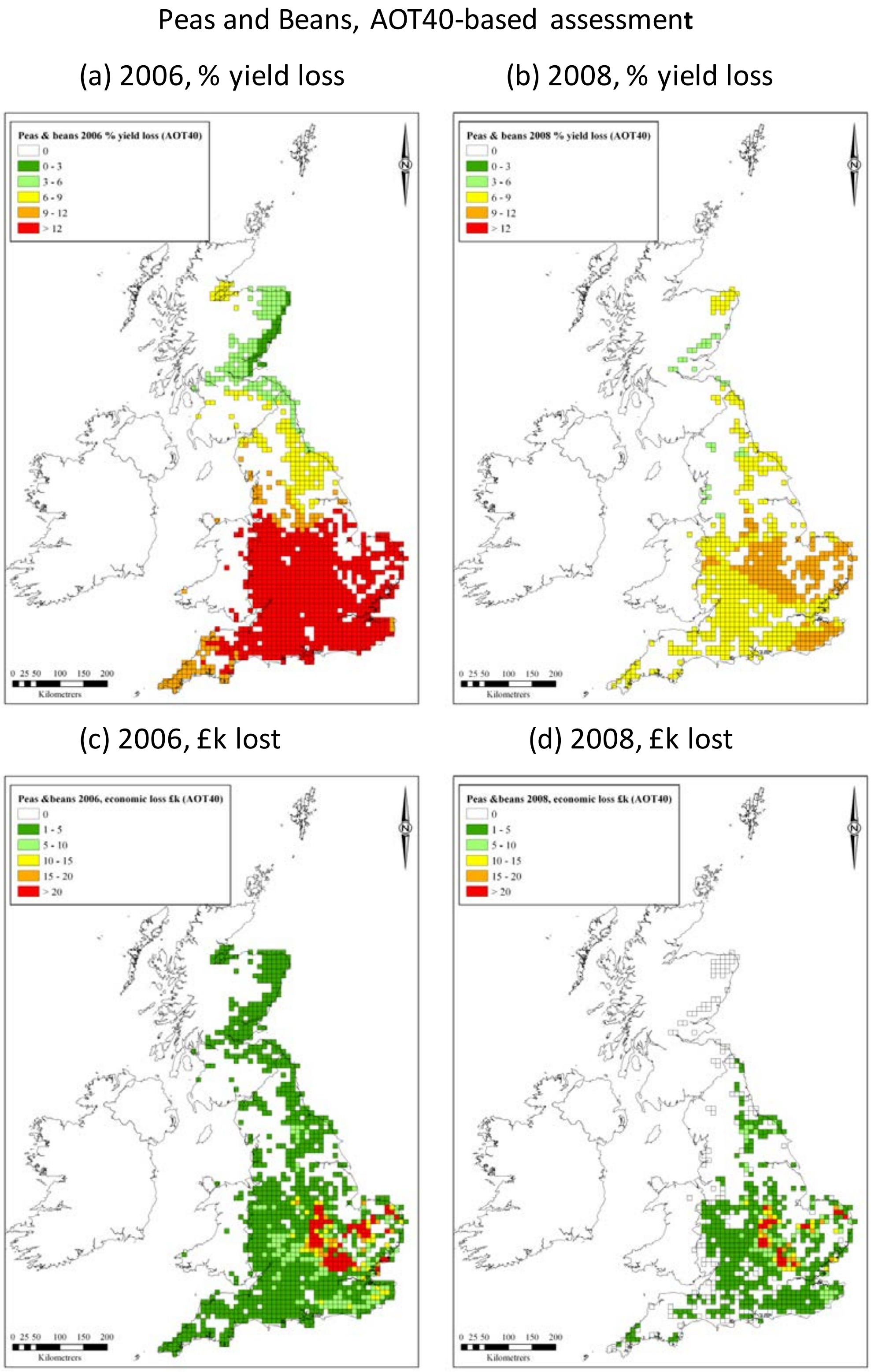


Figure 7.3 Spatial distribution of effects of ozone on combined pea and bean yield loss as predicted using AOT40, presented as a % of total yield and economic loss (£k) per grid square. Only those grid squares where pea and/or bean are grown on greater than 10 ha (0.1% of a grid square) are shown.

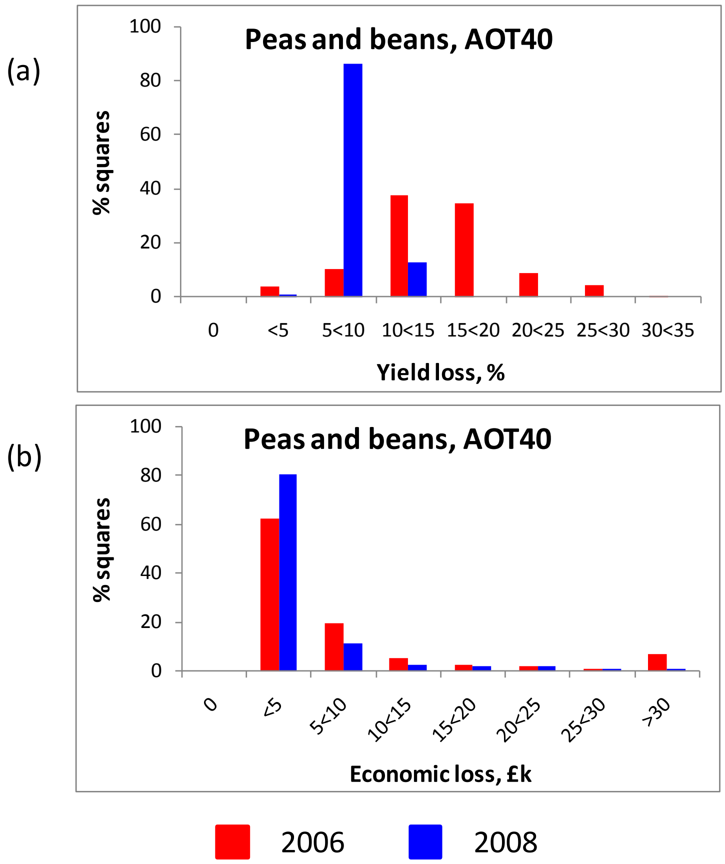


Figure 7.4 Frequency distribution for the effects of ozone on (a) percentage yield loss and (b) economic losses in pea and bean for 2006 and 2008. Only those grid squares where pea and/or bean are grown on > 10 ha (0.1% of the grid squares) are shown.

8. Economic losses for salad leaf crops

Summary: Salad leaf crops

- Many of the crops and ornamental plants that have a market value dependent upon the visible appearance of the foliage develop foliar injury in response to ozone exposure at concentrations experienced in the UK during ozone episodes.
- Based on biomonitoring studies using white clover, the occurrence of at least one day in which the ozone concentration reached/exceeded 60 ppb for one hour in the previous 8 days was selected as the indicator of potentially damage-inducing ozone episodes.
- In 2006, there were more than four incidences of the ozone concentration exceeding 60 ppb within an eight day period in most of the lettuce and salad leaf growing areas of England during April - June and July - September.
- Even though there was less ozone in 2008, there were still enough episodes to cause ozone damage in April – June, but fewer episodes occurred in July-September.
- The first indicative figures for effects of ozone on lettuce and salad leaf crops suggest crop losses in the high ozone year of 2006 of £25.3 million, representing 24% of the economic value.
- The results presented here are very provisional and further research is required to quantify impacts.

8.1 Introduction

The horticultural industry contributes ca. £2.6 billion to the UK economy each year (based on market prices in 2009), with horticultural crops being grown on 166,000 ha in 2006 and 170,000 ha in 2008 (Defra, 2009). Over 70% of the horticultural land area is dedicated to outdoor vegetables, 8% to outdoor plants and flowers, and 1% to glasshouse crops. Many of the crops and ornamental plants have a market value that is dependent upon the visible appearance of the foliage. Any biotic or abiotic stress that causes damage to the leaves has the potential to either downgrade the quality class of the product or even to make the product unmarketable. The potential impact of foliar damage caused by ozone episodes on the UK horticultural industry has not previously been quantified even though many horticultural crops have been shown to develop ozone injury in other European countries (Fumagalli et al., 2001, Mills et al., 2011). For example, ozone damage has been reported on salad leaf crops being grown for the "ready to eat" industry in Sweden in the spring of 2010 (Karlsson, pers. comm.). In Greece, ozone damage to lettuce and chicory following a single episode where ozone concentrations peaked at 80 – 100 ppb for four consecutive days resulted in so much damage that the crop was unmarketable and losses of 15,000 Euro were incurred on a single farm (Figure 8.1). These ozone concentrations should be considered within the context of UK concentrations that in July, 2006, peaked at 147 ppb in rural Oxfordshire (Harwell monitoring station). During the same ozone episode, ozone injury was detected on clover plants growing outdoors in fields near Ascot, Brighton and Bangor as part of the ICP Vegetation ozone biomonitoring study (Hayes et al., 2007b; Mills et al., 2011). Furthermore, ozone injury was detected on several horticultural crops including lettuce, tomato and cucumber together with clover being grown for the ICP Vegetation biomonitoring experiment inside a commercial glasshouse in Bangor following an ozone episode with concentrations peaking at 60 - 80 ppb in May, 2006 (Figure 8.2). Thus, the potential exists for damage in the UK that might be on the same scale as that reported in Greece in a “high” ozone year.

