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Development of a framework for probabilistic assessment of the economic losses caused by ozone damage to crops in Europe

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Executive Summary

Background and objectives

Ozone is present at elevated concentrations in the lower atmosphere through reactions involving oxides of nitrogen (NOx) and volatile organic compounds (VOCs). It has long been recognised as causing losses in crop productivity and changes in the quality of agricultural products. There is now a strong demand from policy makers for the quantification of ozone damages to be fed into cost-benefit analysis of emission control strategies.

The analysis presented in this report investigates the use of both concentration-based (AOT40) and flux-based ($AF_{st}6$) methods to assess the uncertainties in quantifying the ozone-induced loss of production for (largely) arable crops in Europe. The flux-based method is preferred on the grounds that it estimates yield loss against received dose of ozone, rather than against simple exposure to ambient levels. However, the flux-based method can so far only be applied to wheat and potato, and so is not suitable for providing a comprehensive assessment of crop damage involving a wide range of crops. Parallel use of the two methods was intended to improve understanding of their reliability relative to one another.

The objectives of this study were to:

1. To describe the uncertainties present in AOT40-based modelling;

2. To examine the difference between estimates of yield loss made using AOT40-based and flux-based functions

3. To consider how AOT40- and flux-based methods can be combined in the future to enable a reasonably complete estimation of ozone impacts on crop yield in Europe that maximises use of the research that has been carried out in this field.

4. To provide European estimates of the range of expected yield losses under a range of scenarios, taking account of uncertainties where possible.

5. To identify areas for further refinement of the crop loss model

Analysis using concentration-based methods

Using concentration-based methods, this study has quantified a range for ozone-induced losses for 23 crops in 47 countries in Europe of €4.4 to 9.3 billion/year, around a best estimate of €6.7 billion/year for year 2000 emissions (Table (i)). The @RISK package has been used to quantify the combined impact of the uncertainties that affect the analysis. Results for a series of scenarios considered in the EU’s recent CAFE (Clean Air For Europe) Programme for 2020, by when all current legislation should be fully in place, are also shown in the table. The core estimate represents losses equal to 2% of arable agricultural production in Europe. These estimates do not account for damage via visible injury, changes in crop quality, or interactions with pests.

Table (i) Core estimates of total damage to the crops considered across the 47 countries considered in the analysis, with 90% confidence interval. Units: €billion/year.

Scenario	**Core**	**90% confidence interval**
2000	6.7	4.5 – 9.3
2020 baseline	4.5	3.0 - 6.3
D_23 low (CAFE programme scenario)	3.9	2.6 - 5.4
D_23 mid (CAFE programme scenario)	3.7	2.4 - 5.2
D_23 high (CAFE programme scenario)	3.6	2.4 - 5.1
Maximum Feasible Reduction according to the RAINS model	1.7	1.1 - 2.3
EU's Thematic Strategy on Air Pollution	3.9	2.6 - 5.5

The @RISK analysis shows that the largest sources of uncertainty in the concentration-based estimates presented in Table (i) are, in order of decreasing importance:

- Response function for vegetables
- Variation in ozone concentration with height
- Crop yield estimates
- Response function for potato

Analysis using flux-based methods

The use of flux-based methods, that take account of dose received by sensitive plant tissues rather than simply ambient ozone concentration, is strongly preferred from a theoretical perspective, but is not yet possible for crops other than wheat and potato. Results based on the use of flux-based methods for five grid cells representing each of five European climate zones indicates both increases and decreases in flux-based yield loss estimates relative to concentration-based estimates, depending on climatic zone. Additional analysis is required to ensure that the findings on the bias by climatic region relative to concentration-based yield loss estimates are truly representative of the different climate zones, before reaching any firm conclusions on a possible additional factor to be incorporated into the concentration-based analysis to approximate flux.

The analysis performed in this report identifies a number of other issues relative to the use of the flux-based methods that need further assessment:

a) That the increase and decrease in yield loss estimates made in different locations using flux- compared with concentration-based methods truly represent effects found under field conditions and are not an artefact of extrapolation of experimental dose-response relationships to field conditions.
b) That the flux modelling for wheat and potato can provide information on the role dose-modifiers may play in altering crop losses for other crop species estimated using concentration-based functions.

c) That formulation and parameterisation of the stomatal flux model is appropriate for different climate regions. Perhaps the most important issues are to ensure that g_{max} and the flux accumulation period are identified correctly, and that the method to estimate the extent and influence of soil water potential (SWP) on stomatal conductance (gs) provides realistic values.

Policy implications of overall conclusions

In view of the need to investigate a number of factors relating to the flux-based methods in more depth, it may be considered premature to recommend a protocol for adjustment of the concentration-based results using flux estimates at this time. However, although there are clear differences within climate zones, the results presented here show limited evidence for a systematic difference in the results generated by the two methods at the European level.

In the course of this work an alternative, top-down approach was developed at the University of Reading, though so far this method has been applied only for wheat grown in the UK. This generated roughly 50% lower estimates of damage than those given by either of the methods used here, though given the limited nature of the analysis it is not clear whether the same would be found if the method were applied to other crops, to other countries, or to other years. However, given that all three methods give results of the same order of magnitude, it seems likely that the overall level of damage from direct effects of ozone on yield of (largely) arable crops is in the order of a few €billion across Europe each year.

The methods for cost-benefit analysis of air quality policy used at the end of the 1990s in the development of the Gothenburg Protocol to the Convention on Long-range Transboundary Air Pollution gave an indication of the likely robustness of results, but did not take this through to a quantitative assessment of the impacts of uncertainty on the balance of costs and benefits. However, the analysis reported here and in part for the CAFE programme, demonstrates how quantified uncertainties can be factored into the analysis to describe the probability of benefits exceeding costs.

It is recommended that work in the development of these methods, including the work done at the University of Reading, should be continued. Adding impetus to this recommendation is the possibility for a major increase in background ozone concentrations as a consequence of global warming and increasing ozone precursor emissions (e.g. in Asia) over the next decades.

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Contents

1. Introduction

Emissions of oxides of nitrogen (NOx) and volatile organic compounds (VOCs) have led to a significant increase in concentrations of ozone close to the earth's surface since pre-industrial times. Since the middle years of the last century, ozone has been recognised as being toxic to plants and capable of causing significant losses in crop yield (e.g. Fuhrer and Booker, 2003).

Description of this damage is important as it provides an input to policy makers as they consider by how much emissions of NOx and VOCs should be reduced. Much of the work done to support policy in this area has, however, proceeded only so far as identification of those areas where crops are at the greatest risk of damage through the use of critical levels mapping. From the perspective that the 'best' technologies should be applied for pollution control, the demonstration that there is a risk to crops from ozone might be considered sufficient. However, from the perspective that the costs of pollution control should be balanced by the benefits that pollution abatement brings, it is necessary to go further and to quantify the magnitude of crop losses. Frameworks for cost-benefit analysis of this type are already available in work carried out for the UNECE's Convention on Long-range Transboundary Air Pollution and the European Union's Clean Air For Europe (CAFE) Programme and its Thematic Strategy on Air Pollution (Holland et al., 2004, 2005a, 2005b).

Quantification of crop yield reduction from exposure to ozone has been possible for many years, the earliest European quantification probably being that of van der Eerden et al. (1988). The approach taken there, and in most such exercises since (e.g. Holland et al., 2002), has been a concentration-based approach, using experimentally derived functions that equate yield loss with ozone concentration expressed in various ways. European work has most commonly used the AOT40[1] metric to describe ozone levels. An important problem with the concentration-based approach lies in the fact that ambient air ozone concentration external to the plant and the internal ozone concentrations at sites of damage within the leaf can be very different. For example, under hot and dry conditions, ozone concentrations may be high, but dosage low. This has led to significant concern about the reliability of concentration-based approaches, and a recommendation from some influential bodies that damage assessment beyond an appraisal of areas subject to exceedance of critical levels should not be attempted (LRTAP Convention, 2004).

Recently, significant progress has been made using more sophisticated flux-based methods that better characterise ozone dose. However, flux-based functions are available only for wheat and potato, limiting the use of this approach for a comprehensive assessment of agricultural losses in Europe attributable to ground level ozone.

The objectives of this report are as follows:

1. To describe the uncertainties present in AOT40-based modelling;

[1] AOT40 = ozone Accumulated over a Threshold of 40 ppb in daylight hours over a 3 month growing season, with results expressed in ppm.hours or ppb.hours.

2. To examine the difference between estimates of yield loss made using AOT40-based and flux-based functions

3. To consider how AOT40- and flux-based methods can be combined in the future to enable a reasonably complete estimation of ozone impacts on crop yield in Europe that maximises use of the research that has been carried out in this field.

4. To provide European estimates of the range of expected yield losses under a range of scenarios, taking account of uncertainties where possible.

5. To identify areas for further refinement of the crop loss model.

The following issues **are not** considered in this report:

1. Damage caused by other pollutants, such as SO_2. This seems unlikely to be a major problem in Europe at the present time, given the significant reductions that have been achieved in rural SO_2 levels in recent years across the continent. It does not, however, mean that SO_2 impacts on crops should be ignored in other parts of the world where they may be much more significant.

2. Impacts of ozone through visible injury to crops such as lettuce or spinach, where the appearance of ozone-sensitive organs is a prime determinant of saleability. These impacts have been discussed elsewhere (Holland et al., 2004), where it was concluded that the impact is unlikely to be economically significant at the European scale because of the limited number and total value of crops for which this would seem important. However, there is potential for the impact to be highly significant at the local level, where individual farmers may from time to time experience a substantial loss of income.

3. Impacts of ozone on pest performance. Past work (e.g. Riemer and Whittaker, 1989; Bolsinger and Flukiger, 1989) demonstrated significant differences in pest performance under different ozone regimes. However, in recent years it has been the subject of comparatively little research, at least in Europe.

4. Impacts of ozone on nutritional quality and taste of crops. Again, an area subject to relatively little research. However, the work that has been done (e.g. Muntifering et al., 2000; Powell et al., 2003) suggests that this could be a significant problem that would add to the damage estimates quantified in this paper.

2. Methods

2.1 Overview

The basic AOT40 (concentration)-based method for quantifying effects of ozone on crops across Europe is a simple multiplication:

Change in crop yield value =
Crop yield × ozone AOT40 × response function × monetary value [1]

These parameters are discussed in more detail below, with account taken of the uncertainties that are present. Quantification of impacts and associated uncertainties is provided for 23 crops in 47 countries covering the entire European UNECE domain, based on calculations made using the 50 x 50 km resolution EMEP grid.

The flux-based approach, as described in the Mapping and Modelling Manual (LRTAP Convention, 2004) has been applied for wheat and potato in a limited analysis of five EMEP 50 x 50 km grid cells spread across the five climatic zones of Europe (Table 1). Yield response has also been quantified for these grid cells using the AOT40 approach. Limited resources prevent the flux method being used at a pan-European level at the present time. No flux functions are yet available for quantifying impacts on production of crops other than wheat and potato.

Table 1. Grid references of sites in EMEP grid squares representing the five climate zones in Europe.

Climate zone	Country	Latitude	Longitude
Northern Europe (NE)	Sweden	57^o 54 min N	12^o 24 min E
Atlantic Central Europe (ACE)	UK	55^o 19 min N	3^o 12 min W
Continental Central Europe (CCE)	Germany	52^o 48 min N	10^o 45 min E
Eastern Mediterranean (EM)	Slovenia	46^o 7 min N	15^o 6 min E
Western Mediterranean (WM)	Spain	40^o 26 min N	3^o 42 min W

2.2 Model structure

The analysis uses the following models:

1. The EMEP ozone model for providing estimates of ozone concentrations in Europe under a range of scenarios. This model incorporates a deposition module referred to as the DO_3SE model (**D**eposition of **O**zone and **S**tomatal **E**xchange) which describes the ozone loss from the atmosphere to ground surface sinks and hence provides canopy height ozone concentrations by land cover type (Simpson et al., 2003). For vegetated surfaces, this module includes a stomatal conductance algorithm upon which the stomatal flux model (LRTAP Convention, 2004) is based.

2. The LRTAP Convention (2004) stomatal flux and effect model, which estimates ozone flux to wheat and potato to estimate yield loss. This has been applied to five EMEP grid cells, as just discussed, selected so as to provide coverage within the five climatic regions identified by LRTAP Convention (2004) as described in Table 1.

3. EMRC's CROOZ (CROp-OZone) model in Microsoft Access, which combines ozone concentrations with yield statistics for each EMEP 50x50 km grid cell in the European EMEP domain for a range of scenarios.

4. The CROOZ post-processor, which uses the outputs from the above models to generate estimates of the loss of agricultural production in a range of scenarios. The post-processor uses the @RISK package developed by Palisade Inc., linked into Microsoft Excel. For this analysis, we have used Monte Carlo sampling of all listed uncertainties (see Table 6) over 10,000 iterations to derive mean estimates of damage and associated statistics to describe the range around these means.

2.3 Core inputs to the AOT40 based analysis

Crop yield data on the 50 x 50 km EMEP grid were taken from maps developed at the Stockholm Environment Institute (SEI). An updated land cover dataset used in assessing crop yields was derived by SEI through a merge of the existing SEI European Land Cover dataset (Kuylenstierna et al., 1998) and the European Environment Agency (EEA) Corine 2000 Land Cover dataset. For areas beyond the extent of the EEA dataset, the existing SEI information on the spatial location and classification of agricultural land was combined with the FAO Agrostat database. Crop types were matched to agricultural land cover classes according to the class and percentage of that crop grown in that country. For example, in Austria the relative intensity of wheat, barley, rye and oats production from the Agrostat statistics were assigned to the small grains land cover class. This linkage of the agricultural statistics to the land cover map allowed for the identification of the spatial location of crops and their associated yields. For the extent of the EEA dataset, the SEI land cover information has been merged with the boundaries of the relevant EEA classes to derive an updated distribution of land cover. For example, the EEA class delimiting the extent of fruit and berry production has been merged with the SEI data identifying in more detail the type of fruit production, for example, orchards. For areas where the boundaries of the EEA and SEI maps do not overlap the most probable class from the SEI map has been assigned to the EEA polygon. This process ensures that the extent of the EEA class is maintained whilst allowing the identification of detailed crop distribution information. The merged spatial data has then been combined with the Agrostat data using the methodology detailed above. The spatial and statistical data was finally overlaid with the boundaries of the EMEP grid cells to identify by grid the extent and yields of crops in each grid cell.

Ozone data were obtained as AOT40 from EMEP from a number of the scenarios developed by IIASA (Amann et al., 2005a, 2005b) for the European Commission's CAFE Programme (Table 2). The data obtained are calculated at a height of 3 m and for a growing season from May to July. Information on allocation of countries to different growing seasons is given in Table 3 and the factors used here to convert from the fixed period to the zone specific period are given in Table 4. These factors are based on a limited dataset (one grid cell in each climate zone, see Table 1). An average height correction of a factor 0.7 (range 0.5 to 0.9) is adopted to convert AOT40 at 3 m to AOT40 at canopy height – this is discussed in more detail below in the section on uncertainty. Use of this factor is temporary – future work will be able to use canopy height concentration data directly output from EMEP.