It is possible that ozone pollution has already caused damage to UK horticultural crops but that the cause of the damage has not been ascertained. Ozone injury first appears as pin-head sized lesions on the upper surface of leaves; with prolonged ozone exposure these gradually spread to form larger lesions. Such symptoms could be misdiagnosed as being due to insect damage (e.g. by red spider mites), nutrient deficiency or fungal diseases. Examples of ozone injury on salad leaf crops are provided in Figure 8.3. Several other crops for which the quality of the foliage determines the market value are also sensitive to ozone injury, for example, spring onion and herbs such coriander and basil (Figure 8.4).

In this chapter, a first attempt is made at quantifying impacts of ozone on lettuce and salad leaves. The characteristics of ozone exposure in the previous 8 days before ozone injury was detected in the field on ozone-sensitive clover species, were examined using data from the UK and Germany (described in Section 2.2.2) as a surrogate for effects on lettuce as this was the only dataset available. The suggestion in the LRTAP Convention’s Modelling and Mapping Manual to use a critical level of an AOT30 of 0.16 ppm h accumulated over the previous 8 days was rejected because this critical level is likely to be widely exceeded across the UK; use of VPD-modified AOT30 was not possible because humidity data was not available on a suitable geographic scale. In the following analysis, many assumptions are made in order to give a provisional quantification of the impacts. It is clear, however, that much further analysis is required, including monitoring of impacts in commercial glasshouses and fields and the development of an easily applicable flux-based indicator, in order to improve the quantification of impacts of ozone on UK horticulture.

8.2 Methods for salad leaf crops

8.2.1 Selection of an appropriate parameter representing ozone episode occurrence

In the Modelling and Mapping Manual (LTRAP Convention, 2010), a short-term critical level exists for indicating the risk of visible ozone damage. Described in full by Pihl-Karlsson et al. (2004), this critical level is based on a VPD modified-AOT30 accumulated over a period of eight days prior to the development of injury. The critical level was derived from biomonitoring and ozone exposure experiments using clover species in northwest Europe. Within the Modelling and Mapping Manual it states that when VPD data is unavailable, as in this study, an alternative critical level of an AOT30 of 0.16 ppm h should be used. As this critical level is likely to be extensively exceeded in the UK, for this study we investigated other indices of ozone damage using data from the ICP Vegetation biomonitoring database. Data from sites from Germany with similar climates to the UK (Hohenheim, Trier and Deuselbach) together with those from UK sites (Bangor, Brighton, Lullington Heath) were selected for this analysis.

The aim was to identify a surrogate critical level that could be used in the future to alert growers of leafy vegetables to the potential for ozone injury occurrence. Based on the recommendation of Pihl-Karlsson et al. (2004), ozone data was analysed over separate eight day periods since their analysis indicated that injury occurred up to eight days after an ozone episode. The most reliable indicators were based on relatively low thresholds such as 50 and 55 ppb (Table 8.1). However, ozone concentrations exceed 50 ppb quite regularly in the UK and we believe that that thresholds set this low would over-estimate the number of damaging ozone episodes. For this reason, we selected the occurrence of at least one day in which the ozone concentration reached at least 60 ppb for one hour in the previous 8 days as the indicator of ozone episodes to be used in this study. The number of such occurrences over separate eight day periods within the early (April to June) and later growing seasons (July to September) were determined for each 10 x 10 km grid square. Such an approach may over-estimate the number of episodes when an episode results in a peak of greater than 60 ppb occurring on two consecutive days, with one of these days in each of two consecutive 8 day periods.

Figure 8.1 Ozone damage to lettuce on a commercial farm in Greece (a) hydroponically-grown indoor crop and (b) outdoor crop. Photos courtesy of D. Velissariou.

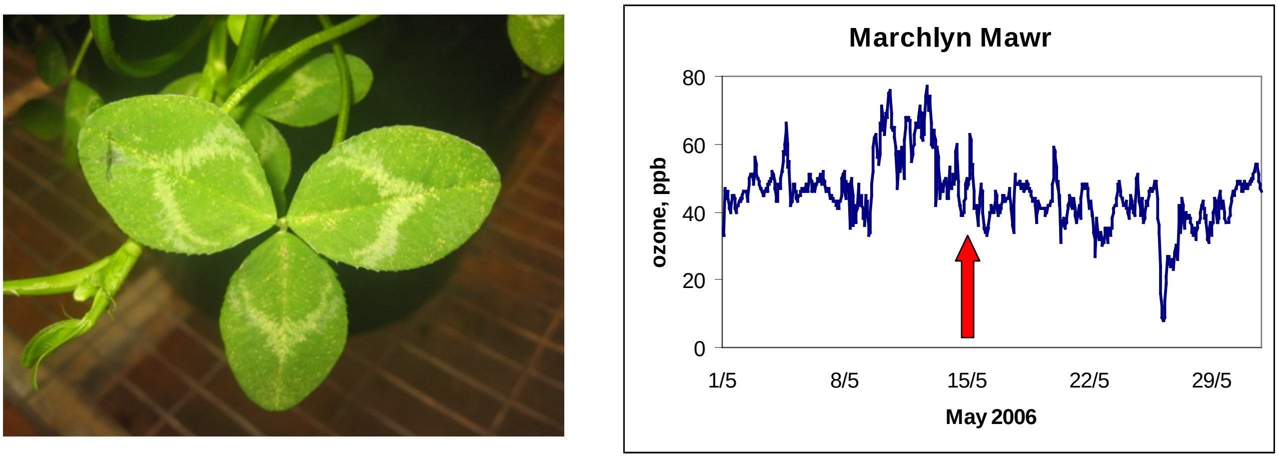


Figure 8.2 (a) Ozone injury on white clover growing in a commercial greenhouse in Bangor, 15 May, 2006. The ozone injury is the fine speckling on the leaves which on a leafy salad crop would be sufficient to reduce the value and marketability. (b) Ozone concentrations at the nearby (but higher altitude) monitoring site at Marchlyn Mawr. The red arrow indicates 15 May, 2006, the date on which the injury shown in (a) was detected.

Figure 8.3 Examples of ozone injury on lettuce and corn salad. Photos courtesy of J Bender.

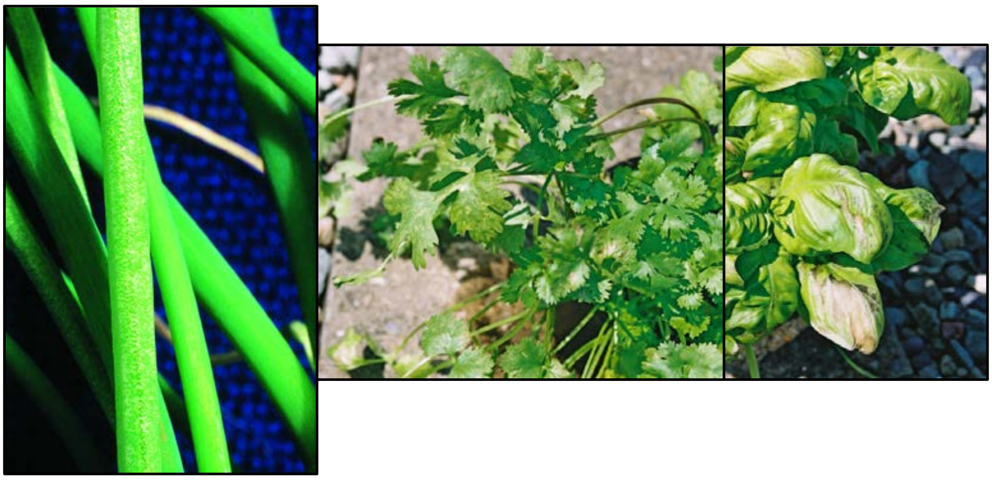


Figure 8.4 Ozone injury on salad onion (photo by J Bender), coriander and basil.

Table 8.1 The number of incidences of ozone damage on clover species at sites in Germany and the UK, and their relationship with ozone variables in the eight days prior to ozone injury occurring. The database contained 37 incidences of ozone injury recorded from 2000 to 2006.

variable	no. of sites where injury occurred	Incidences of injury explained, % of total	
		all data	Excluding 3 unusually low data points
Any hours >50 ppb	33	89.2	97.1
1 or more days with 4h > 50ppb	32	86.5	94.1
1 day > 55 ppb	31	83.8	91.2
10 or more hours >50ppb	31	83.8	91.2
2 or more days with 4h > 50 ppb	29	78.4	85.3
2 days > 55ppb	28	75.7	82.4
15 or more hours >50ppb	28	75.7	82.4
1 day > 60 ppb	27	73.0	79.4
2 days > 60 ppb	23	62.2	67.6
Mean daily max > 50 ppb	23	62.2	67.6
1 day > 70 ppb	22	59.5	64.7
2 consecutive days > 60 ppb	21	56.8	61.8

8.2.2 Mapping and quantifying impacts

The distribution of areas of lettuce and salad leaf growing areas was mapped as described in Section 2.1. Several assumptions had to be made in order to provide a provisional quantification of the economic impacts of ozone episodes on marketable value. These were:

- There was only one lettuce/salad crop per ha per three months, with two crops per year (in April to June and July to September)
- An ozone episode occurred within an 8 day period if the ozone concentration during that period exceeded 60 ppb
- Each episode caused the same amount of damage amounting to a 5% loss in the marketable value
- The marketable value of lettuce/salad leaf crop, ex-farm gate is £9k per ha (HDC leaflet FV294) per three month period

The production statistics available for this analysis indicated a three-fold larger area of lettuce/salad leaf crop in 2008 than in 2006 which needs further investigation as the figures do not tally with the national statistics. For this reason, economic impacts were not quantified for 2008.

8.3 Spatial and economic impacts of ozone on lettuce and salad leaf production (provisional)

In 2006, there were more than four incidences of the ozone concentration exceeding 60 ppb within an eight day period in most of the lettuce and salad leaf growing areas of England during April to June and July to September (Figure 8.5). Even though there was less ozone in 2008, there were still enough episodes to cause ozone damage. Incidences of ozone damage were the greatest in the April to June, 2008, period with areas along the south coast, parts of East Anglia and the north-east experiencing greater than four ozone episodes. In contrast in the period July to September 2008, between two and three ozone episodes occurred in South and East England, with fewer episodes occurring in the other lettuce and salad leaf growing areas. The contrast between the two years is evident in the frequency distributions of the number of ozone episodes per three months shown in Figure 8.6. It is of particular note that there were up to 8 ozone episodes with the potential to cause damage in both the April to June and the later July to September time periods in 2006.

This analysis shows the potential for impacts on economic value of salad leaves, with several parts of the UK in 2006 having economic losses predicted to exceed £40k per 10 x 10 km grid square (Figure 8.7). In both the early and late season, the greatest number of grid squares were in the >£0k to 20k economic loss per grid square category (Figure 8.8).

The first indicative figures for effects of ozone on lettuce and salad leaf crops suggest crop losses in the high ozone year of 2006 of £25.3 million, representing 24% of the economic value (Table 8.2). As indicated above, these figures are very provisional and further research is required to quantify impacts. This valuation has assumed that 5% of the crop is unmarketable for each ozone episode; it is currently unknown whether consecutive ozone episodes on the same crop would have the same impact as there may be specific growth stages that are particularly sensitive to ozone. A more detailed analysis would also consider the staff costs involved in farmers removing ozone damaged leaves in order to retain an, albeit smaller in weight, but marketable salad leaf crop. We have assumed here that there are two crops of lettuce per hectare per year which may be an overestimate for many farms. The crop value of £9k per hectare used may be too low for the higher value salad crops such as the crinkly leaved varieties. Further uncertainty in this provisional valuation of damage arises from the use of ozone concentration as the indicator of ozone damage. A flux-based approach taking into account the factors that influence ozone uptake such as temperature, humidity and plant growth stage would provide a more robust estimate of the cost of damage.

Despite these uncertainties, this provisional analysis suggests that ozone pollution does potentially pose a threat to the current and future horticultural industry and methods of ameliorating ozone impact need development. The financial impacts could potentially be quite large.

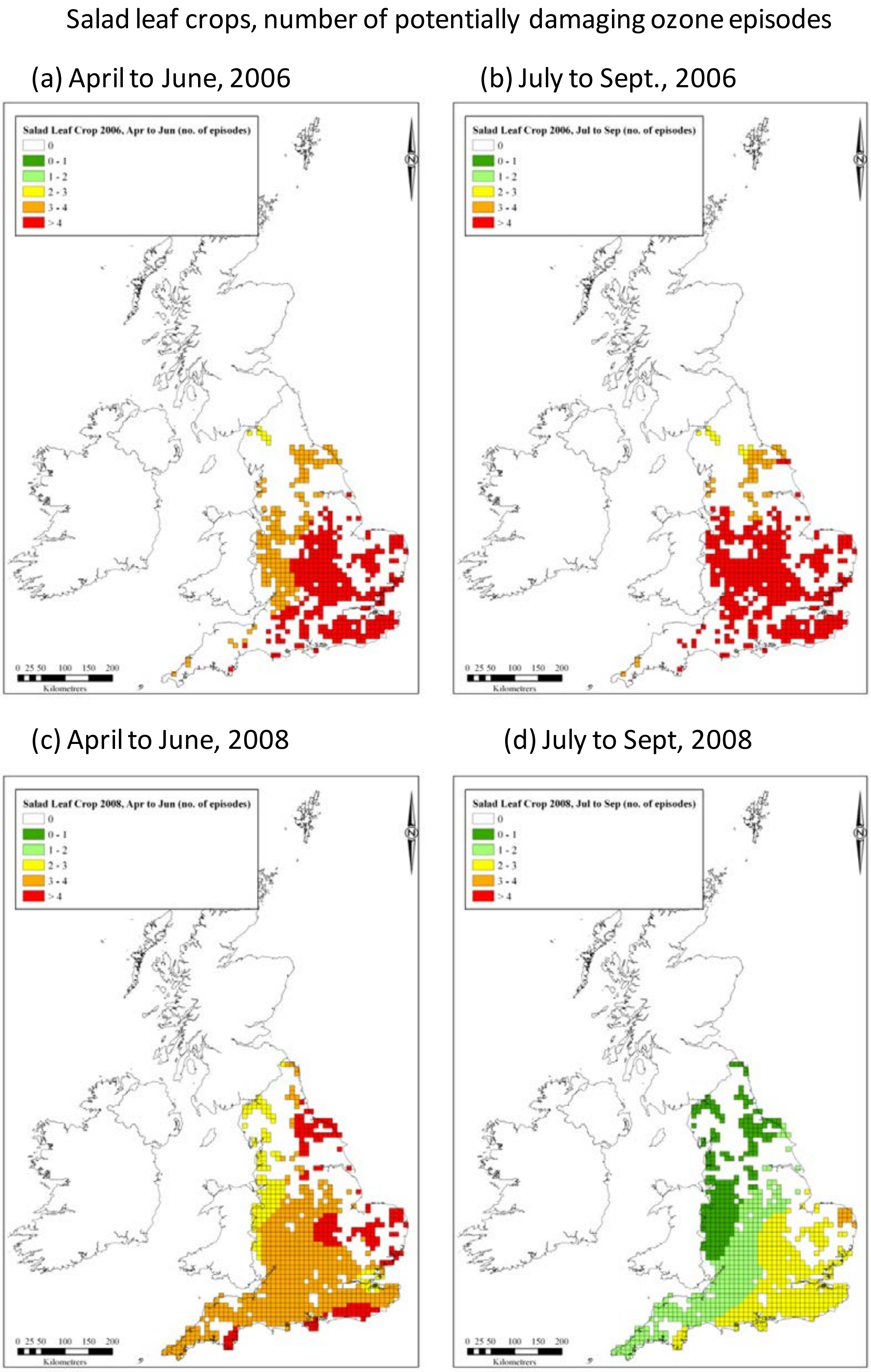


Figure 8.5 Spatial distribution of the number of potentially damaging ozone episodes (defined here as the number of distinct 8 day periods in which the ozone concentration exceeds 60 ppb) within the period April to May and July to September, 2006 and 2008.