Response functions (Table 5) were derived from analysis of all available data from Europe and the USA (Mills et al., submitted).

Valuation data in the year 2000 prices are also shown in Table 5. These were taken from the FAO website and represent world market prices. Use of world prices partially removes the distortion caused by the Common Agricultural Policy (CAP) in Europe.

Table 2**.** Scenarios for which ozone data has been obtained for this analysis.

CLE_2000_M1997	Baseline emissions, current legislation, year 2000, 1997 meteorology
CLE_2020_M1997	Baseline emissions under full implementation of current legislation, year 2020, 1997 meteorology
MFR_2020_M1997	Maximum feasible reduction in emissions based on measures included in the RAINS model, year 2020, 1997 meteorology
D23_Low	Emission scenario for which human exposure to ozone (SMO35 metric) in the EU25 is reduced by 60% of the gap between CLE_2020 and MFR_2020, year 2020, 1997 meteorology
D23_Med	Emission scenario for which human exposure to ozone (SMO35 metric) in the EU25 is reduced by 80% of the gap between CLE_2020 and MFR_2020, year 2020, 1997 meteorology
D23_High	Emission scenario for which human exposure to ozone (SMO35 metric) in the EU25 is reduced by 90% of the gap between CLE_2020 and MFR_2020, year 2020, 1997 meteorology
D28_2020_MET1997	Similar to D23_low, year 2020, 1997 meteorology, emission scenario for the EU’s Thematic Strategy on Air Pollution.

Table 3. Assumed growing period in each region, used for calculation of corrected AOT40 for each country.

Region	**Three month time period**	**Countries**
Eastern Mediterranean (EM)	1 March to 31 May	Albania, Bosnia and Herzogovina, Bulgaria, Croatia, Cyprus, Greece, FYR Macedonia, Malta, Slovenia, Turkey, Yugoslavia
Western Mediterranean (WM)	1 April to 30 June	Italy, Portugal, Spain
Continental Central Europe (CCE)	15 April to 15 July	Armenia, Austria, Azerbaijan, Belarus, Czech Republic, France1, Georgia, Germany, Hungary, Kazakhstan, Krygyzstan, Liechtenstein, Moldova, Poland, Romania, Russian Federation, Slovakia, Switzerland, Ukraine
Atlantic Central Europe (ACE)	1 May to 31 July	Belgium, Ireland, Luxembourg, Netherlands, United Kingdom
Northern Europe (NE)	1 June to 31 August	Denmark, Estonia, Faeroe Islands, Finland, Iceland, Latvia, Lithuania, Norway, Sweden

Table 4[2]. Factors for converting AOT40 period from the fixed period May to July to the zone specific periods, based on EMEP model outputs for one 50x50 km square in each climate zone using an emission scenario for 2000 with 1997 meteorology.

Zone	**AOT40 (ppm.hours)**		**Dates for variable period**	**Ratio**
	Fixed May to July	**Variable period**		
NE	6.78	8.84	1 June to 31 August	1.30
ACE	7.39	7.39	1 May to 31 July	1
CCE	15.52	14.07	15 April to 15 July	0.91
EM	21.77	10.84	1 March to 31 May	0.50
WM	12.61	10.66	1 April to 30 June	0.85

[2] is based on comparison of AOT40 for different periods at 50 m, and has been used for the quantification in this paper. However, towards the end of the work, after the main analysis had been completed, a comparison was made for the different growing season assumptions based on AOT40 at canopy height. The new factors generated for each region were as follows:

NE = 1.39, implying that the results given here underestimate damage by 6% in the NE region
ACE = 1 (no change)
CCE = 0.96, implying that the results given here underestimate damage by 6% in the CCE region
EM = 0.63, implying that the results given here underestimate damage by 20% in the EM region
WM = 0.68, implying that the results given here overestimate damage by 25% in the WM region

These factors can be integrated into future analysis. For the purposes of this report, however, the pattern of under- and over-estimation between regions is such that the total European damage estimates that would be calculated with these revised factors are probably very close to those given here.

Table 5. Response functions with standard errors and other statistics relevant to their derivation, and valuation data, for each crop included in the analysis.

Crop	No. of data points	No. of cultivars	No. of climate zones	Function, % yield change /ppm.h	Standard error	Value, €/tonne
Barley	47	6	4	0	-	120
Carrot	-	-	-	0.0065	Note 1	340
Cotton	17	5	1	0.016	0.0027	1350
Fruit	12	3	2	Note 2	-	680
Grape	4	1	1	0.00301	0.00131	360
Hops	-	-	-	0.0065	Note 1	4100
Maize	19	1	1	0.00363	0.0012	100
Millet	-	-	-	Note 2	-	90
Oats	-	-	-	Note 2	-	100
Olives	-	-	-	Note 2	-	530
Potato	21	3	4	0.00539	0.0036	250
Pulses	43	10	3	0.0165	0.0039	320
Rapeseed	23	2	2	0.0056	0.0027	240
Rice	32	6	2	0.00386	0.0014	280
Rye	-	-	-	Note 2	-	80
Soya	51	7	1	0.0115	0.0013	230
Sugar beet	14	5	2	0.0058	0.0025	60
Sunflower	-	-	-	0.0065	Note 1	240
Tobacco		1	1	0.00554	0.0015	4000
Tomato	39	14	3	0.00845	0.00147	800
Vegetables	-	-	-	0.0065	Note 1	340
Watermelon	4	1	1	0.0321	0.00595	140
Wheat	65	9	4	0.0161	0.000808	120

Note 1: No data are available for carrot, hops, sunflower seeds and other vegetables. For these crops,. the best estimate of the function is calculated as the average of functions for all other crops (including those regarded as insensitive to ozone). A triangular distribution is assumed, spanning the range of functions for other crops (0 to 0.0321). Note 2: Available information suggests that these crops are not sensitive to ozone.

3. Uncertainties present in the AOT40 analysis

3.1 Methods of establishing uncertainties

Although simple in outline, each element of the equation given above (Equation 1) is associated with its own range of uncertainties. These are summarised in Table 6.

Table 6. Uncertainties in yield loss modelling using AOT40 relationships. Shading highlights the uncertainties that are not accounted for in this paper.

Factor	Uncertainty	How uncertainty is accounted for
Crop production	Variability between years	Use of average production statistics for each crop in each country over a 5 year period from 1997 to 2004
Ozone concentration	Variability between years	Modelled concentration data from EMEP is available only for 1997 for all scenarios. However, one scenario has been run for several years, and variability in AOT40 has been assessed from these runs.
	Variation in ozone concentration with height	Can be accounted for directly using factors to adjust EMEP AOT40 estimates at 3 m to crop height. Future EMEP results will be based on canopy height AOT40, eliminating the need to account for this factor.
	Uncertainty through varying specificity of period for which ozone data are available compared to growing season of specific crops	Use of ranges based on variation in modelled estimates of AOT40 over different periods
	Uncertainties in modelling ozone concentrations	EMEP model is partially validated against monitored data, limiting the potential for error. However, errors remain that are not accounted for in this paper.
Response function for $crop_x$	Experimental variability	Use standard errors of the response function slope
	Variability between cultivars	Factor derived from examination of results for wheat
	Variability between experiments	Factor derived from examination of results for wheat
	Variability between climate zones	Factor derived from examination of results for wheat
	Effects of ozone on visible injury, food quality and pest performance	Not accounted for
Valuation of crop losses	Variation in crop price	Average world prices used with range based on price variations 1997 – 2001
	Lack of account of changes in type and quantity of each crop grown as a result of ozone-yield effects	It is questionable whether ozone impacts are sufficiently consistent and large to cause a change in cropping patterns. In the absence of detailed information this is not accounted for.

A detailed review of the likely magnitude or spread of most of these uncertainties follows. In two areas, we currently feel unable to pass judgement on the size of uncertainties, these relating to the general level of uncertainty in the EMEP ozone model and the potential for farmers to mitigate damage by planting more ozone resistant crops or crop varieties. For reasons given below, we do not believe these uncertainties to be critical to the analysis. However, it seems preferable in this report to highlight the fact that they are not quantified, than to speculate on their size.

For all uncertain or variable parameters, distributions need to be defined in terms of:

1. Most probable estimate
2. Their shape
3. Their spread.

Here, we have considered using three alternative shapes for the distributions of each of the parameters listed in Table 6, normal, triangular, and uniform (where each value within the range has an equal probability). The normal distribution is used only for the response functions, as these are calculated using information on the standard error of the slope. In all other cases we have used a triangular distribution, where the range defines absolute lower and upper boundaries. The uniform distribution has not been used as we prefer to accept the best estimates as a more likely position for each parameter than the extremes of the ranges. Routine use of the normal distribution (in place of the triangular distribution preferred here for most variables) risks giving an impression that we have more detailed information than is available.

3.2 Uncertainties due to crop production

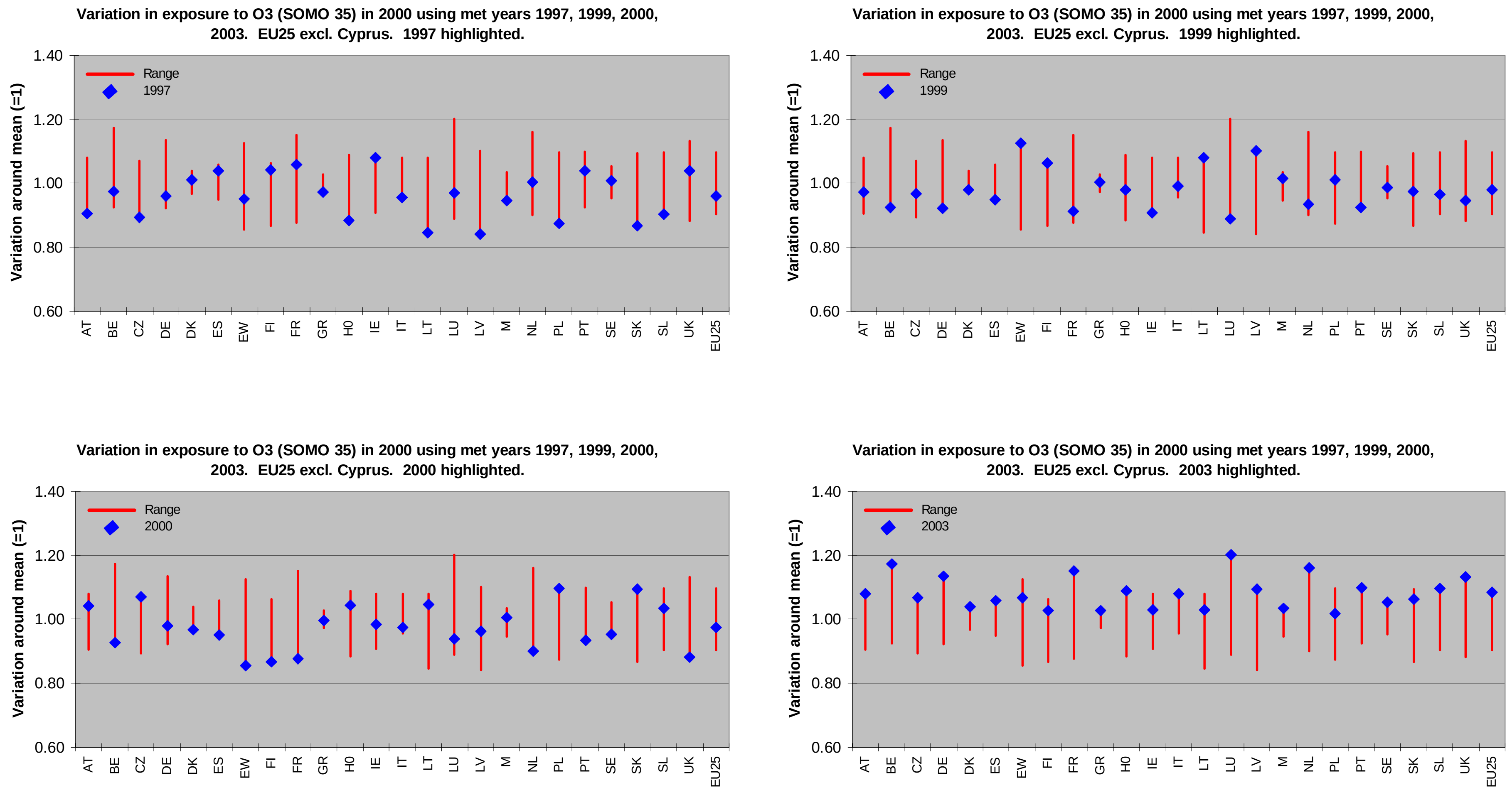
Crop production statistics from the FAO (Food and Agriculture Organisation of the United Nations) have been examined. They imply a variation in yield year on year of up to 20%. The best estimate is taken as the average of 5 years between 1997 and 2004 (the precise years considered depending on the availability of statistics for each country).

3.3 Uncertainties due to ozone concentration

3.3.1 Variability between years

The cost-benefit analysis of the Clean Air For Europe Programme (Holland et al., 2005a, 2005b) considered this source of uncertainty, relative to forecasts made by the EMEP model, in some detail in relation to the metric SOMO35 (sum of mean ozone over 35 ppb). Although used for human health assessment, the variation in SOMO35 between years should be similar to AOT40, as the difference in concentration threshold is only 5 ppb. The main concern for the comparison is that SOMO35 is aggregated over the full year rather than just the growing season.

Figure 1 shows variation in SOMO35 exposure in each Member State of the European Union, as calculated by EMEP using an emission scenario for the year 2000 with meteorology data for 1997, 1999, 2000 and 2003 (the emission scenarios analysed below only use results based on the 1997 meteorology year). Results for each year are shown relative to the average of the four meteorology years which is normalised to one. The red bar shows the spread of results for each country, whereas the blue point shows the position of each year within the range. The top left graph shows that 1997 under-predicts average ozone exposure across the EU25 by on average about 5%: for this reason a factor of 1.05 has been introduced to bring results in the present analysis, overall, up to an average level. For a number of countries, it is the year with the lowest SOMO35 of the four. For Spain, Finland and Ireland, however, it was the year with the highest SOMO35. A range of ± 15% with a triangular distribution has been selected around the best estimate to account for the observed variation.



<u>Figure 1</u>. Sensitivity to choice of meteorological year with respect to human ozone (SOMO 35) exposure in 1997, 1999, 2000 and 2003.

3.3.2 Variation with height

There is a steep gradient in ozone concentrations close to the surface, requiring that ozone concentrations above the canopy are reduced by some factor in order to more accurately describe crop exposure. The uncertainty associated with this procedure is compounded by the use of the 40 ppb threshold for the AOT40 based analysis. In absolute terms, a 10% over- or under-estimation of canopy level ozone concentration is not great, but it can make a large amount of difference once a threshold is introduced (e.g. Tuovinen, 2000).