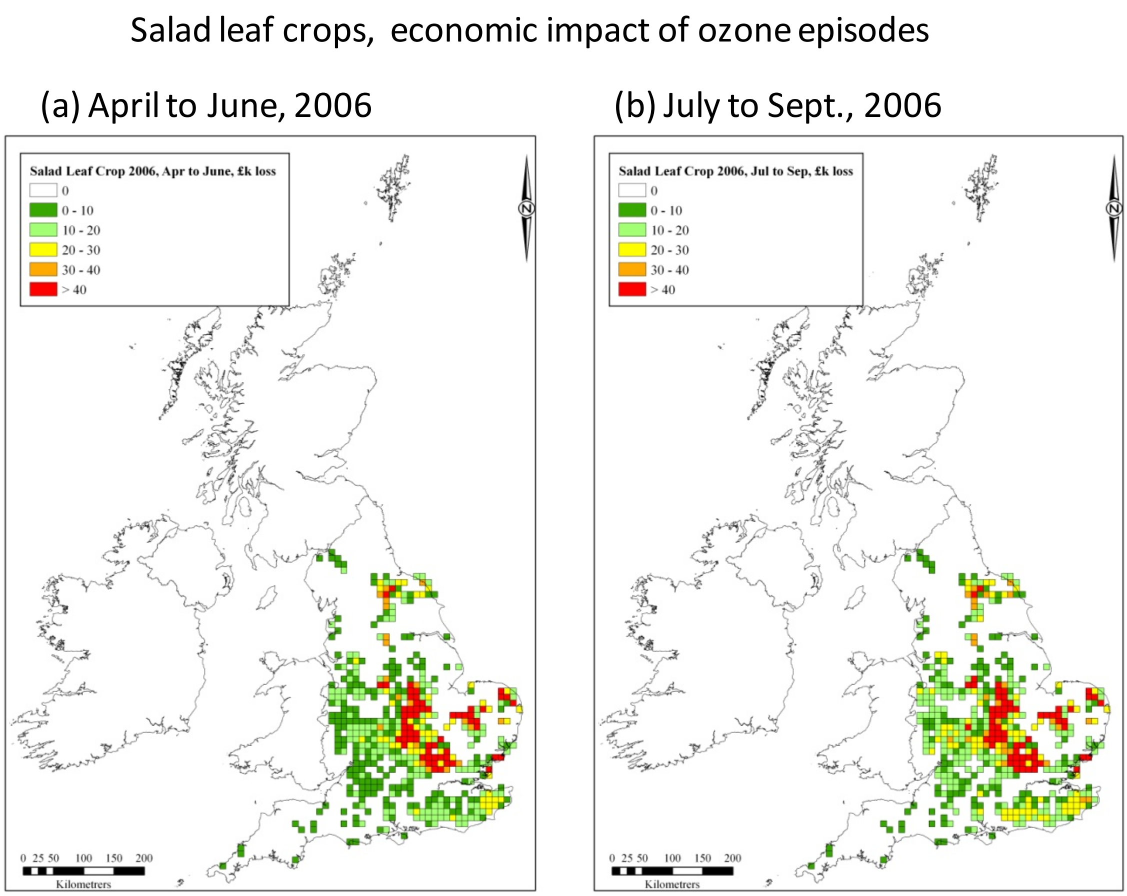


Figure 8.6 Spatial distribution of the potential economic losses associated with ozone induced leaf damage in lettuce and salad leaf crops in 2006 and 2008 (provisional figures). *Note: economic losses are not presented for 2008 because the area of lettuce in the data provided was three times that in 2006, and much higher than indicated in the Defra statistics (to be further investigated)*

Table 8.2 Impacts of ozone on salad leaf crops in the UK (provisional)

	2006
Salad leaf crops	**AOT40**
Million ha grown	0.01
Production, million t	n.a.
Total value, £ million*	105
Lost production, million t	n.a.
Lost production, £ million	**25.27**
% economic loss	**24.00**
* based on two crops per year at £9k/ha	
Certainty of estimates	Low

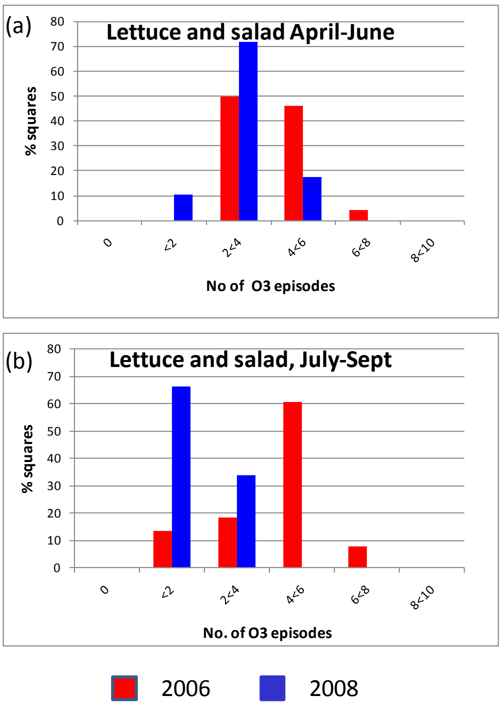


Figure 8.7 Frequency distribution of the number of ozone episodes with the potential to damage alad leaf crops in 2006 and 2008, (a) April to June and (b) July to September.

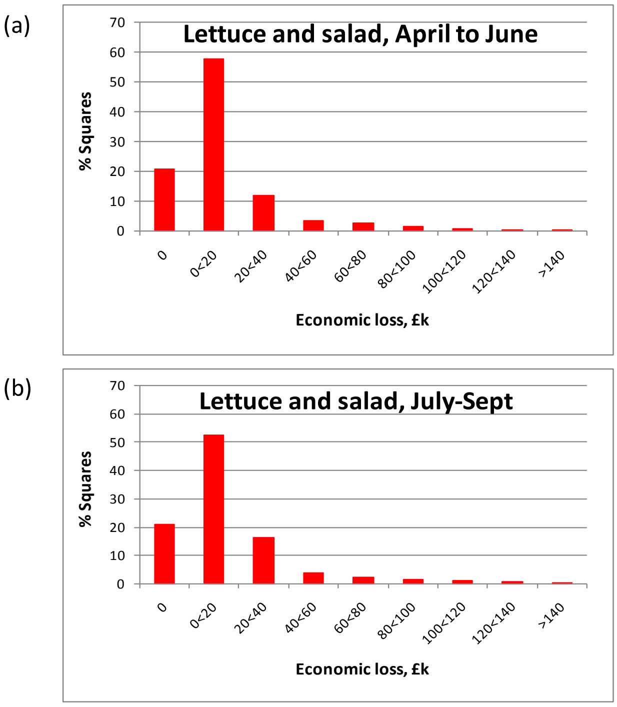


Figure 8.8 Frequency distribution of the potential economic losses associated with ozone episodes in 2006: (a) April to June and (b) July to September (provisional data).

9. Effects of ozone on pasture in the UK

Summary: Pasture

- The clover component of pasture provides an important role as a nitrogen fixer and is very sensitive to ozone pollution.
- Higher fluxes to clover were predicted in the UK in 2008 than in 2006, even though AOT40 values were higher in 2006 than 2008
- The highest flux and AOT40s were predicted for the SW England and SW Wales, with many areas of the UK being potentially at risk of clover reduction in pasture.
- The flux-based response relationship for clover appeared to exaggerate impacts.
- Further research is needed to fully quantify the impacts of ozone on pasture, including effects on pasture quality (e.g. protein content) and carrying capacity, and the need to increase fertilizer use to compensate for reduced nitrogen fixation by a smaller clover fraction.

9.1 Introduction

At the outset of this study, the intention was to quantify ozone impacts on pasture and make the links through to effects on meat and milk quantity and quality. The first stage of this was to conduct a flux-based assessment of the impact of ozone on the clover component of pasture. Clover species are amongst the most ozone sensitive identified (Hayes et al., 2007), with ozone injury being routinely detected on clover across Europe, including in the UK in recent years (Mills et al., 2011). Significant reductions in clover biomass have also been detected in ambient air in several European countries as part of the ICP Vegetation biomonitoring experiments, with effects as large as a 40-50% reduction in the biomass of an ozone sensitive biotype being reported in Greece (Hayes et al., 2007b). Reductions in the clover component of pasture reduces impacts on pasture quality and carrying capacity and ultimately could impact on the protein content of sheep and cow meat For example, a 10% reduction in the clover component of a mixed grass-clover sward causes a 1% reduction in forage protein content (Better returns programme, 2010). At the optimum clover content of 25-35% of the sward, clover fixes at least 150 kg N/ha. In addition to impacting on meat and milk production, ozone induced reductions in the clover content would necessitate the application of additional nitrogen fertiliser at an associated economic and environmental cost.

When setting critical levels, databases were sought that included exposure of grass : clover mixtures to a range of ozone concentrations, with monitoring of microclimate and stomatal conductance measurements. Suitable data were available for one species, *Trifolium repens* (white clover) from experiments conducted in the UK (CEH Bangor and Newcastle University) and Switzerland. A flux-based critical level was derived using POD_1 as the ozone metric for application to productive grasslands, with the intention of protecting against a 10% reduction in clover biomass. As the clover :

grass mixtures were maintained with adequate water supply in these experiments and there was no suitable data available for effects of soil moisture content on ozone flux, application of the critical level and associated response function assumes that soil moisture is not limiting to clover production.

In this study, the response function for clover was applied to areas where pasture is present in the UK to determine the potential reduction in the clover content of pasture caused by ambient ozone in 2006 and 2008. As shown below, the results indicated that ambient ozone is causing a an average of 30 to 40% clover biomass reduction in early pasture and 40 to 50% biomass reduction in late pasture. The authors considered these losses to be too high, and after consultation with the contract manager at Defra, did not continue with the analysis of economic impacts on meat and milk production. Nevertheless, this study has shown that there is the potential for ozone to impact on pasture in the UK and has also shown the spatial distribution of the areas with the highest potential impact. Further studies are required to improve the quantification of effects.

9.2 Methods used for pasture

The method used for pasture follows that described in Chapter 2, with the clover response function shown in Figure 9.1.

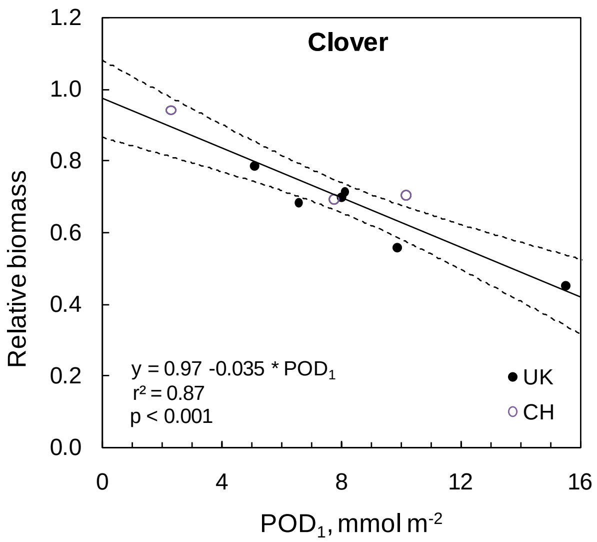


Figure 9.1 The relationship between the relative above-ground biomass and POD_1 for sunlit leaves of clover, based on data from the UK and Switzerland.

9.3 Spatial distribution of ozone impacts on pasture

Ozone impacts are presented in Figures 9.2 and 9.3 as maps of the POD_1 and AOT40 accumulated over the early-season (April to June) and late-season (July to September). The highest POD_1 values were found in the late seasons in both years, with values greater than 16 mmol m^{-2} in coastal areas of S England and SW Wales in 2006. The highest fluxes were predicted to cover a larger area of SW and coastal SE England in 2008. Temperature may have been limiting in the early seasons with the mean daily maximum temperature being in the range 10 to 14°C (Figure 1.4), well below the optimum for stomatal conductance for white clover of 24°C.

The AOT40 values in 2006 and 2008 showed a different spatial pattern and exceeded 6 ppm h in SW England, East Anglia, parts of mid Wales and the far North of Scotland in the early growing season of

2006 (Figure 9.3). In 2008, the AOT40 values in the early growing season were greater than 6 ppm h in East Anglia, but were lower than 1.5 ppm h in SW England, W Wales, Northern England and most of Scotland and Northern Ireland. AOT40 values were very low in the late growing season in 2008 and did not exceed 1.5 ppm h anywhere in the UK.

Application of the flux-effect relationship shown in Figure 9.1 to the flux values shown in Figure 9.2 indicated that there would be a very high proportion of losses in clover biomass (Figure 9.4). Impacts were predicted to be bigger for late pasture and were normally distributed around the 30 - 40% clover loss category for 2006 and the 40 - 50% clover loss category in 2008. For early pasture, the highest percentage of grid squares were present in the 30 to 40% clover loss category in both years. Intuitively, these percentage reductions seem to be too high and it is recommended that further research is conducted to improve the reliability of the dose response relationship for grass : clover mixtures that are used in the UK. It is also important to quantify the impacts of soil moisture on stomatal conductance in order to improve the flux model as fluxes may have been overestimated in drier areas, especially in 2006.

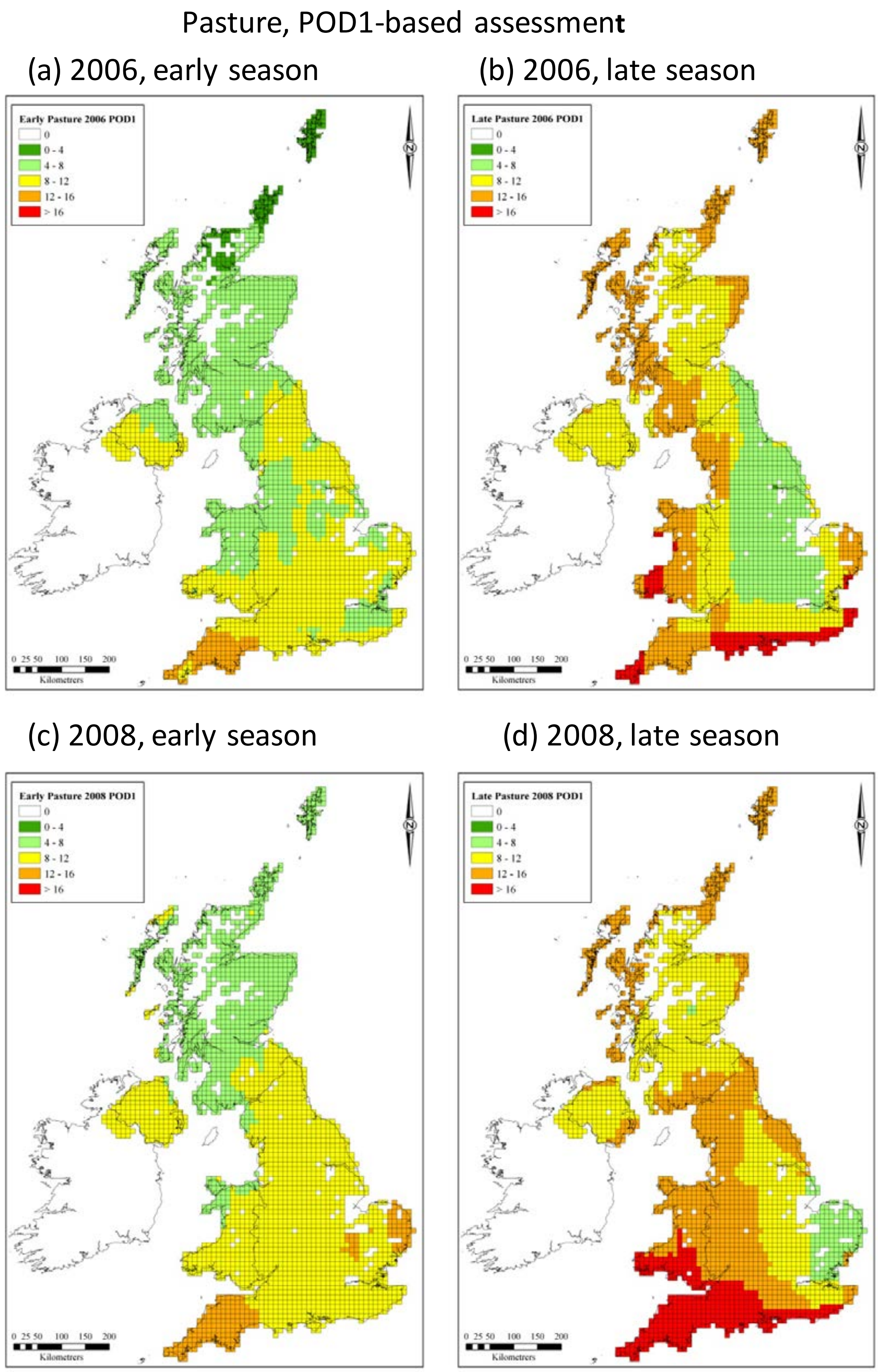


Figure 9.2 The spatial distribution of ozone flux to clover (POD1, mmol m^{-2}) in early season (April to June) and late season (July to September) in the pasture growing areas (>100 ha or 1% of each 10 x 10 km grid square) in 2006 and 2008.