Analysis using EMEP ozone model outputs provided both at the planetary boundary layer (i.e. approximately 50m above ground surface) and at canopy heights (assumed 1m above surface) allows quantification of the difference between ozone concentrations and AOT40s calculated at these different heights. These calculations were made for the five grid cells for which EMEP output data were provided (see Table 1). Ratios of canopy height to 50m ozone ranged from 0.79 to 0.86 before account is taken of the 40 ppb threshold. These values are lower than the 0.88 factor given in the Mapping Manual due to less conservative assumptions made in DO_3SE module embedded in the EMEP ozone model about the strength of the canopy as an ozone sink. The Mapping Manual method assumes a constant f_{phen} of 0.6 thus reducing the flux to the crop in comparison to the DO_3SE-calculated O_3 gradients in which f_{phen} will reach 1 over the growth period. As such, the O_3 sink offered by the Mapping Manual method will tend to be lower than that estimated using the full DO_3SE model and result in reduced O_3 loss from the atmosphere to the vegetation and hence a higher O_3 canopy concentration.

The EMEP outputs used for the European scale quantification given here provide estimated ozone concentrations at 3m. In future it will be possible to use EMEP estimates for canopy height AOT40. In the meantime, for this analysis the best estimate for the 3m to canopy height correction factor is taken to be 0.7 in a range of 0.5 to 0.9, based on outputs from the EMEP model.

3.3.3 Variation in growing season for each crop

The analysis to this point has accounted for variation in the growing season in different parts of Europe (Tables 3 and 4), but not for the likely variation in growing season within each region for individual crops. Analysis of variation of the growing season by 2 weeks in either direction shows that this uncertainty is of the order ±10% (Table 7). A triangular distribution is again assumed. It is to be noted that these growth period-related accumulation periods are based on wheat only. Other crops may well have rather different growth periods, both in terms of length and positioning within the year. Full analysis of this was outside the scope of the current project but should be considered in future assessments.

Table 7. Difference (expressed as a ratio of the canopy height AOT40 calculated using climate specific growth periods) resulting from varying the assumed growing season by 2 weeks in either direction.

Zone	AOT40, season starting 2 weeks earlier	AOT40, season starting 2 weeks later
NE	0.79	0.95
ACE	1.09	1.18
CCE	0.92	1.05
EM	0.80	1.20
WM	0.97	1.10
Mean	**0.92**	**1.10**

3.3.4 Uncertainty in the EMEP model

An assessment of the general reliability of the EMEP model is not accounted for in this analysis. There is limited information available from EMEP addressing uncertainty in model estimations.

3.4 Uncertainty within the response functions

There are several factors that will cause variation in experimental results for yield response to ozone for any individual crop. These include:

- Routine variation between experiments;
- The sensitivity of the cultivar selected for the experiment;
- The weather in the year in which the experiment was conducted;
- Other factors (prevalence of pests and pathogens).

Consideration has been given to accounting for each of these factors separately. However, as this would risk double counting errors it is more appropriate to seek to develop an overview of the likely uncertainty associated with them collectively.

For crops for which a large amount of experimental data are available from several locations (e.g. wheat, tomato, soya – see Table 5) the overall slope and its standard error should already take account of these variations. However, this is clearly not the case for crops where response is based on a very limited number of experiments (e.g. watermelon and grape).

An indication of the potential unreliability of response functions drawn from a limited amount of data can be drawn from inspection of the different slopes derived from individual experiments on a crop for which a large number of experiments have been performed. Figure 2 plots the slopes from 15 experiments carried out on wheat using data from Fuhrer et al. (1997) and Gelang et al. (2000). These data were used also in LRTAP Convention (2004, Figure 3.4, p.III-12). Data shown are taken from experiments in Switzerland (CH), Sweden (S), Denmark (DK), the USA (US) and Finland (FIN). In total, nine cultivars are represented in these experiments, Abe, Albis, Arthur, Drabant, Dragon, Echo, Ralle, Roland and Satu. Two additional slopes are plotted, one based on regression of 'all data', and the other using the average of the 15 experimental slopes and intercepts. The figure extrapolates in several cases well beyond the concentration range used experimentally. Of the 15 experiments considered, only five considered concentrations beyond 20 ppm.hours, whilst six did not consider concentrations beyond 10 ppm.hours. This explains why the figure shows far more scatter than is apparent in Figure 3.4 from LRTAP Convention (2004). However, the figure is valid for the purpose to which it is put here: demonstrating the variability in slopes estimated using different experimental materials and conditions.

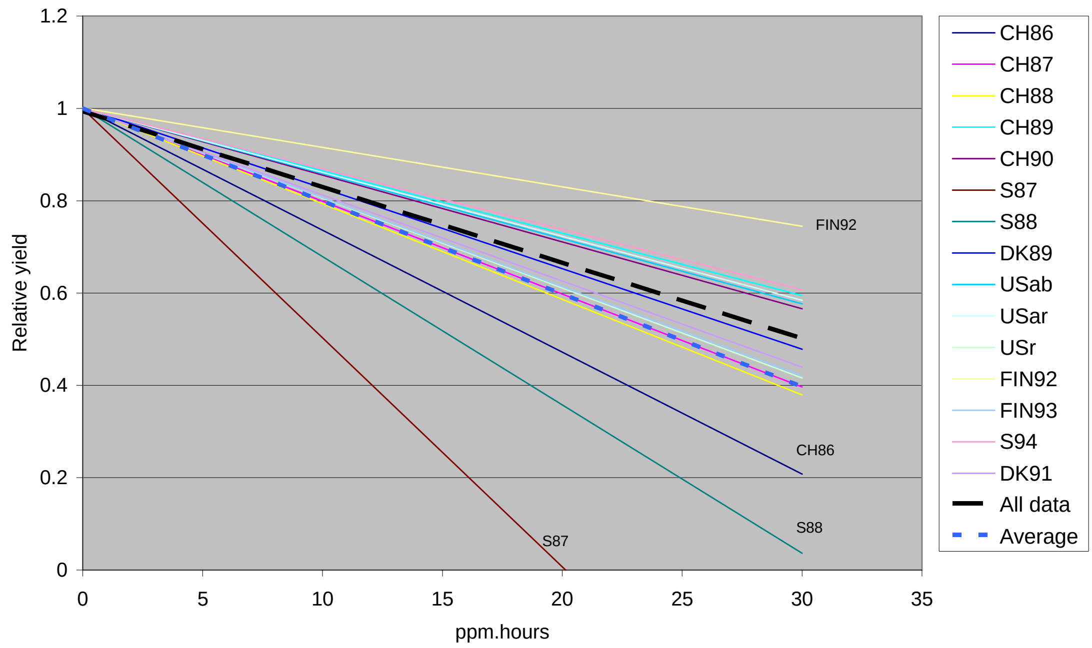


Figure 2. Comparison of different slopes showing yield response to ozone, obtained from regression analysis of the results of 15 different experiments on wheat. The key shows country and year for each experiment. For illustration purposes, all regressions are extrapolated to 30 ppm h, well beyond the range of data for the following experiments: Maximum AOT40 below 10 ppm h at S87, S88, B91 & FIN91 and between 10 and 20 ppm h at DK89, FIN92, FIN93, S94, DK91.

There is quite strong clustering of results at an exposure of 30 ppm.hours between a relative yield of 0.6 and 0.4. However, four country/year combinations are significantly outside this range:

- S87 and S88, both for the cultivar Drabant grown in Sweden
- CH86 for the cultivar Albis, grown in Switzerland;
- FIN92 for the cultivar Satu, grown in Finland.

There is some consistency within cultivars. Both sets of results for Drabant show a high sensitivity. Results for Albis in CH87 and CH88 are both towards the lower end of the central group and hence not far removed from CH86. For Satu, however, the difference between experiments is large, with a reduction of 25% using results from FIN92 compared to nearly 60% based on FIN93. Such differences may be related to differential uptake of ozone in the two years which would be accounted for using a flux-based index rather than AOT40.

The overall range at 30 ppm.h ozone exposure is predicted to cause a loss of wheat of between 25% and 100%, depending on which set of experimental data is used, around a best estimate from the "all data" slope of 50%. This demonstrates the potential for significant error in quantifying the response of crops for which there is limited experimental data. In these cases the standard error of the slope will not provide robust guidance on the potential distribution of the response function, and an additional uncertainty should be added. It is then necessary to ask for which crops adjustment to the range of the response function is needed. Based on the information presented in columns 2 to 4 of Table 5, we set the dividing line according to the following criteria:

1. >5 cultivars tested
2. Experiments conducted in >2 climate zones
3. >20 data points available.

The following crops regarded as ozone sensitive meet two or more of these criteria: potato, pulses, rice, soya, tomato and wheat. For these crops, we accept the standard error of the slope as given in Table 5 as a reasonable estimate of the uncertainty in the response function.

Cotton, grape, maize, rapeseed, sugar beet, tobacco and watermelon meet less than two of the criteria. For these crops we inflate the range around the slope to ±75%, broadly in line with the range shown in Figure 2.

As noted below Table 5, we have no data for carrot, hops, sunflower seed and 'other vegetables'. An option would be to ignore these crops from the analysis. Given that this would generate a systematic bias to underestimation we prefer to include them. The response function in each case is taken as the average of all other crops (including those regarded as insensitive). A triangular distribution is adopted for the response function for each of these crops going from 0 (i.e. insensitive) to the slope for watermelon (the most sensitive of the crops that have been tested).

A number of crops – barley, fruit, millet, oat, olive and rye – are regarded as insensitive to ozone, though only for barley is there sufficient data to be truly confident in this conclusion. Further account of uncertainty in this assumption is not taken.

3.5 Uncertainty due to valuation

3.5.1 Variation in crop price

Variation in crop price has been accounted for through inspection of price data on the FAO website (http://www.fao.org/). For the period 1997 to 2002, there was some upward movement in prices, but this is masked by year to year variation in supply. A triangular distribution of range ±10% has been taken. It is assumed that this correlates negatively with crop yield (i.e. that prices are high when supply is low and vice versa). This will cause these uncertainties to cancel out to a significant degree.

3.5.2 Changing cropping patterns in response to ozone impacts on yield.

This is not accounted for in the present analysis. It is not clear that the effect is significant for policy relevant incremental changes in concentration.

3.6 Grid systems

In the course of the work we became aware that there exists the ‘official’ EMEP grid on a 50 × 50 km scale, and a different version used for the EMEP model. The two should be made consistent as the difference clearly increases the potential for error when using model outputs, or trying to correlate mapped pollution data with other mapped data.

3.7 Summary of uncertainty factors

The information given above on uncertainty factors is summarised in Table 8. In cases where a best estimate is provided either in the table or elsewhere in this report, parameters are entered to the Monte-Carlo analysis using dummy variables with a best estimate of 1 and the ranges around 1 as shown.

Table 8. Summary of uncertainty information.

Factor	**Source of uncertainty**	**Range**	**Shape of distribution**	**Source**
Crop yield	Variability between years	± 20%	Triangular. Negatively correlated with crop price.	FAO website
Ozone concentration	Variability between years	± 15%	Triangular	EMEP outputs
	Variation in ozone concentration with height	Best estimate of ratio between AOT40 at canopy level and 3 m = 0.70, in a range of 0.5 to 0.9 (i.e. ± 30%)	Triangular, skewed right	Inferred from DO_3SE model outputs.
	Uncertainty in growing season for each crop	± 10%	Triangular	Table 4
	Uncertainties in modelling ozone concentrations	Not accounted for		
Response function for $crop_x$	Observed experimental variability	Specific to each crop	Normal, except for crops with functions based on average of others	(see Table 5 and text)
	Variability in experimental response between cultivars, geographic zones, experimental years	Included in SE of slope for some crops. SEs expanded for crops where function is based on limited data.	As previous row	See text surrounding Figure 2
Valuation of crop losses	Variation in crop price	± 10%	Triangular. Negatively correlated with crop yield.	FAO website
	Lack of account of changes in type and quantity of each crop grown as a result of ozone-yield effects	Not accounted for	Questionable whether ozone impacts are sufficiently consistent to cause a change in cropping patterns	

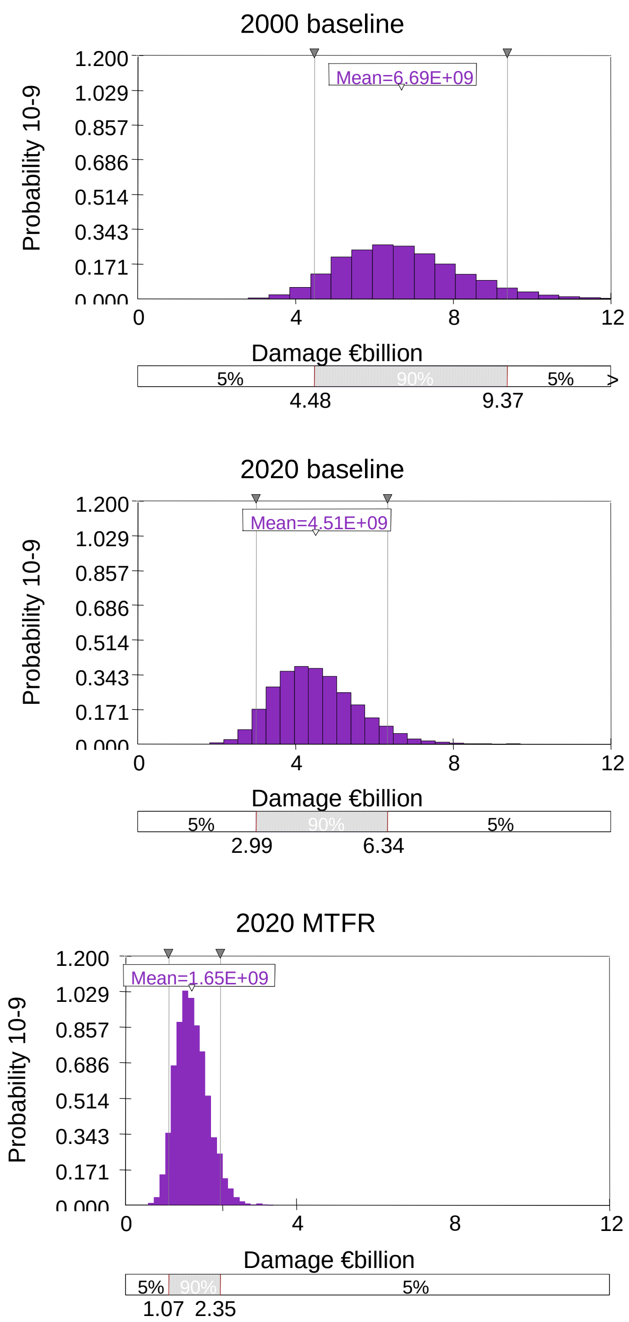
4. Estimates of crop loss and associated uncertainty in Europe

4.1 Uncertainty analysis around the AOT40 results

Probability distributions for total damage under each scenario are shown in the figures that follow. Scales are consistent throughout. The Thematic Strategy scenario is not shown – this gives a result almost indistinguishable from D-23 low (Figure 3d). Distributions are skewed left as a result of the multiplicative nature of the analysis.

For guidance, each figure shows the following. At the bottom of each graph a bar identifies the 90% confidence interval. In the first figure, giving results for the year 2000, this goes from €4.20 to 9.76 billion/year. The graph is labelled to show the mean value (here, €6.71 billion/year), whilst the bars in the graph show the probability of values within the overall range which goes from around €3.5 to 12 billion/year. As ozone concentrations fall, damage naturally reduces also. Although the range shown in each successive figure contracts, there is a reasonably consistent factor of -33% to go from the core estimates to the lower 5%iles, and a factor of +40% to go to the upper 5%iles. These factors can be applied more widely to the core estimates for each scenario that follow.