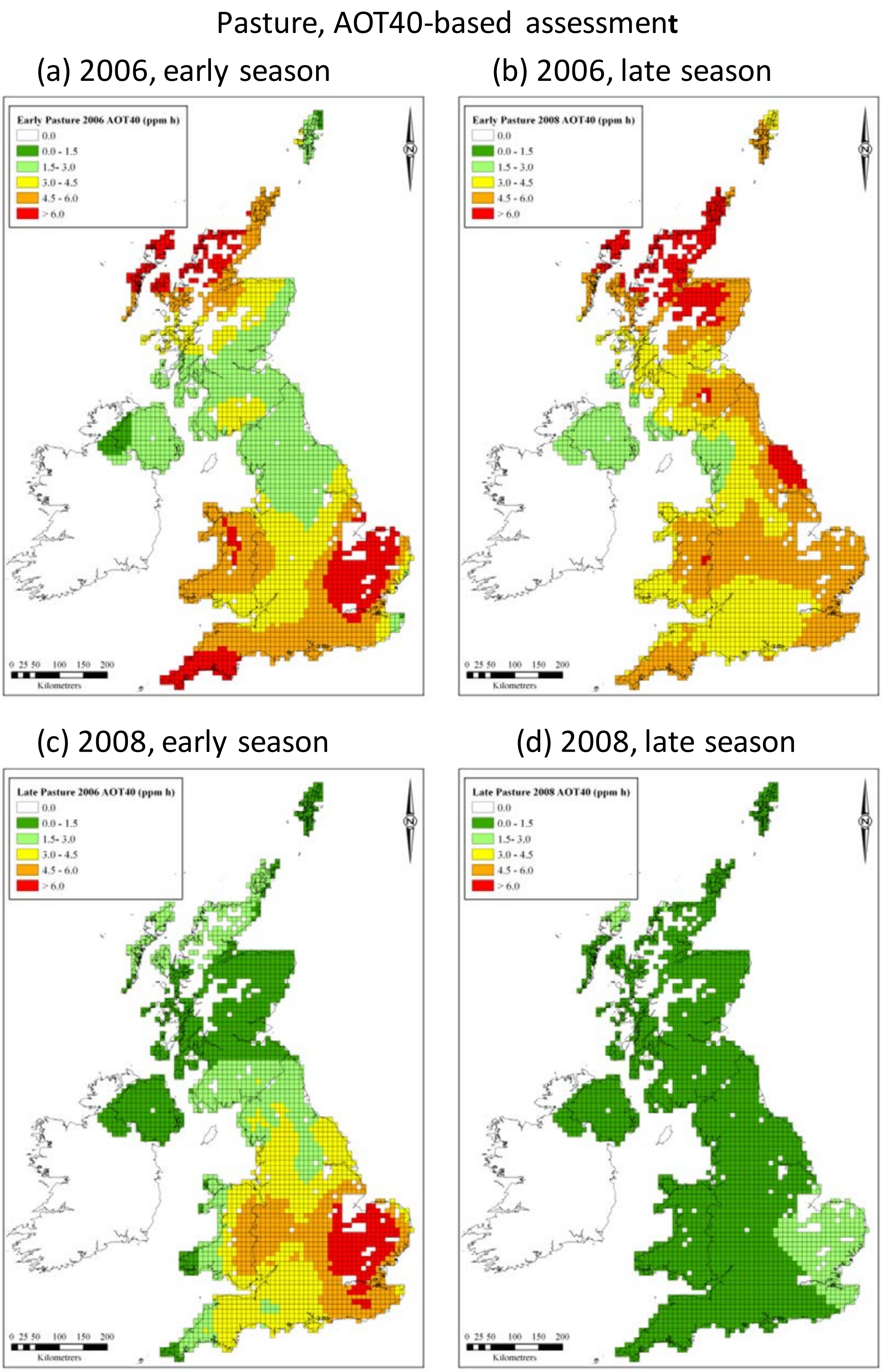


Figure 9.3 The spatial distribution of AOT40 (ppm h) in early season (April to June) and late season (July to September) in the pasture growing areas (>100 ha or 1% of each 10 x 10 km grid square) in 2006 and 2008.

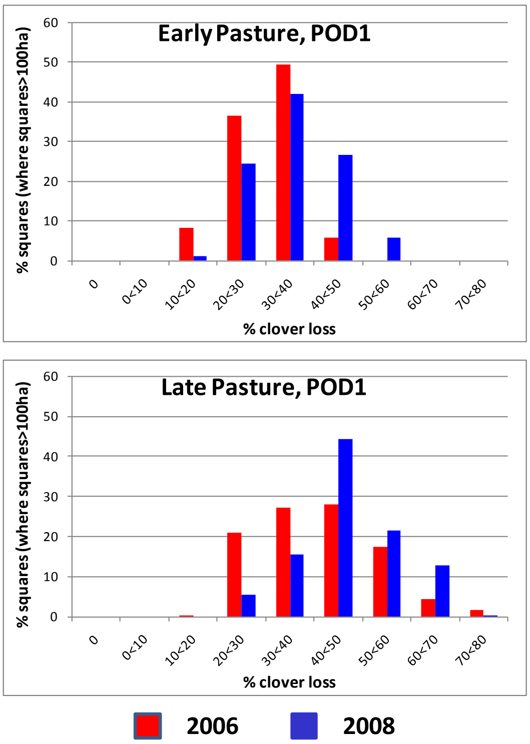


Figure 9.4 Frequency distribution of the basic predicted percentage clover loss in the grid square shown in Figures 9.3 and 9.4 as estimated using the dose response function in Figure 9.1

10. Conclusions and recommendations

10.1 Evaluation of approach

This is the most comprehensive study to date on the magnitude of economic impacts of ozone pollution on UK crops. The unique aspects of this study include incorporation of the flux-based methodology, analysis using a 10 x 10 km grid including flux, AOT40 and crop production data, the range of crops studied, impacts of ozone episodes on salad leaf crops, and analysis of impacts for two contrasting years representing a typical current and a projected future year. The few other studies conducted have used AOT40 or other concentration-based metrics and were usually for one crop only (wheat) or have investigated effects in the UK as part of a European project conducted on a coarser scale. Recently, Kaliakatsou et al. (2010) determined economic losses using an econometric approach involving analysing data from 13 years of wheat field trials together with AOT40 data, and concluded that a 10% increase in AOT40 would decrease yields by 0.23%. Using the unit value lost per unit of AOT40 data in Table 3.3. and the total wheat value in the UK (Table 3.2), the current study indicated a 0.26% loss in economic value for a 10% increase in AOT40 and thus is broadly in agreement. In the other study, Neeliah and Shankah (2010) investigated ozone effects on wheat profits in the UK and showed that a 10% increase in average AOT40 would decrease variable profits by 1.3% and wheat output supply by 1%. An earlier analysis by the same authors of wheat yields on 116 cereal farms for six years (1993 – 98) indicated that ozone pollution had a statistically significant negative impact (Shankah and Neeliah, 2005). As part of a study of ozone impacts on crop production in 47 European countries using AOT40 as the ozone metric and a 50 x 50km grid, Holland et al. (2005) estimated impacts on crop production in the UK to total 163 million Euro in 2000 using world market prices. The more detailed study conducted here, including use of the more sophisticated flux-based approach indicated higher overall losses at £205 million and £183 million for 2006 and 2008 respectively. The European study is currently being updated using flux-based methodology and the latest scenario for ozone concentrations in 2020 (Mills et al., in prep.). Overall, the results presented here are in broad agreement with other studies published on ozone effects on crop yield in the UK.