A limited supplementary analysis suggests that the -33% to +40% range for the 90% confidence interval applies to individual countries as well as the whole of Europe. For individual crops, however, the range can be broader around the best estimate, around a factor of 2.



<u>Figure 3a, b, c.</u> Total damage in the 2000 and 2020 baseline scenarios and the MFR scenario, with range defining 90% confidence interval.

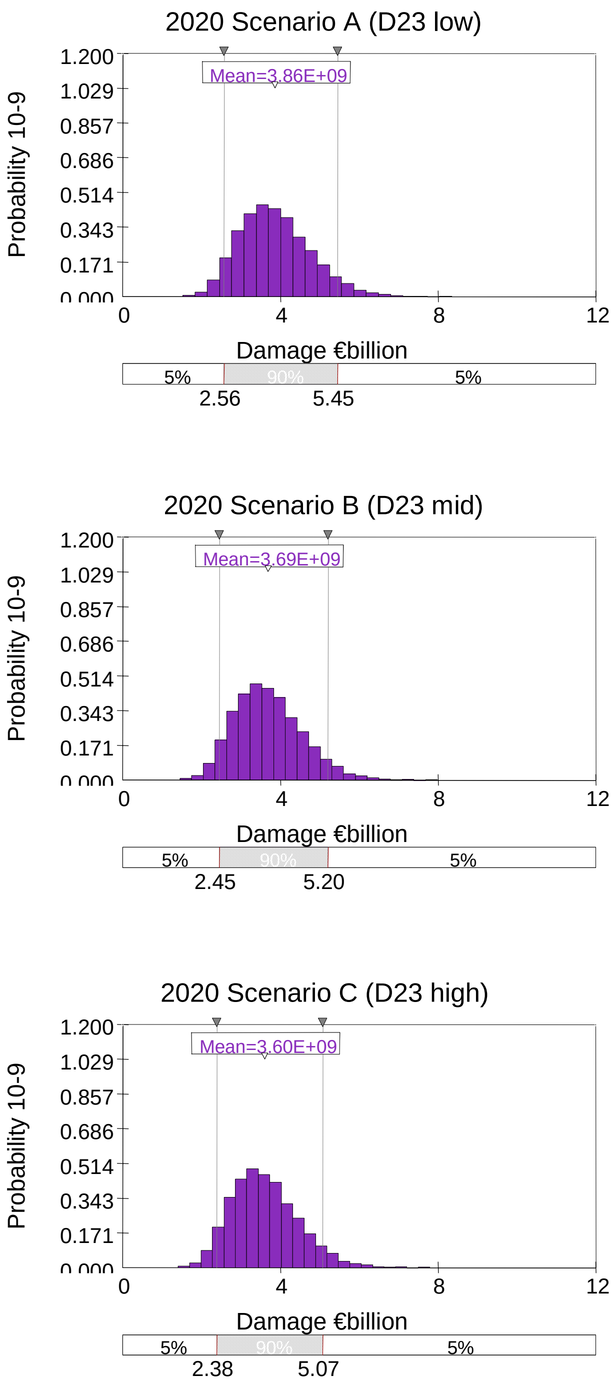


Figure 3d, e, f. Total damage in the 2020 D_23 series scenarios that were used in the development of the EU's Thematic Strategy on Air Pollution.

Figure 4 identifies the factors that most contribute to uncertainty in the AOT40 analysis. The figure has been generated within the @RISK model, which runs a regression where each iteration represents an observation. The dependent variable here is total annual ozone damage, and the independent variables are each 'random' @RISK function in the spreadsheet covering the distributions of input variables for response functions, valuations, annual variability in crop yield and ozone concentration, etc.

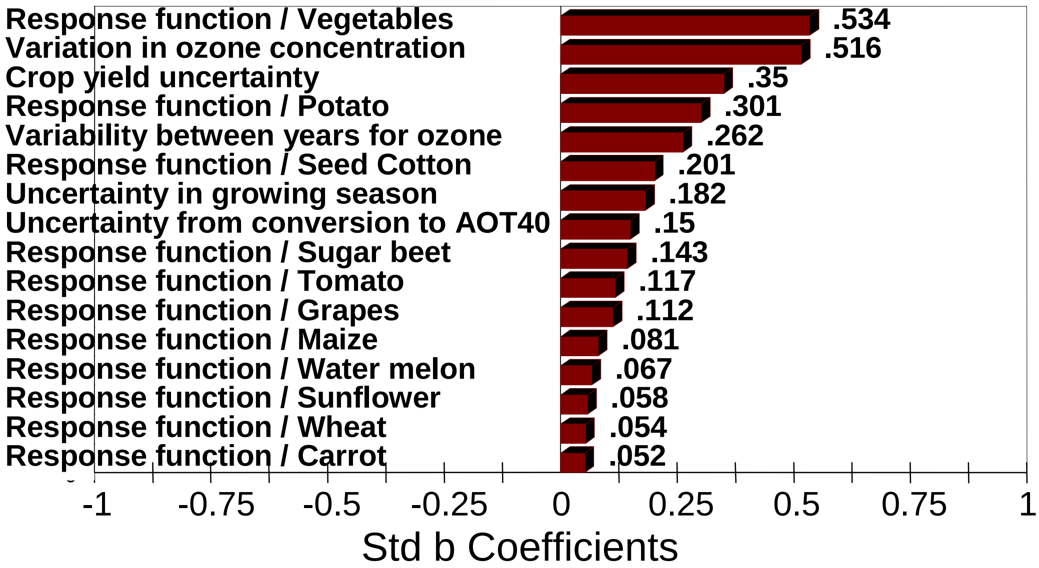


Figure 4. Contribution of the leading variables to uncertainty in the final results for the 47 countries considered in the analysis, referenced to the standardised (beta-weight) coefficient.

Figure 4 shows the response of total yield loss to a change in each input variable. Hence if the response function for vegetables were to increase by 1 standard deviation, total damage would increase by 0.534 standard deviations. According to the inputs used here, the five most critical factors are:

1. The response function for vegetables;
2. The factor for converting ozone at 50 m to ozone at canopy height;
3. Uncertainty in crop yield;
4. The response function for potato;
5. Variability between years for ozone.

[2], [3] and [5] are particularly important as they are applied to all crops. [1] and [4] are important because they address uncertainty in the response function for two of the four crops that generate the largest damage (the others being tomato, which ranks 11th in the list in Figure 4, and wheat, which ranks 15th).

4.2 Direct estimates from the AOT40 approach

A full set of the core estimates from the AOT40 analysis is given in Appendix 1 for the 7 scenarios considered in this report (see list in Table 2). To save space we have not provided a confidence interval for each estimate, but the information provided in the previous section applies also for the pan-European estimates. Results for individual crops will be subject to a differing level of uncertainty, but generally the 90% confidence interval should be within a factor 2 of the core estimates shown.

An overview of the results is shown in Table 9, which finds total damage across the region studied according to the AOT40 method of around €6.7 billion per year in 2000 with a 90% confidence interval of €4.4 to 10 billion/year. The core estimate falls by €2.2 billion/year between 2000 and 2020 (Table 10). Beyond that point, we estimate that, according to the AOT40 method, there is potential for a further saving of around €2.9 billion/year if all measures contained in the RAINS model database were implemented in the EU25 (see the result for the MFR – Maximum Feasible Reduction – scenario). Analysis adopting RAINS MFR in all countries has not yet been undertaken. Results for 2000 imply a loss of 3% of the crop species considered, whilst results for 2020 see this fall to about 2% of the European production of these crops.

Table 9. Total damage to the crops considered across the 47 countries considered in the analysis. Units: €billion/year.

Scenario	**Core**	**90% confidence interval**
2000	6.7	4.5 – 9.3
2020 baseline	4.5	3.0 - 6.3
D_23 low (CAFE programme scenario)	3.9	2.6 - 5.4
D_23 mid (CAFE programme scenario)	3.7	2.4 - 5.2
D_23 high (CAFE programme scenario)	3.6	2.4 - 5.1
Maximum Feasible Reduction according to the RAINS model	1.7	1.1 - 2.3
EU's Thematic Strategy on Air Pollution	3.9	2.6 - 5.5

Table 10. Incremental damage between combinations of scenarios. Units: €billion/year.

	47 countries
2000 to:	
2020 baseline	2.2
2020 baseline to:	
D_23 low	0.65
D_23 mid	0.82
D_23 high	0.91
MFR	2.9
EU's Thematic Strategy	0.64

The split of results between different crops for the 2020 baseline scenario is shown in Figure 5. This shows that the largest damages are forecast to accrue to wheat, then vegetables, then tomatoes and then potatoes. Together, these four crops contribute over 70% of the total damages. Results for other scenarios show a similar pattern.

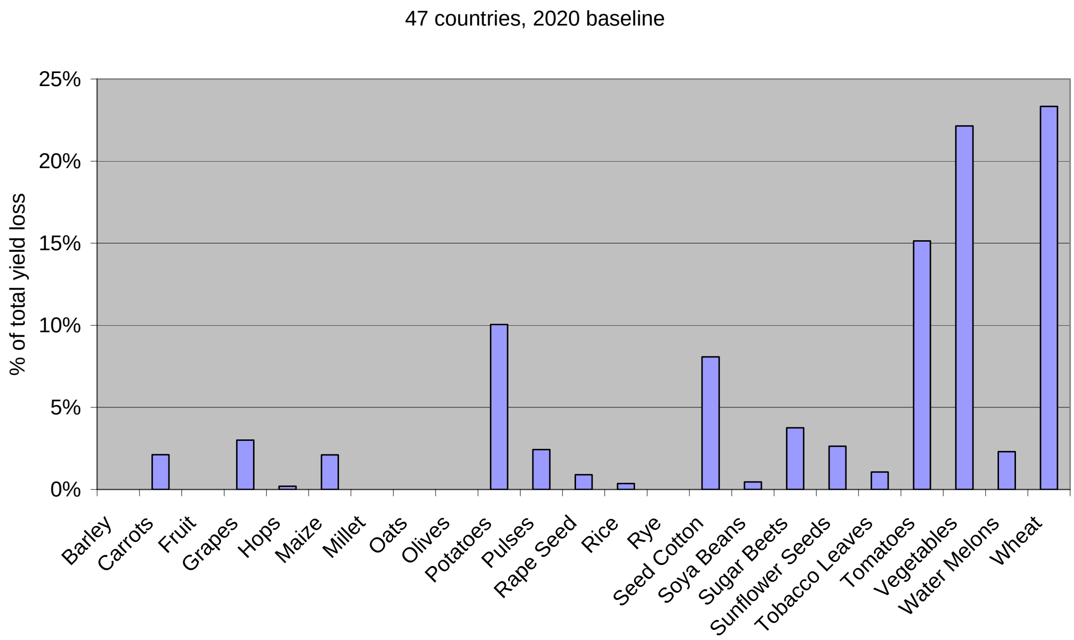


Figure 5. Percentage of loss attributable to each crop in the baseline scenario for 2020, assuming full implementation of current legislation.

The results for tomato and vegetables require further consideration. In the case of tomatoes there is the problem that most of the production may be in glasshouses or under cover of some sort where ozone concentrations are significantly lower than in the ambient atmosphere. Table 11, however, shows that tomatoes contribute more than 10% of all quantified crop loss to ozone in only one northern European country, the Netherlands. Much of the southern European tomato production may be in the open air and/or during the winter months. The overall results may therefore not be too seriously biased, though this issue should be reviewed in the future.

The situation is also complex for vegetables, as this is of course a broad category containing crops of varying sensitivity. Lost production of vegetables accounts for >10% of total losses in all but 4 of the 32 countries considered. In some countries a significant part of vegetable production may occur under glass or other cover where ozone concentrations are low, providing a source of bias in the results for vegetable production. Damage to vegetables will need to be analysed in greater detail in future work.

Damages estimated for each country are shown in Table 13 and for the 2020 baseline scenario in Figure 6. Damage is forecast to be highest in Italy, then France, Germany, Spain, Romania and Greece.

Table 11. Tomato yield loss as a % of total yield loss in each country. Grey highlighting denotes country/scenario combinations where tomatoes contribute more than 10% of damage.

Year	**2000**	**2020**	**2020**
Scenario		**CLE**	**MFR**
Albania	25%	25%	25%
Armenia	31%	30%	30%
Austria	2%	2%	2%
Azerbaijan, Republic of	19%	20%	16%
Belarus	4%	4%	4%
Belgium	9%	9%	9%
Bosnia and Herzegovina	5%	5%	5%
Bulgaria	14%	13%	15%
Croatia	7%	7%	7%
Cyprus	28%	28%	26%
Czech Republic	1%	1%	1%
Denmark	1%	1%	1%
Estonia	2%	2%	2%
Faeroe Islands	0%	0%	0%
Finland	6%	6%	6%
France	4%	4%	4%
Georgia	24%	24%	24%
Germany	0%	0%	0%
Greece	20%	20%	20%
Hungary	6%	6%	6%
Ireland	2%	2%	2%
Italy	37%	37%	37%
Kazakhstan	8%	8%	8%
Latvia	2%	2%	2%
Liechtenstein	0%	0%	0%
Lithuania	0%	1%	0%
Luxembourg	0%	0%	0%
Macedonia, FYR	19%	18%	19%
Malta	31%	31%	31%
Moldova, Republic of	9%	9%	10%
Netherlands	12%	13%	13%
Norway	4%	4%	4%
Poland	3%	3%	2%
Portugal	43%	41%	40%
Romania	12%	14%	12%
Russian Federation	8%	8%	7%
Serbia and Montenegro	8%	8%	8%
Slovakia	6%	6%	7%
Slovenia	2%	2%	2%
Spain	26%	26%	26%
Sweden	3%	4%	5%
Switzerland	5%	5%	5%
Turkey	24%	24%	24%
Turkmenistan	2%	2%	1%
Ukraine	8%	8%	9%
United Kingdom	1%	1%	1%
Uzbekistan	8%	8%	8%

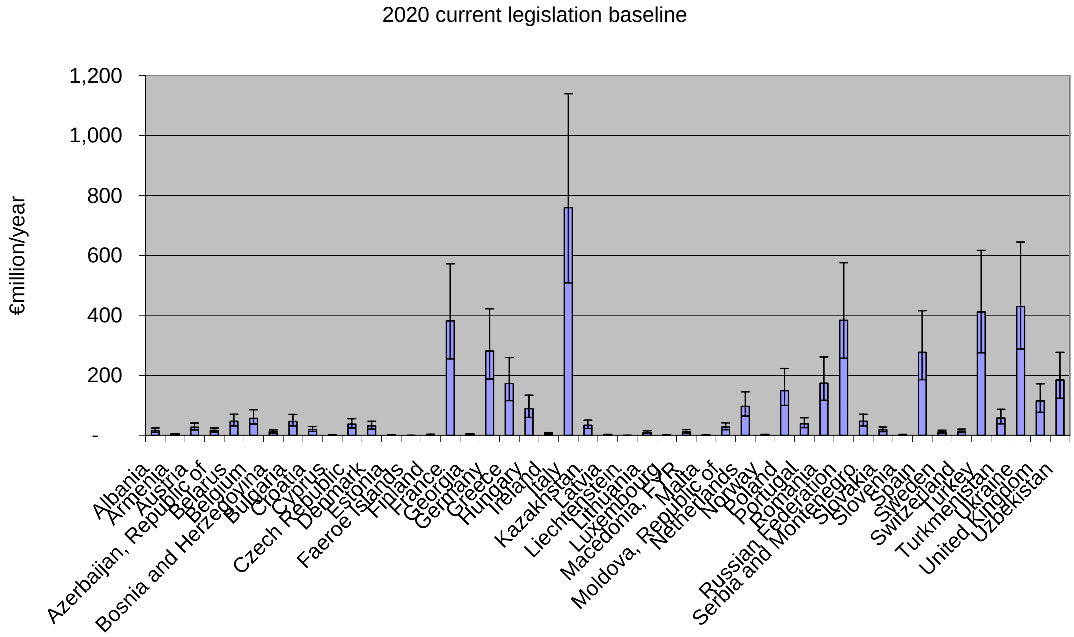
Table 12. Vegetable yield loss as a % of total yield loss in each country.