The certainty of the predicted crop losses varied for each crop. 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. This model, selected to enable cross referencing with health impacts work for the UK, is a Lagrangian model linked to a post-processor which calculates ozone flux to vegetation. The underestimates in 2006 (flux calculated from measured values was 1.5, 2.23 and 1.5 x that modelled by OSRM-SOFM for wheat, potato and oilseed rape in 2006 respectively) were larger than those in 2008 (0.98, 1.8 and 1.09) leading to difficulty in comparing values for the two years without use of a correction factor. Uncertainties were also introduced by the use of a threshold for flux accumulation (Y=6 nmol m^{-2} s^{-1}) and use of modelled soil moisture content and light - such uncertainties would be common to all currently available regional air quality models. It would be interesting to compare flux maps generated with the OSRM-SOFM model with other models in use within the UK such as the Eulerian EMEP4UK model adapted for the UK from the EMEP model being used by the LRTAP Convention.

In the absence of suitable flux models for all crops, we have used AOT40-based approaches where necessary. It is clearly preferable to estimate impacts based on the amount of ozone taken up by the plant rather than the concentration in the air above the plant. Where it has been possible to use both metrics, ozone impacts were systematically predicted to be higher for AOT40 than for flux (discussed further in the next section). This analysis provides a good example to support the recommendation in the LRTAP Convention's Modelling and Mapping Manual that AOT40-based methodology should not be used for economic impact assessment (LRTAP Convention, 2010). However, it's use here has provided an indication of what the potential impacts could be for crops such as maize and sugar beet.

The flux modelling method is the most advanced for wheat as this crop has been the focus of study within the LRTAP Convention and the linear relationship between yield impacts and POD_6 is highly significant (r^2 = 0.84, p<0.001, see Table 2.4). The same relationship is slightly less strong for potato yet still significant (r^2= 0.79, p=0.017) and considerably weaker for oilseed rape (r^2 = 0.19, p = 0.02). Thus, of all the results presented here, we have the most confidence in those based on ozone flux for wheat.

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 (Table 2.5). 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 even 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 presented here decreased in the order: wheat > potato, oilseed rape and sugar beet > barley, maize, peas and beans > salad leaf crops and pasture. Further research is needed to increase the certainty of the evaluations conducted (see Section 10.3).

10.2 Overall conclusions

Many of our most important food crops respond to ozone pollution by decreasing vegetative growth, seed production and root growth leading to reductions in both quantity and quality of yield. Several horticultural crops, including the so-called "ready-to-eat" salad leaf crops, develop visible leaf damage following ozone episodes that reduces their market value. Based on AOT40-response functions, the agricultural crops studied decreased in sensitivity as follows: pea and bean > wheat > potato and oilseed rape > sugar beet > maize and barley (Figure 3.2). Using these and flux-based response functions where available, we quantified the impacts of ozone pollution on agricultural production in the UK for 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.

An important conclusion from this study is that the ozone impacts in 2008 were almost as high for the eight crops studied as those in the more extreme year, 2006 (Table 3.3). Using 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[1], representing 6.6% of the total value whilst those in 2006 (a typical future year which occurs occasionally now) totalled £205 million[1] 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 3.4).

The results also indicate 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 (Figures 3.1,10.1 and 10.2). 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 totalled ca. £600k of economic loss. Should there be times of food shortages these effects may be particularly relevant. During such times we may not be able to rely on excess production from our 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.

Throughout this study, AOT40-based analyses consistently over-estimated 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. An important difference between the two methodologies is that the flux method differentiated between the drier conditions in 2006 and wetter conditions in 2008. As part of the test of the OSRM-SOFM model, the factors influencing instantaneous ozone flux at a rural location near Peterborough were presented for each year for wheat (Figure 4.5). These figures showed that the two most critical components of the stomatal flux algorithm were temperature and the plant available water in the soil (PAW). Early in the accumulation period, the lower temperatures had a greater negative impact on accumulated flux in 2008 than in 2006, whilst the negative impact of reduced soil water availability on ozone uptake was much more pronounced in the drier second half of the season in 2006 than in the wetter summer of 2008. 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.

Impacts on cereals

Overall, the economic impacts were predicted to be the greatest for wheat, the most extensively grown crop with monetary loss estimates of £77.6 million in 2006 and £91.2 million in 2008 based on mean crop value (Table 4.1, Figure 4.3). 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 (Figure 4.11), potentially impacting on barley supply for the malting industries.

The other cereal crop studied here 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 here 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, Figure 4.14 and Table 4.5).

Impacts on oilseed rape

For oilseed rape, the flux-effect model 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 £30-33million in 2008, representing 6.6 to 7.2% of the

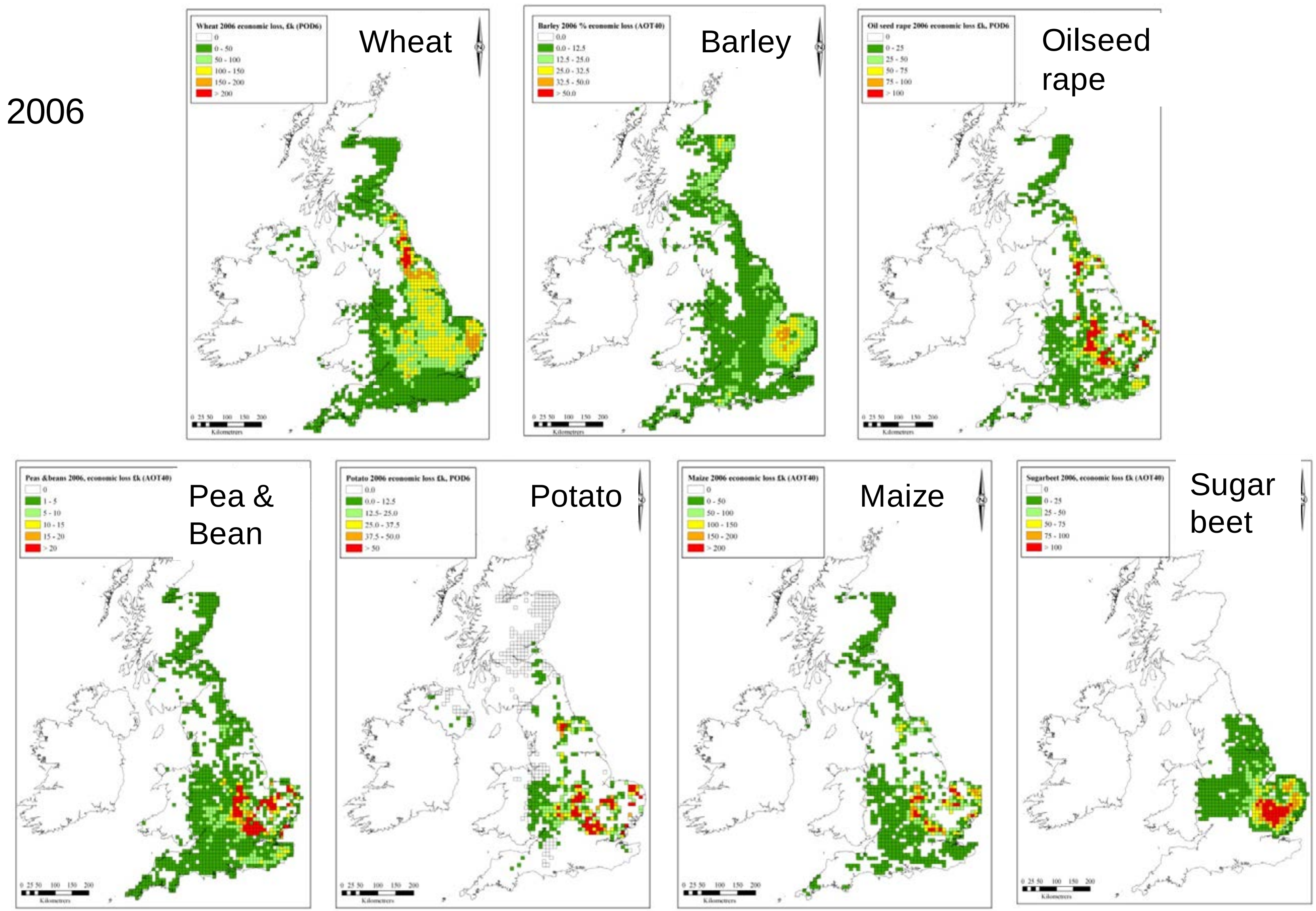


Figure 10.1 The economic impacts of ozone on UK crops in 2006 .(£k loss per 10 x 10km grid square). Maps ordered by production area in the UK .Those for wheat, potato and oilseed rape were prepared using the flux-based methodology whilst those for barley, sugar beet and peas and beans were prepared using AOT40 as the ozone metric.

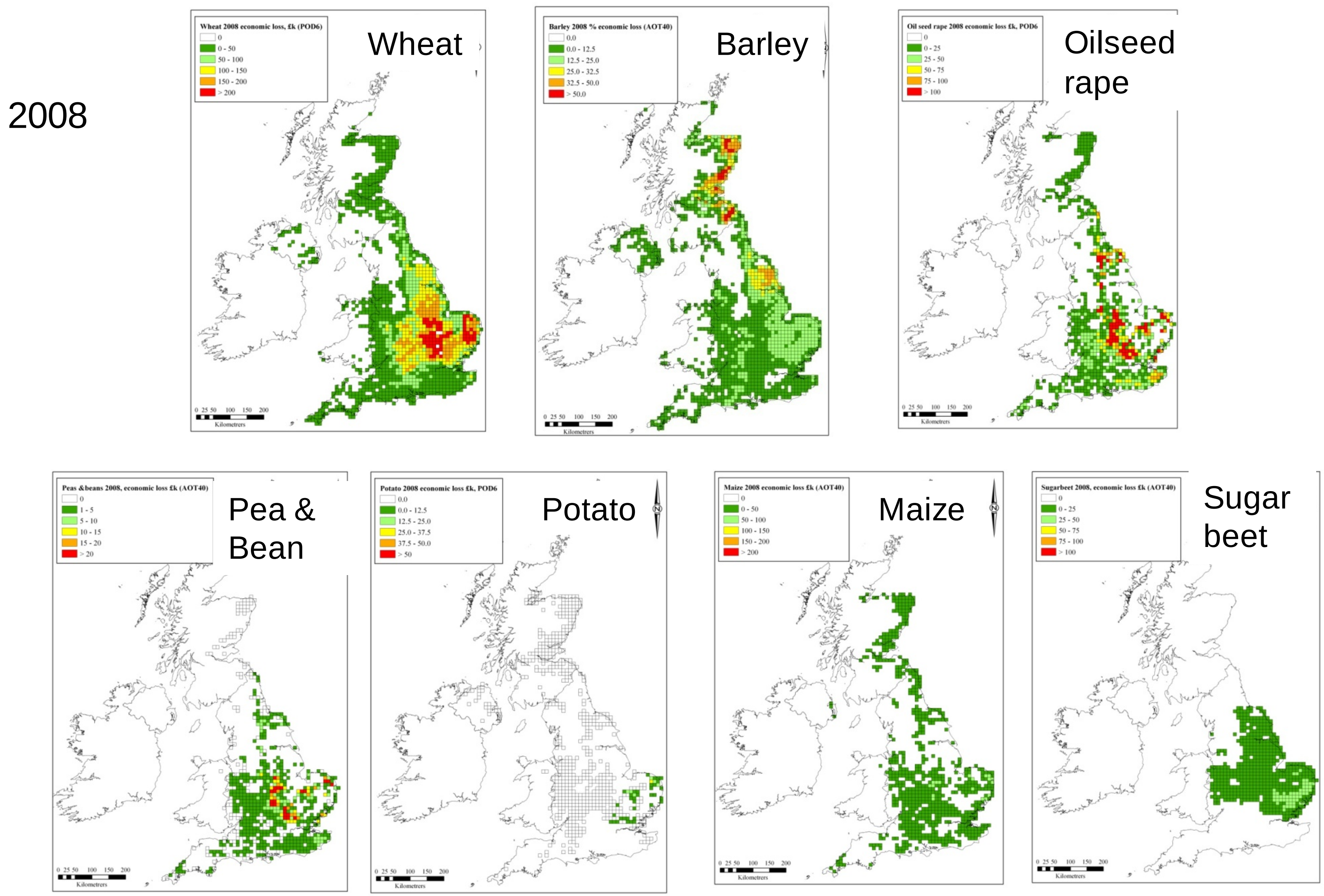


Figure 10.2 The economic impacts of ozone on UK crops in 2008 .(£k loss per 10 x 10km grid square). Maps ordered by production area in the UK. Those for wheat, potato and oilseed rape were prepared using the flux-based methodology whilst those for barley, sugar beet and peas and beans were prepared using AOT40 as the ozone metric.

economic value (Table 5.1, Figures 5.3 and 5.4). 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 6.1, Figure 6.3). 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, Table 6.1, Figure 6.4). Economic losses predicted for sugar beet using the AOT40-based methodology were £17.5 million in 2006 and £4.4 million in 2008 (Table 6.3, Figure 6.11). 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 (Figure 7.3). 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 7.1). 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 3.2, Figure 8.6). Not only would ozone pollution impact on profits due to reduced 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.

Impacts on pasture

The clover component of pasture, vital for nitrogen fixation, is vulnerable to ozone at the current and expected future ozone concentrations. Higher fluxes were predicted for 2006 than for 2008 but these totals may have been impacted by soil water availability, a factor that it is currently not possible to include in the flux model due to a lack of data. The highest fluxes and AOT40s were predicted for the SW of England and SW Wales, with many areas of the UK being potentially at risk of clover reduction in pasture. Since a 10% reduction in clover content of pasture is sufficient to induce a 1% reduction in forage protein content (Better returns programme, 2010) and at the optimum clover content of a sward (25 – 35%) clover fixes at least 150 kg of nitrogen per hectare, there is the potential for ozone pollution to reduce the quality of forage leading to increased compensatory fertilizer usage. Indeed, one experimental study has shown that ozone can reduce the consumable food value of a grass : clover mixture (Gonzalez et al., 2008). In this study, the effect of ozone on the clover component of pasture may well be exaggerated using the available flux-effect relationship (which excludes the impact of sol moisture content). Further research is required to improve our understanding of the impacts of ozone on the sustainability and forage quality of pasture.

10.3 Policy considerations and recommendations

Improved quantification of impacts on agricultural 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 is 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.

- **Recommendation (1):** Further experimentation using current cultivars of the most important UK crops of wheat, oilseed rape and potato to improve existing response-relationships, and to develop new relationships for those crops for which no flux-effect relationships currently exist (e.g. barley, maize, sugar beet and oats). New/improved relationships should take into account effects on both yield quantity and quality.

- **Recommendation (2):** Further ozone exposure experiments should be conducted for the grass : clover mixtures currently in use and being developed for sustainable pasture allowing impacts on this potentially very vulnerable agricultural system to be quantified.

Improved quantification of impacts on the horticultural industry

This initial study has highlighted the potential for significant economic losses within the horticultural industry as a result of ozone pollution. Losses were tentatively quantified for salad leaf crops, but ozone could be damaging many other crops for which the visible appearance of leaves determines the quality of the product such as cabbage, salad onions, herbs, foliage plants etc. and hence the value.

- **Recommendation (3):** A more detailed investigation of ozone impacts on the horticultural industry is required. This should include surveys for ozone injury following episodes and on-farm measurements of stomatal conductance, climatic conditions and ozone to facilitate the development of ozone-flux based indicators of damage, facilitating a more reliable estimate of economic losses.

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) .

- **Recommendation (4):** 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

It is not currently possible to determine whether effects are 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). Together with improved quantification described above, further research to apportion effects would facilitate cost-benefit analysis for UK emission control strategies.

- **Recommendation (5):** To inform policy development, new experiments are required to quantify the beneficial effect of different emission control strategies (including for scenarios being considered by the UK and the LRTAP Convention for 2020 and 2030) on crop yield, including effects of reducing peak concentration within an ozone climate where background ozone is increasing.

Improved tools for farm-scale decision making

Although not included within the remit of this study, the following points have arisen during the course of the study that are worthy of consideration for future research plans, leading to improved 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. Further work is needed to understand interactions between ozone and nitrogen, and the extent to which fertiliser input can offset the effects of ozone.

- There is a growing body of evidence that ozone reduces drought tolerance in crops as well as other plant species. Other studies have shown that ozone can render some species more susceptible to insect and fungal attack. Such interactions would benefit from further study if future impacts in a changing climate are to be appropriately quantified and planned for.

- In order to provide guidance to farmers on how to avoid impacts of ozone, the following research would be beneficial:

    - A review of current knowledge on effectiveness of potential avoidance strategies
    - A screen of the ozone sensitivity of most commonly used UK cultivars
    - Studies of the potential for avoiding ozone damage by withholding water in irrigated crops, thereby closing the stomatal pores on the leaf surface and preventing ozone uptake (reaching a balance between reduced ozone uptake and drought-reduced crop growth).
    - Screening of currently available or soon-to-be registered possible chemical protectants for ozone damage.
    - Cost-benefit analysis of proposed strategies at the farm-scale.

- Assuming suitable avoidance strategies are available, the feasibility of using an early warning system for farmers and growers that would signal the need to take evasive action could be explored.

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