Shading denotes country/scenario combinations where vegetables contribute more than 10% of damage.

Year	**2000**	**2020**	**2020**
Scenario		**CLE**	**MFR**
Albania	21%	21%	21%
Armenia	32%	32%	32%
Austria	21%	22%	21%
Azerbaijan, Republic of	17%	18%	15%
Belarus	25%	24%	25%
Belgium	32%	33%	34%
Bosnia and Herzegovina	60%	61%	61%
Bulgaria	17%	16%	18%
Croatia	20%	20%	19%
Cyprus	26%	26%	29%
Czech Republic	9%	10%	11%
Denmark	6%	6%	6%
Estonia	18%	18%	18%
Faeroe Islands	0%	0%	0%
Finland	14%	14%	13%
France	20%	20%	20%
Georgia	31%	30%	30%
Germany	16%	16%	17%
Greece	11%	11%	11%
Hungary	23%	23%	22%
Ireland	22%	22%	22%
Italy	26%	26%	26%
Kazakhstan	14%	14%	15%
Latvia	19%	19%	21%
Liechtenstein	0%	0%	0%
Lithuania	20%	24%	7%
Luxembourg	26%	26%	26%
Macedonia, FYR	27%	27%	27%
Malta	50%	50%	50%
Moldova, Republic of	16%	16%	16%
Netherlands	39%	40%	41%
Norway	22%	22%	22%
Poland	28%	28%	26%
Portugal	30%	28%	28%
Romania	29%	33%	29%
Russian Federation	28%	27%	22%
Serbia and Montenegro	18%	18%	17%
Slovakia	15%	16%	17%
Slovenia	18%	18%	19%
Spain	31%	31%	31%
Sweden	8%	8%	7%
Switzerland	21%	22%	21%
Turkey	20%	20%	20%
Turkmenistan	1%	1%	1%
Ukraine	19%	19%	22%
United Kingdom	14%	14%	13%
Uzbekistan	8%	8%	8%

Table 13. Damages (€million/year) estimates in each country for 4 of the 7 scenarios considered. Results for all 7 scenarios are given in Appendix 1,Table 17. A 90% confidence interval of -33% to +40%. Of the best estimate is recommended.

	2000	**2020**	**2020**	**2020**
Scenario		**CLE**	**MFR**	**EU TSAP**
Albania	22	17	5	14
Armenia	4	4	2	4
Austria	64	27	9	20
Azerbaijan, Republic of	14	17	8	16
Belarus	53	47	2	43
Belgium	88	57	37	49
Bosnia and Herzegovina	19	12	3	10
Bulgaria	75	47	8	42
Croatia	32	20	5	17
Cyprus	3	2	0	2
Czech Republic	95	37	13	27
Denmark	56	31	12	25
Estonia	1	1	0	1
Faeroe Islands	0	0	0	0
Finland	6	3	0	2
France	738	381	159	275
Georgia	3	4	1	3
Germany	599	281	133	217
Greece	247	173	52	151
Hungary	188	90	20	69
Ireland	11	6	3	5
Italy	1,260	759	358	626
Kazakhstan	24	34	23	34
Latvia	4	2	0	2
Liechtenstein	0	0	0	0
Lithuania	16	10	1	8
Luxembourg	2	1	0	1
Macedonia, FYR	17	13	3	11
Malta	1	1	0	1
Moldova, Republic of	34	28	3	26
Netherlands	155	97	64	84
Norway	4	2	1	2
Poland	340	149	34	111
Portugal	55	39	20	30
Romania	258	174	30	160
Russian Federation	274	384	36	374
Serbia and Montenegro	70	47	8	41
Slovakia	46	19	5	13
Slovenia	5	3	1	2
Spain	463	277	131	202
Sweden	21	12	3	9
Switzerland	31	14	6	11
Turkey	521	411	116	392
Turkmenistan	46	58	57	58
Ukraine	432	430	29	406
United Kingdom	163	115	65	97
Uzbekistan	150	185	185	185
Totals				
EU25	4,625	2,573	1,123	2,028
All 47 countries	6,708	4,520	1,653	3,876



<u>Figure 6</u>. Damage by country for the 2020 baseline scenario.

5. Comparison of results from AOT40- and AF_{st}6-based methods

5.1 Theoretical considerations

The intention of this part of the project was to investigate the use of flux-based yield loss assessment methods to indicate how concentration- (i.e. AOT40) based methods could be adapted for "dose modifiers". Here, the rationale is that the concentration based dose-response relationships derived from chamber experiments would provide information on risk under conditions tending towards the optimum for ozone uptake. Such a situation occurs for two main reasons. Firstly, the plants were kept well watered in the experiments so soil drought would not be expected to occur and hence stomatal conductance would not be limited by reduced soil water potentials. Secondly, exposure experiments increase ozone levels whilst maintaining ambient environmental conditions (though it is recognised that experimental chambers will cause some modification to the microclimate of the experimental plants). As such, the artificially high ozone concentrations occur experimentally under conditions that might be considered more optimum for uptake than might be expected to occur during real ozone episodes in the field where elevated ozone will tend to co-occur with conditions that would be expected to limit uptake (e.g. high atmospheric and soil water deficits, high temperatures and lower atmospheric mechanical turbulence). The use of the flux-based approach, which incorporates environmental factors known to limit ozone uptake, would intuitively be expected to result in reduced yield loss estimates as compared to the concentration-based methods.

One key aspect that also needs consideration when comparing the theoretical application of these two risk methods is that the concentration-based approach assumes that only those concentrations above 40 ppb will contribute to damage. Further analysis of the flux-based method (as described for wheat and potato in LRTAP Convention, 2004), which uses a similar "flux threshold" concept shows that, under conditions optimal for ozone uptake, ozone concentrations somewhat lower than 40 ppb can contribute to damage. This is described in Figure 7. which shows the relationship between ozone flux (F_{st}) and ozone concentration (ppb) for wheat and potato assuming conditions are optimal for ozone uptake (i.e. stomatal conductance is at a maximum of 750 nmol O_3 m^{-2} s^{-1} for potato (green line) and 450 nmol O_3 m^{-2} s^{-1} for wheat (blue line)). The flux threshold at 6 nmol O_3 m^{-2} s^{-1} is indicated by the red line and shows that, in contrast to the AOT40 40 ppb cut-off concentration, ozone concentrations above 15.5 and 21 ppb can contribute to damage for wheat and potato respectively. As such, the frequent occurrence of local environmental conditions optimal for ozone uptake may well produce yield loss estimates in excess of those predicted using the concentration-based approach.

It should be noted that the following analysis was conducted for wheat only.

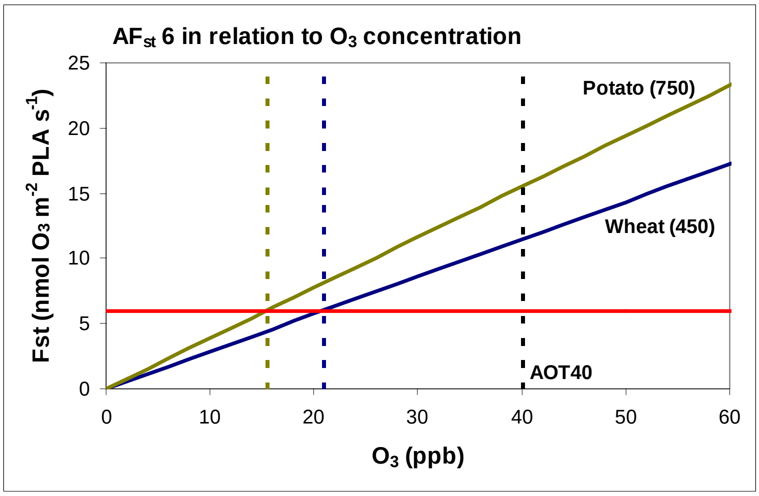


Figure 7. The relationship between ozone flux (Fst) and ozone concentration (ppb) for wheat (blue line) and potato (green line) assuming conditions are optimal for ozone uptake. The flux threshold at 6 nmol O_3 m^{-2} s^{-1} is indicated by the red line with the dashed, drop down lines indicating the levels above which ozone concentration will lead to damage.

5.2 Crop loss estimates

Data from five EMEP grid squares located in different climate regions across Europe (Table 1) were selected for application of both the flux- and concentration-based methods to assess the variation between the methods in estimates of yield loss. This assessment has concentrated on wheat (both winter and spring wheat) since this is the crop for which the phenology windows used in the AOT40 assessments are based.

The wheat stomatal ozone flux and flux-effect model is described in detail in the Mapping Manual (LRTAP Convention, 2004). The stomatal flux part of the model incorporates a multiplicative stomatal conductance (gs) model as described in equation [2]; this algorithm has been parameterised using gs observations collated from studies across Europe, further details of the parameterisation can be found in LRTAP Convention (2004).

$$gs = g_{max} * [min\{f_{phen}, f_{O3}\}] * f_{light} * max\{f_{min}, (f_{temp} * f_{VPD} * f_{SWP})\} \qquad [2]$$

where gs is the actual stomatal conductance (mmol O_3 m^{-2} sunlit projected leaf area (PLA) s^{-1}) and g_{max} is the species-specific maximum stomatal conductance (mmol O_3 m^{-2} PLA s^{-1}). The parameters f_{phen}, f_{O3}, f_{light}, f_{temp}, f_{VPD} and f_{SWP} are all expressed in relative terms (i.e. they take values between 0 and 1) as a proportion of g_{max}. These parameters allow for the modifying influence of phenology and O_3, and four environmental variables (irradiance, temperature, water vapour pressure deficit and soil water potential) on gs to be estimated.

Stomatal flux of ozone (F_{st}) is calculated assuming that the concentration of O_3 at the top of the canopy represents a reasonable estimate of the concentration at the upper surface of the laminar layer near the flag leaf. F_{st} in nmol m^{-2} PLA s^{-1} is calculated as a function of ozone concentration and conductance to ozone, where conductance incorporates both cuticular and stomatal deposition.

The accumulated flux above the ozone stomatal flux threshold of 6 nmol m^{-2} s^{-1} ($AF_{st}6$) is calculated as described in equation [3] with the accumulation taking place over a defined period within the crop growing season. In this report, the accumulation period is defined using the effective temperature sum phenological models for winter and spring wheat that are described in LRTAP Convention (2004).

$$AFst6 = \sum_{i=1}^{n}[Fst_i - Y] \text{ for } Fst_i \geq 6 \text{ nmol m}^{-2} \text{ PLA s}^{-1} \quad [3]$$

where Fst_i is the hourly O_3 mean flux in nmol m^{-2} PLA s^{-1}, and n is the number of hours within the accumulation period. Finally, the stomatal flux effect model for wheat is given in equation 4.

$$RY_{wheat} = 1.00 - (0.048 * AF_{st}6) \quad [4]$$

This wheat flux-response relationship is based on 13 open-top chamber (OTC) experiments from four different European countries all using field-grown crops and common agricultural practice. The experiments are described in more detail in Pleijel et al. (2004).

The stomatal flux and flux-effect model has been applied using ozone concentration data (representing 1997 meteorological conditions and 2000 emission scenarios) and associated meteorological data (irradiance, temperature, vapour pressure deficit, and wind speed) provided by EMEP for the five grid squares. Soil water potential was calculated using a “water budget” model that uses the DO_3SE models estimation of canopy gs in conjunction with the atmospheric water deficit to estimate the actual canopy transpiration. As such, the modelling of the accumulation of SMD, the resulting SWP and influence on gs (determined according to species/cover type specific f_{SWP}, soil type and rooting depth) is modelled in an internally consistent manner.

Figure 8 shows the flux modelling yield loss estimates in comparison with the yield losses resulting from application of AOT40 using both the fixed May to July accumulation period and the climate specific accumulation period (as described in Table 3). In both cases, AOT40 is calculated using the same canopy height ozone concentration data used in the flux modelling.

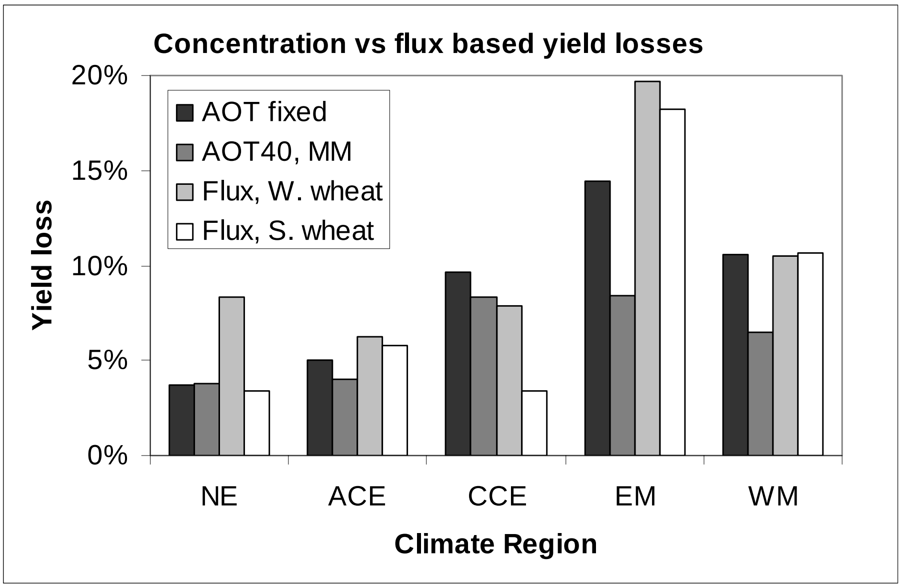


Figure 8. Wheat yield losses estimated for the five EMEP grid square locations using both flux-based ($AF_{st}6$, for winter and spring wheat) and concentration- based (AOT40, with fixed and Mapping Manual variable time window) methods.

Table 14 shows the ratio between the climate-specific accumulation period AOT40 yield loss estimates for spring wheat and the flux-based estimates for spring and winter wheat in each climatic zone. According to the mean values shown in the last line of the table, AOT40 under-predicts yield loss by on average a factor 1.5 compared to $AF_{st}6$. The data are not conclusive in identifying obvious trends in these ratios by climatic region, since both under-prediction and over-prediction occurs.

Table 14. Ratio between the AOT40 (estimated using climate specific accumulation periods) and flux yield loss estimates for wheat by climatic zone.

Climate zone	Spring wheat	Winter wheat
NE	0.90	2.19
ACE	1.43	1.55
CCE	0.41	0.94
EM	2.16	2.16
WM	1.64	1.61
Mean	**1.31**	**1.69**

The results shown in Figure 8 show that the relationship between AOT40- and flux-yield loss estimates vary substantially across the site locations and are dependent upon the crop type (i.e. spring or winter wheat affecting the timing if the growth period). For all locations except continental central Europe (CCE) the flux method estimates either a similar or increased yield loss due to ozone. For CCE, the yield loss estimates are lower, especially for spring wheat. To understand the drivers for these differences in loss estimates it is necessary to take a closer look at the comparisons between the frequency of ozone concentration class that comprise both indices and the evolution of the respective ozone indices in relation to the key environmental drivers over the course of the accumulation periods.

Investigation of the frequency of occurrence of a) ozone concentrations above and below 40 ppb contributing to $AF_{st}6$ and b) ozone fluxes above and below 6 nmol m^{-2} s^{-1} contributing to AOT40 will enable comparison of the ozone concentration classes comprising each index by region.

A difficulty in making such assessments in relation to the yield losses predicted from $AF_{st}6$ and AOT40 indices (Figure 8) is that the accumulation period for AOT40 yield loss is greater (by approx. 1 month) than the equivalent $AF_{st}Y$ period (i.e. comparison of frequency distributions will not incorporate the AOT40 index contributions that fall outside of the $AF_{st}Y$ accumulation period). Thus, the $AF_{st}Y$ and AOT40 cannot be compared directly as they will not necessarily translate proportionally into yield loss. To try and overcome this, the flux and AOT40 indices were standardised scaling according to the highest value found in all squares. This resulted in the following ratios of 0.68 (NE), 0.67 (ACE), 0.28 (CCE), 1.0 (EM) and 1.16 (WM) suggesting that the use of flux in the CCE grid would show the greatest reduction in risk relative to AOT40, whilst the use of flux in WM would suggest the greatest increase in risk relative to AOT40.

If the difference between flux and AOT40 can be largely explained by the varying importance to each index of different ozone concentrations (as hypothesised above) then it might be expected that for CCE, a large proportion of ozone concentrations above 40 ppb do not contribute to the $AF_{st}6$. In contrast, for WM it would be expected that a larger proportion of ozone concentrations above 40 ppb contribute to flux as well as a substantial proportion of concentrations below 40 ppb. This would seem to be the case from the percentage frequency occurrence of each combination of ozone concentrations contributing, or not contributing to flux for the selected grid squares (Figure 9). For CCE, the number of instances of concentrations that contributed to both $AF_{st}6$ and AOT40 is much smaller than the proportion of ozone concentrations above 40 ppb that did not contribute to $AF_{st}6$. In addition, few concentrations below 40 ppb contribute to $AF_{st}6$ for this grid square. This resulted in a proportionately reduced $AF_{st}6$ in comparison with AOT40. In contrast, in WM there are more instances of both concentrations above and below 40 ppb contributing to flux, relative to the contributions above 40 ppb that do not contribute to $AF_{st}6$ resulting in a higher flux in comparison with AOT40. NE and ACE are interesting since here (as for CCE), few concentrations contribute both to AOT40 and $AF_{st}6$, however, the instances where concentrations contribute to one index but not the other are both high and will tend to balance out the discrepancies between the indices and result in both indices providing similar indications of risk albeit related to different ozone exposures.

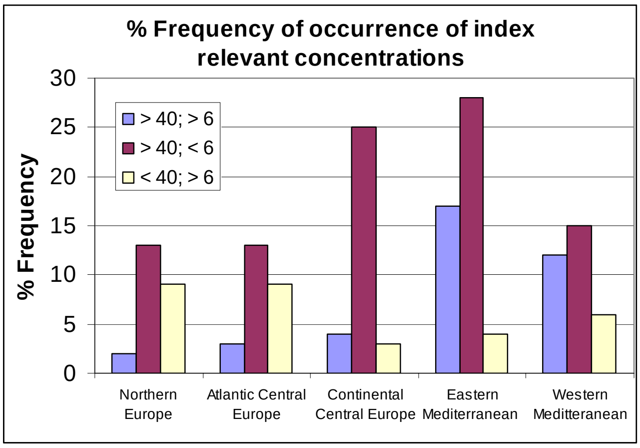


Figure 9. The percentage frequency occurrence of each combination of ozone concentrations contributing to AOT40 (greater than 40 ppb) and the flux index, $AF_{st}6$ (greater than 6 nmol m^{-2} s^{-1}).

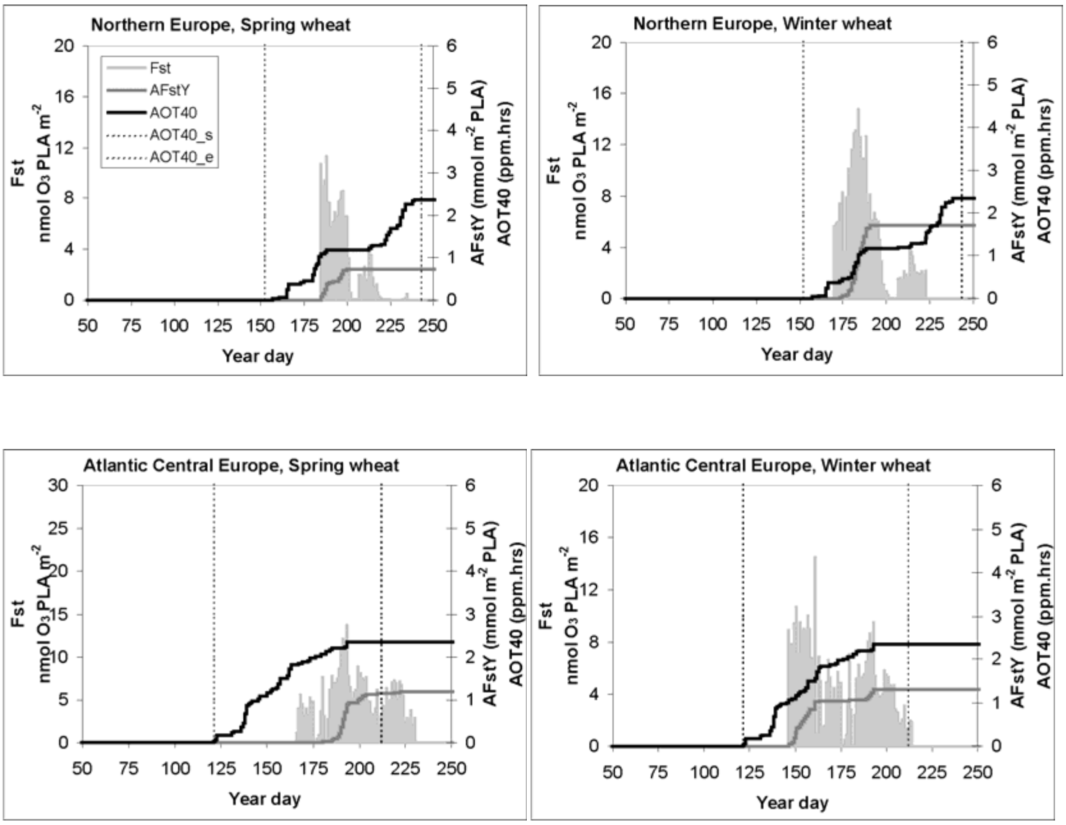
To understand the role of key environmental drivers in the evolution of the respective ozone indices over the course of the accumulation periods it is easiest to investigate each location in turn (Figures 10 and 11). For Northern Europe (NE), both AOT40 and spring wheat flux loss estimates are similar, whilst for winter wheat substantially greater yield losses are predicted. This is due to winter wheat having an earlier flux accumulation period which coincides with reduced soil moisture deficits providing conditions more optimal for ozone uptake and hence damage.

Yield loss estimates made for Atlantic Central Europe (ACE) are reasonably similar using both flux and AOT40. Fluxes are limited to a certain extent by temperature over the entire accumulation period but spring wheat has a higher limitation to ozone flux during its peak potential accumulation period, again showing the importance of the positioning of the accumulation period in relation to the prevailing environmental conditions.

Continental Central Europe is the only location where the flux-based method consistently estimates reduced yield losses compared to the AOT40 approach. This is due to the strong limiting effect of soil moisture deficit on ozone uptake. Again, the later growth period of spring wheat allows greater soil moisture deficit to build up resulting in reduced yield losses compared to winter wheat.

The Eastern Mediterranean region shows the greatest contrast between the two AOT40 accumulation periods. This is to be expected as the climate specific accumulation period for this region (1^{st} March to 31^{st} May) is most dissimilar from the fixed May to July period. It is also interesting to note the effective temperature sum derived flux accumulation periods do not coincide with the climate specific window but rather with the initiation of the sensitive growth period occurs as the climate specific accumulation period ends. This would explain the closer loss estimates between the fixed AOT40 window and flux. The EM location experiences higher precipitation levels than might be expected to be the norm in the EM climate region and hence these results should not be considered to be representative of the region as a whole. This may explain why the ozone uptake tends not to be limited by environmental conditions and hence results in larger yield losses than might have been expected for this region.

Finally, the Western Mediterranean (WM) location climate specific AOT40 and flux accumulation periods seem to coincide well. The early positioning of this accumulation period within the year prevent large soil moisture deficits from occurring and hence result in conditions optimal for ozone flux resulting in larger yield losses being associated with the flux method. Were the flux method to have been applied to later growing crops the situation might be expected to be rather different as the limiting influence of soil moisture may be much stronger.



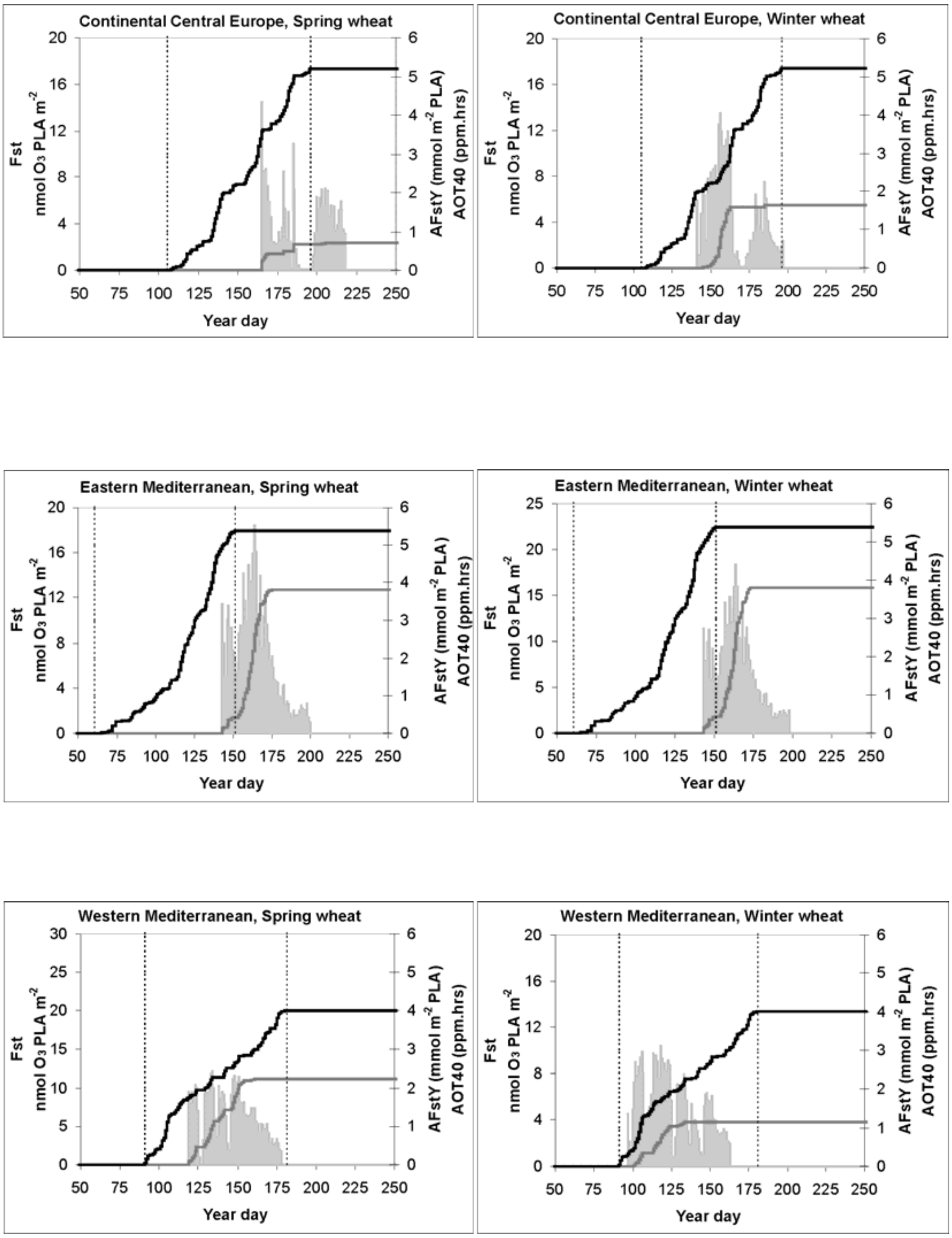
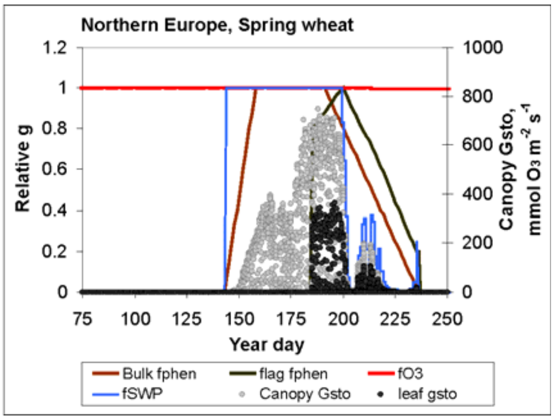
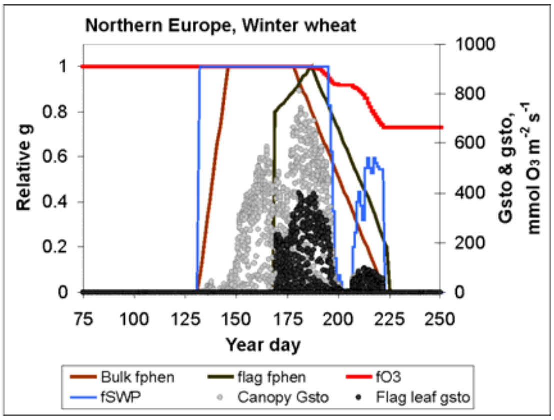
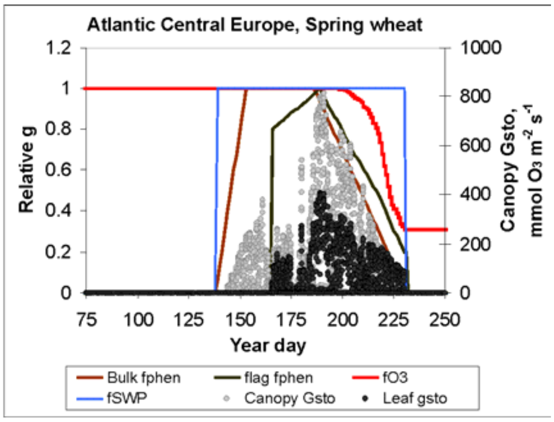
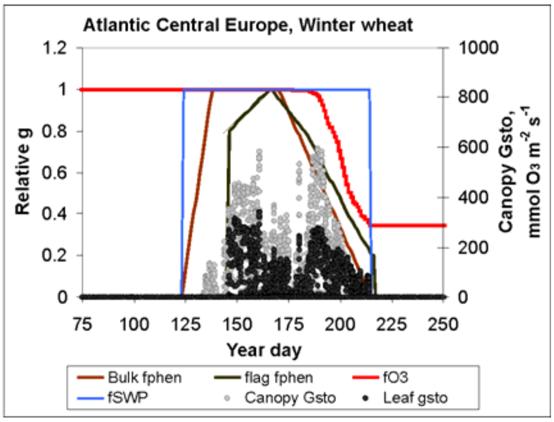


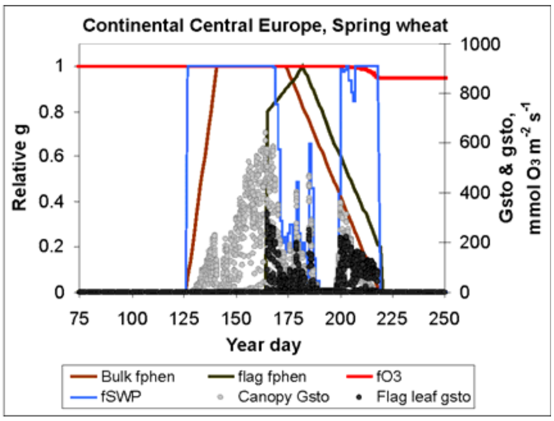
Figure 10. Stomatal ozone flux (Fst, nmol m^{-2} PLA s^{-1}) and the evolution of stomatal ozone flux above threshold 6 (Afst6, mmol m^{-2} PLA) for spring and winter wheat in contrast to the evolution of AOT40 (ppm.hrs) (estimated for specific climate zones, represented by AOT40_s and AOT40_e as the start and end of the AOT40 accumulation period) for the five EMEP grid square locations. Legends as indicated for Northern Europe.

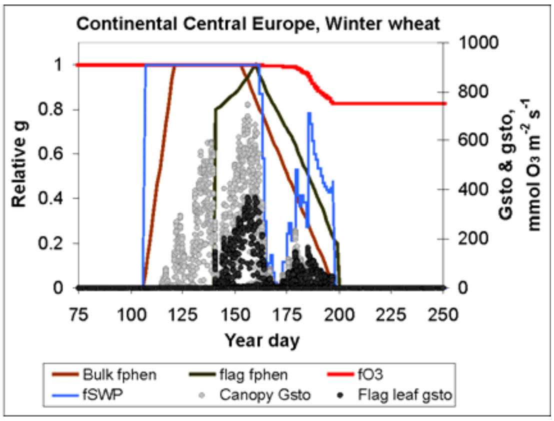

Northern Europe, Spring wheat
Relative g
Canopy Gsto, mmol O3 m-2 s-1
Year day
Bulk fphen
flag fphen
fO3
fSWP
Canopy Gsto
leaf gsto


Northern Europe, Winter wheat
Relative g
Gsto & gsto, mmol O3 m-2 s-1
Year day
Bulk fphen
flag fphen
fO3
fSWP
Canopy Gsto
Flag leaf gsto


Atlantic Central Europe, Spring wheat
Relative g
Canopy Gsto, mmol O3 m-2 s-1
Year day
Bulk fphen
flag fphen
fO3
fSWP
Canopy Gsto
Leaf gsto


Atlantic Central Europe, Winter wheat
Relative g
Canopy Gsto, mmol O3 m-2 s-1
Year day
Bulk fphen
flag fphen
fO3
fSWP
Canopy Gsto
Leaf gsto


Continental Central Europe, Spring wheat
Relative g
Gsto & gsto, mmol O3 m-2 s-1
Year day
Bulk fphen
flag fphen
fO3
fSWP
Canopy Gsto
Flag leaf gsto


Continental Central Europe, Winter wheat
Relative g
Gsto & gsto, mmol O3 m-2 s-1
Year day
Bulk fphen
flag fphen
fO3
fSWP
Canopy Gsto
Flag leaf gsto

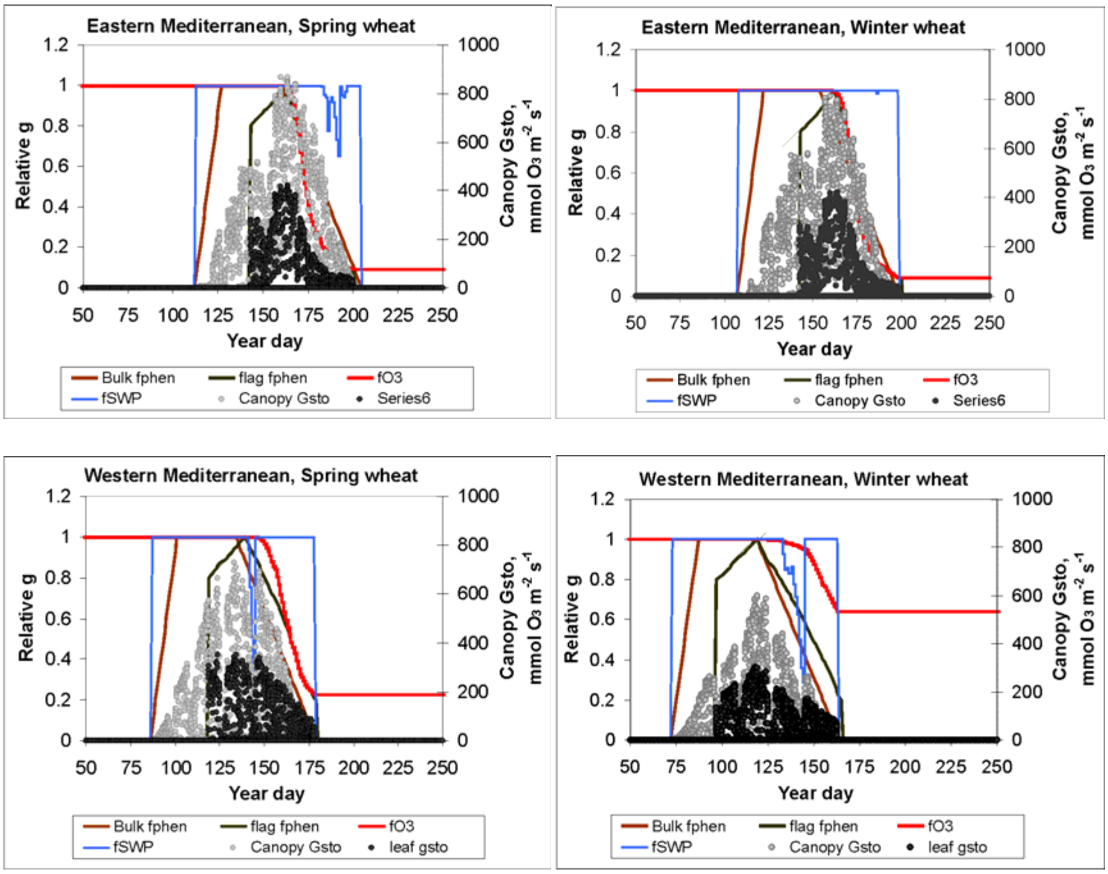


Figure 11. Canopy and leaf stomatal conductance (mmol m^{-2} PLA s^{-1}) in relation to key g_s limiting factors (presented between 0, full limitation) and 1 (no limitation) i) canopy and leaf age (bulk and flag leaf f_{phen}), ii) ozone effect (fO_3) and iii) soil water potential (f_{SWP}) for spring and winter wheat.

5.3 Further requirements for flux-based methods

This analysis has revealed a number of key points that it is felt require further consideration before using flux-based methods to assess the uncertainty of AOT40-estimated yield losses:-

1. Extended analysis of additional locations within each climate region is necessary. The individual grid squares cannot be expected to be representative of the entire climate region, and in fact, for the Eastern Mediterranean, the location is unfortunately rather unrepresentative.

2. The positioning of the accumulation period using both methods is shown to be extremely important. The analysis performed here using effective temperature sum (ETS) methods to estimate growth stages (and identify the sensitive growth period around anthesis) generally show that the use of climate specific accumulation periods for concentration-based assessments is an improvement on the fixed May to July period. However, further evaluation of these periods is necessary, both in terms of the accuracy of the ETS models on a pan-

European scale and also as some locations (in particular EM) seem inconsistent with ETS-estimated growth periods.

3. The importance of identifying the accumulation period is also highlighted as this determines the prevailing environmental conditions to which the crop is exposed. In more Northern parts of Europe, the later growth periods tend to lead to exposure to higher ozone levels and warmer conditions that may be optimal for ozone uptake if SMD is not limiting. In contrast, the earlier accumulation periods further south result in exposure to reduced ozone levels but also conditions more optimal for ozone uptake as temperatures and atmospheric and soil water deficits are also more moderate.

There are also some key issues to be addressed in relation to the validity of the flux modelling approach given the rather substantial yield losses that are being predicted which range between 5 to nearly 20% for wheat. It is hard to tell whether such large yield losses are realistic. Given that the year 1997 was a relatively low ozone year, analysis of additional years could result in even greater yield loss estimates, though it should also be kept in mind that higher ozone years may also be characterised by environmental conditions (warmer temperatures, reduced precipitation) which may lead to reduced ozone uptake. The advantage of the flux approach is that it does provide a means of integrating such conditions in comparison to the concentration-based approach where higher ozone years would automatically translate into enhanced ozone damage.

The issue of reliability of the flux model can be viewed in terms of firstly ensuring the modelling of ozone uptake (dose) is performed accurately and secondly that the translation of this dose into effects is appropriately described by the flux-response model. Key aspects in the estimation of stomatal flux include appropriate definition of the maximum stomatal conductance term (g_{max}); there is some observational evidence to suggest that g_{max} may vary with climatic region with cooler wetter regions tending to be populated by plants with higher g_{max} values whilst hotter drier regions will be dominated by plants with lower g_{max} values. This is supported on consideration of plant water balance processes since the stomates determine the amount of water lost through transpiration and mechanisms to reduce water loss in more arid regions would be beneficial to plant productivity.

The estimation of soil water potential also requires evaluation against observational data especially since this is a key driver limiting ozone flux. Similarly, evaluation of the effective temperature sum models across the whole of Europe should be viewed as a priority.

In terms of the flux-effect modelling, probably most important is ensuring that an appropriate flux-threshold has been identified. Analysis performed by Pleijel et al., 2004 indicated that although 6 nmol O_3 m^{-2} s^{-1} gave the strongest correlations with yield loss, alternative threshold values also performed reasonably well. Further investigation both considering detoxification processes and also application (i.e. the fact that lower thresholds can be applied at the regional scale with more certainty) should be a priority for the future.

Assessments using dose-response relationships as described here provide “bottom up” estimates of damage which ideally would be complemented with “top down” assessments. A variety of such methods have been developed and applied for different vegetation types and include passive and active biomonitoring (e.g. as employed by two of the UNECE International Cooperative Programmes (ICPs) to assess effects of air pollutants on forests and natural vegetation and crops), transect studies (assessing growth across a gradient of pollutant exposure) and epidemiological style studies employing regression methods (e.g. McLaughlin and Downing, 1995; Braun et al., 1999, Shankar and Neeliah, 2005). Such methods could prove extremely valuable in validating dose-response based risk assessments and ensuring yield and associated economic loss estimates are realistic.

6. Conclusions

6.1 Progress in quantification

The analysis presented in this report demonstrates that the AOT40 method can be applied across Europe (here represented by 47 countries) to assess the expected range in yield losses for a wide variety of crops (23 species) that account for a large share of arable production. Associated estimates of lost production in 2000 range between €4.4 and 10 billion/year with a best estimate of €6.7 billion/year, a figure that falls to €4.5 billion/year under current legislation in 2020. It has been possible to take account of uncertainties in each step of the AOT40 assessment, generating a 90% confidence interval around the best estimates in the order of -33% to +40%. Extremes of the range go roughly a factor of 2 either side of the best estimates. The spread around estimates for individual crops tends to be broader, particularly for those that have not been studied in detail.

Preliminary results also suggest that across Europe, there is no consistent pattern in the relationship between AOT40- and flux-based estimates – in some locations AOT40 gives a higher result, whereas in others, particularly the Mediterranean regions, the flux method gives a higher result. This result may at first appear counter-intuitive. It has been widely anticipated that the use of a flux-based approach would generate systematically lower estimates of damage than the AOT40-based method since the AOT40 critical level is considered to provide protection against crop damage under most sensitive conditions (i.e. non-limiting soil moisture). However, since relatively low ozone concentrations (above approximately 20 ppb for wheat) can contribute to the accumulated dose index for damage it may be considered less surprising that flux can result in higher yield losses than AOT40 when conditions are optimum for uptake. The rationale behind the selection of the flux threshold and associated flux-response (LRTAP Convention, 2004) may need to be further investigated in this respect if it is considered that these are too sensitive under ambient conditions. The analysis has shown how dependant flux-based yield losses are on the prevailing environmental conditions. Temperature is important, especially in determining the timing of the ozone accumulation period and, in combination with precipitation, the exposure of the crop to SMD. Flux-based yield losses that are higher than AOT40-based yield losses tend to be associated with later growth periods that coincide with higher ozone concentrations and optimum conditions for ozone uptake, whereas lower yield losses tend to be associated with higher SMD, which limits uptake. In addition, it is clear that further analysis of the flux-based method for additional grid squares within the different climate regions, and additional years, is necessary to understand whether climate-specific bias between AOT40 and flux exists. For example, the results from the Eastern Mediterranean region should not be viewed as representative of that region since the location of the EMEP grid square considered for the region actually occurs in an area receiving unusually high precipitation levels (1600 mm average annual precipitation, making it one of the wettest parts of Europe). The analysis does, however, clearly show that the flux-based method provides an opportunity to incorporate environmental drivers that have long been considered important in determining ozone uptake and hence response.

It is not yet possible to combine lessons learned from application of flux based methods directly to the results of concentration based analysis. At the start of the project it was hoped that this would be possible, but a number of issues have been identified that need to be resolved before conversion factors can be adequately defined.

6.2 Refinements to the analysis

6.2.1 Short term

One refinement to the results presented here will be possible in the near future, the use of direct estimates of canopy height ozone concentrations instead of ozone at 3m. This is now modelled by EMEP, though results were not available in time for this report. It will, however, remain necessary to factor in uncertainty around the estimation of canopy height concentrations.

6.2.2 Longer term

We divide these recommendations into six parts:

1. Improvements to the AOT40 approach.

   It will be necessary to review the ranges identified for the parameters used in the AOT40 analysis, to check that they provide a thorough account of the component uncertainties in the analysis and also that they do not double count uncertainties. Consideration of the use of additional factors for adjusting AOT40-based estimates in line with lessons learned from the more limited flux analysis should also be made. It would also be useful to consider issues specific to individual crops, for example, variation in growing seasons around the periods assumed here, and variation in growing conditions that would alter response. This is of particular concern for tomatoes which generate a large damage estimate here but account has not been taken of the fact that they are often grown under cover, and for high-value crops such as many vegetables that are perhaps typically more irrigated than most crops.

2. Improvements to the flux-based approach.

   The analysis presented here has helped to identify some of the key drivers important in determining stomatal ozone flux and hence contributing to the likelihood of damage, these are identification of the sensitive growth period, which affects both the ozone levels as well as the prevailing environmental conditions to which the crop is exposed. Of these environmental conditions, the accumulation of soil moisture deficits (SMDs) is perhaps the most important in terms of producing differences in the concentration- versus flux-based yield loss assessments, the SMD to which the crop is likely to be exposed is itself related to the timing of the crop growth period so these two factors are inextricably linked. Both methods to assess timing of growth period (i.e. effective temperature sum models) and soil moisture deficit (internally consistent water budget method) require further pan European evaluation before they can be applied with any real certainty in the absolute values estimated. However, they do already provide a useful indication of the relative importance of these drivers across Europe.

The analysis has also highlighted the need to conduct flux modelling at a larger number of carefully selected locations, and for a range of different years (representing low, medium and high ozone exposures) within each climate region to provide a more robust indication as to whether any climate specific relationships between concentration and flux based yield loss estimates.

Finally, this analysis has not conducted any formal assessment of the uncertainty in the flux approach. Ideally such an assessment would be conducted in a manner similar to that performed here for AOT40, with emphasis on the two key components of the flux-based method, namely an assessment of the certainty with which both ozone uptake and the associated flux-response can be determined.

3. Improvements to valuation procedures.

    A static approach to valuation has been used in this report, assuming that the economic consequences of crop production changes do not entail changes in price (and consequent differentiation of impacts on producers and consumers) or cropping patterns. When firmer agreement is made on the magnitude of crop losses and the way that it varies from year to year, the valuation approach will need to be reconsidered.

4. Investigation of top-down methods.

    This would be an extension to the work described in this paper, building on the recent paper by Shankar and Neeliah (2005). Results in this paper are limited to wheat production in the UK, and indicate roughly 50% lower estimates of damage than those quantified here – reasons for this difference need to be explored, though it is perhaps comforting that there would seem to be agreement on general orders of magnitude. There are several benefits to using what is basically an epidemiological approach, considering farm level data and national ozone maps. First, it provides an independent route for validation of damage estimates made using bottom-up response function methods. Second, it may open opportunity for consideration of additional factors, for example, links between ozone exposure and pest prevalence (perhaps assessed through pesticide application rates) as well as inadvertent adaptation by farmers e.g. through selection of resistant crop and cultivar types.

5. Investigation of secondary impacts.

    There is a large body of evidence that demonstrates that exposure to ozone leads to changes in crop production costs and the value of produce through mechanisms beyond the direct phytotoxic impact of ozone on plant functions. These include the stimulation of insect pests and (negative) changes in the taste and nutritional quality of produce. Again, once agreement is reached on the magnitude of yield losses linked to ozone, such questions should be reconsidered.

6. Investigation of impacts under significantly different ozone scenarios.

    This could assess the effects of using different thresholds for the concentration based assessment. As concentrations fall, does the AOTX method lead to a significant variation in damage estimates when different thresholds are considered? Is the concept of a threshold actually appropriate, or did it simply provide a useful metric for assessing overall ozone exposure in past work that is not particularly relevant to the emerging European ozone climate? Heading in the other direction, given that background concentrations of ozone are forecast to rise sharply as one consequence of climate change, what are the consequences for crop production?

6.3 Reliability of the results from the concentration-based approach for policy support

Quantification of economic impacts of air pollution on crops remains controversial, with several prominent European experts arguing that it should not be used to advise policy makers, and that critical levels exceedance mapping, which identifies the areas at greatest risk, is sufficient.

It is clear that significant progress has been made in this report with respect to method development to inform economic assessment. The question of whether the results shown here are fit for use in policy making can be addressed from two perspectives. First, do estimates of yield loss add useful information beyond that provided by critical levels mapping? We argue that they do, partly by factoring in the variable response of different crops from those that are not sensitive to ozone, such as barley, to those that are highly sensitive, such as water melon. Also, by facilitating the calculation of economic yield loss estimates, they provide a basis for comparing the benefits of emission reduction directly with associated costs. A further point is that many decision makers are unfamiliar with the critical levels concept.

Secondly, are yield losses quantified well enough to be used by policy makers? Again, we argue that they are. The AOT40- and flux-based methods, and the work by Shankar and Neeliah all indicate best estimates of damage within a factor 2 of each other, and the methods outlined in this paper make it is possible to describe ranges and associated distributions around estimated yield losses. These ranges can be factored into cost-benefit analysis, to assess the probability that benefits of air pollution abatement will or will not exceed costs. Probabilised CBA, mainly focused on health benefits, has already been used in the CAFE programme to assess the likelihood of benefits exceeding costs. This is illustrated in Figure 12, which demonstrates how a probabilised assessment was integrated in the CAFE analysis with sensitivity analysis, considering both different approaches for mortality valuation (VOLY median, VOLY mean, etc.) and uncertainty in the costs estimated by the RAINS model (Amann et al., 2005a).

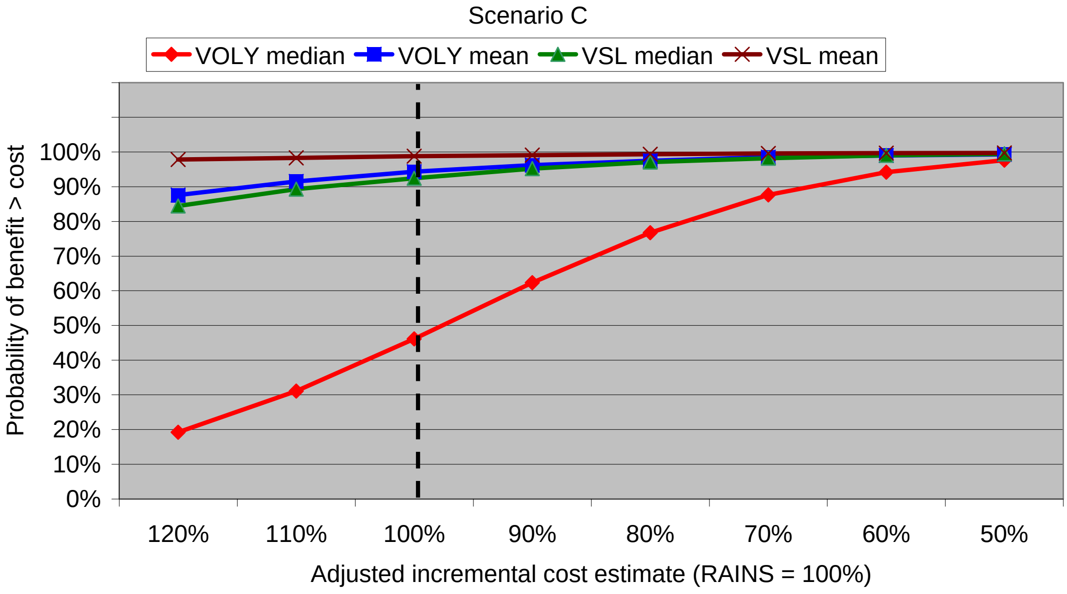


Figure 12. Sensitivity to uncertainty in incremental costs of pollution abatement of the probability of a net benefit in moving from CAFE Scenario B to CAFE Scenario C (from Holland et al., 2005c).

The fact that there is inconsistency in which of the two methods gives the larger damage estimates from place to place in Europe implies that for wheat, errors implicit in the concentration-based approach might possibly cancel out to a significant extent once results are aggregated to the level of the EU25 or UNECE.

CBA can also account for uncertainty in other elements of the analysis, including the costs, for which uncertainties are larger than usually thought (Watkiss et al., 2005). There are, indeed, good reasons for suspecting that the critical uncertainties affecting air pollution CBA in Europe are not related to the benefits assessment but to abatement cost curves (Holland et al., 2005b).

It is certainly possible to improve on the estimates of damage made in this paper. However, this applies to all analysis in support of policy development on air pollution. The development of a framework for quantifying uncertainties in this report is a major step forward for reliable integration of pollution control benefits in CBA. In contrast, a failure to include crop loss estimates in such work biases analysis artificially in favour of the current situation.

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Appendix 1 Detailed results from AOT40 approach

Table 15. Best estimates of damage to each crop in each of the 7 scenarios considered in this report across all 47 countries included in this analysis. Units: €million/year. 90% confidence intervals will extend to roughly a factor 2 around the values for many crops, though this will be less for crops like wheat for which data are taken from a large number of experiments.

	2000	2020	2020	2020	2020	2020	2020
Scenario		**CLE**	**A (D23_low)**	**B (D23_mid)**	**C (D23_high)**	**MFR**	**EU TSAP**
Barley	0	0	0	0	0	0	0
Carrots	142	95	81	77	75	32	81
Fruit	0	0	0	0	0	0	0
Grapes	229	136	109	103	100	56	109
Hops	17	9	7	6	6	4	7
Maize	160	95	79	74	72	30	79
Millet	0	0	0	0	0	0	0
Oats	0	0	0	0	0	0	0
Olives	0	0	0	0	0	0	0
Potatoes	676	454	391	372	362	128	391
Pulses	168	109	92	87	85	34	92
Rape Seed	82	41	31	28	27	17	31
Rice	24	16	13	13	12	7	13
Rye	0	0	0	0	0	0	0
Seed Cotton	396	365	346	340	337	237	346
Soya Beans	31	20	17	16	16	7	17
Sugar Beets	284	170	139	131	127	62	139
Sunflower Seeds	164	119	105	101	99	24	105
Tobacco Leaves	72	48	41	39	38	18	41
Tomatoes	1,009	684	585	560	546	267	586
Vegetables	1,488	1,001	853	814	793	345	854
Water Melons	136	104	93	90	89	34	93
Wheat	1,628	1,054	891	847	823	352	891
Total	6,708	4,520	3,872	3,699	3,607	1,653	3,876

Table 16. % damage in each scenario attributable to each crop across the 47 countries based on core estimates.

EU25: Year	2000	2020	2020	2020	2020	2020	2020
Scenario		**CLE**	**A (D23_low)**	**B (D23_mid)**	**C (D23_high)**	**MFR**	**EU TSAP**
Barley	0%	0%	0%	0%	0%	0%	0%
Carrots	2%	2%	2%	2%	2%	2%	2%
Fruit	0%	0%	0%	0%	0%	0%	0%
Grapes	4%	4%	4%	4%	4%	4%	4%
Hops	0%	0%	0%	0%	0%	0%	0%
Maize	3%	3%	3%	3%	3%	2%	3%
Millet	0%	0%	0%	0%	0%	0%	0%
Oats	0%	0%	0%	0%	0%	0%	0%
Olives	0%	0%	0%	0%	0%	0%	0%
Potatoes	9%	9%	9%	9%	9%	9%	9%
Pulses	2%	2%	2%	2%	2%	2%	2%
Rape Seed	2%	1%	1%	1%	1%	1%	1%
Rice	0%	0%	0%	0%	0%	1%	0%
Rye	0%	0%	0%	0%	0%	0%	0%
Seed Cotton	3%	3%	4%	4%	4%	3%	4%
Soya Beans	0%	1%	1%	1%	1%	1%	1%
Sugar Beets	5%	5%	4%	4%	4%	5%	4%
Sunflower Seeds	2%	2%	2%	2%	2%	1%	2%
Tobacco Leaves	1%	1%	1%	1%	1%	1%	1%
Tomatoes	16%	17%	18%	18%	18%	18%	18%
Vegetables	23%	24%	24%	24%	24%	24%	24%
Water Melons	1%	1%	1%	1%	1%	1%	1%
Wheat	26%	24%	24%	23%	23%	24%	24%

Table 17. Best estimates of damage by country under each scenario. Units: €million/year. The 90% confidence interval for each country will extend to roughly -33% and +40% of these estimates.

47 countries	**2000**	**2020**	**2020**	**2020**	**2020**	**2020**	**2020**
Scenario		**CLE**	**A (D23_low)**	**B (D23_mid)**	**C (D23_high)**	**MFR**	**EU TSAP**
Albania	22	17	14	14	13	5	14
Armenia	4	4	4	4	4	2	4
Austria	64	27	20	18	17	9	20
Azerbaijan, Republic of	14	17	16	16	16	8	16
Belarus	53	47	42	41	40	2	43
Belgium	88	57	49	46	44	37	49
Bosnia and Herzegovina	19	12	10	10	9	3	10
Bulgaria	75	47	42	40	39	8	42
Croatia	32	20	17	16	15	5	17
Cyprus	3	2	2	2	2	0	2
Czech Republic	95	37	27	24	23	13	27
Denmark	56	31	25	23	22	12	25
Estonia	1	1	1	0	0	0	1
Faeroe Islands	0	0	0	0	0	0	0
Finland	6	3	2	2	2	0	2
France	738	381	274	254	244	159	275
Georgia	3	4	3	3	3	1	3
Germany	599	281	218	199	188	133	217
Greece	247	173	151	145	141	52	151
Hungary	188	90	69	63	60	20	69
Ireland	11	6	5	5	4	3	5
Italy	1,260	759	626	591	573	358	626
Kazakhstan	24	34	34	33	33	23	34
Latvia	4	2	2	2	2	0	2
Liechtenstein	0	0	0	0	0	0	0
Lithuania	16	10	8	8	8	1	8
Luxembourg	2	1	1	1	1	0	1
Macedonia, FYR	17	13	11	11	10	3	11
Malta	1	1	1	1	1	0	1
Moldova, Republic of	34	28	26	25	25	3	26
Netherlands	155	97	84	79	76	64	84
Norway	4	2	2	2	2	1	2
Poland	340	149	111	100	94	34	111
Portugal	55	39	30	28	27	20	30
Romania	258	174	160	155	153	30	160
Russian Federation	274	384	374	369	367	36	374
Serbia and Montenegro	70	47	41	39	38	8	41
Slovakia	46	19	13	12	11	5	13
Slovenia	5	3	2	2	2	1	2
Spain	463	277	201	188	179	131	202
Sweden	21	12	9	8	8	3	9
Switzerland	31	14	11	10	10	6	11
Turkey	521	411	392	383	379	116	392
Turkmenistan	46	58	58	58	58	57	58
Ukraine	432	430	406	397	393	29	406
United Kingdom	163	115	97	90	86	65	97
Uzbekistan	150	185	185	185	185	185	185
Totals							
EU25	4,625	2,573	2,025	1,888	1,814	1,123	2,028
All 47 countries	6,708	4,520	3,872	3,699	3,607	1,653	3,876

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