# Economical Estimation of the Losses of Crops Due to High Ozone Levels

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## Summary

Harmful effects on crops, caused by long-term exposures to high ozone concentrations, are studied. The exposures are measured by the values of AOT40 (Accumulated exposure Over Threshold of 40 ppb). The Danish Eulerian Model has been used to calculate the AOT40 values on a square grid with step 50 km., which covers Bulgaria. When the exposure is greater than the critical level of 3000 ppb.hours, there are some losses, which can be estimated by using a statistically determined linear relationship. Localized information about the actual yield of crops and the prices is also needed in order to prepare the necessary economical estimates. The algorithm for economical evaluation of the losses can be applied with different scenarios for variation of some key parameters (the emissions, the meteorological conditions, the prices and so on). Some preliminary results, obtained by our algorithm for Bulgaria and Bulgarian regions, are presented.

**Keywords:** air pollution models, ozone exposure for crops, AOT40, economical estimates

## 1 Damaging effects of high ozone concentrations on crops

High ozone concentrations have damaging effects on crops. This is why this problem has been extensively studied during the last ten years. Leading European specialists discussed at two meetings: in Switzerland in 1993 ([5]) and in Finland in 1995 ([6]) the basic tools that can be used to evaluate the losses of crops due to high ozone pollution levels. The major conclusion of these two meetings, based on results from many experiments in different European countries, was that a specially defined parameter, called AOT40 (Accumulated exposure Over Threshold of 40 ppb), can be applied to evaluate the losses of crops. The AOT40 values for Bulgaria are used in this paper (i) to evaluate the losses of some crops in different regions of Bulgaria and for the whole country and (ii) to evaluate the price of the losses. The following input data is used in the calculations: (a) the AOT40 values for Bulgaria, (b) the relationship between the AOT40 values and the losses of crops, (c) information about the yield of crops in the different regions of Bulgaria and (d) the average market prices of the crops in the years under consideration.

## 2 Measuring the ozone exposures

Let $c$ be some critical ozone concentration (measured in ppb). Then the function AOT(c) is defined by the sum:

$$\text{AOT}(c) = \sum_{i=1}^{N} \max(c_i - c, 0) \tag{2.1}$$

where $N$ is the number of daytime hours in the period under consideration (for crops this period contains the months May, June and July), $c_i$ is the calculated by some model or measured at some station ozone concentration. If a model is used, then the AOT(c) values can be calculated for each grid-square of the model domain.

The critical concentration $c$ is often chosen to be 40 ppb. (this is done in nearly all papers in [5] and [6] as well as in the draft of the EU Ozone Directive, [1]). We shall also use the notation AOT40 when $c = 40$ ppb. The critical exposure level for crops is 3000 ppb.hours and AOT40 should not exceed this level. However, the truth is that in many European countries this level is exceeded by a factor of five and even more. This is also true for Bulgaria.

If AOT40 exceeds 3000 ppb.hours, then a linear relationship can be applied to evaluate the amount of losses of crops due to the high ozone exposure. This relationship is discussed in more detail in Section 5 (see equation 5.2) as well as in [8].

## 3 The AOT40 values for Bulgaria and the surrounding area

The Danish Eulerian Model (DEM) has been used to compute the AOT40 values for Bulgaria and the surrounding area. DEM is fully described in [12]. The numerical methods in DEM are discussed in [2, 13, 14, 15, 16]. Information about the model and results obtained by the model are also given in the web-site for the model [11].

The ability of this model to produce reliable AOT40 values has been validated in [3] and [17], where the AOT40 values calculated by the model were compared with the corresponding values at more than 90 measurement stations located in different European countries (unfortunately, no measurements made in Bulgaria were available at that time).

The values of AOT40 for 1996 and 1997, computed with DEM over a part of the EMEP grid (a square grid with step 50 km.) that covers Bulgaria and its surroundings, are shown in Fig. 1. It should be mentioned that the well-known EMEP grid is used, because the meteorological data, used as an input for DEM, has been received from EMEP.

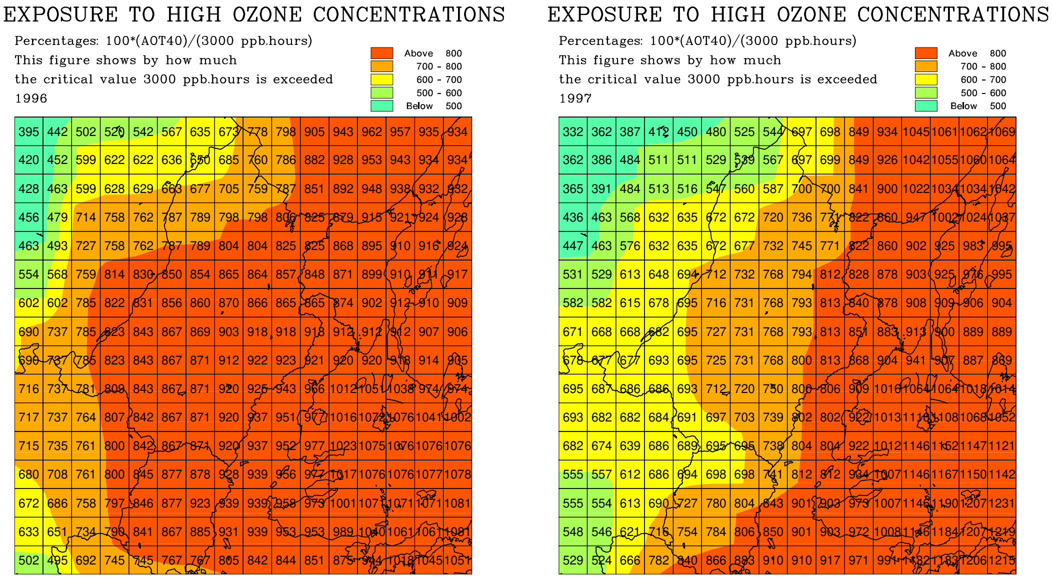


**Figure 1** AOT40 maps of Bulgarian region for 1996 and 1997, computed by DEM.

## 4 Yield from crops in the Bulgarian regions in 1996 and 1997

Table 1 contains data for the yield of three grain crops (wheat, corn and sunflower) in 1996 and 1997 for the nine Bulgarian regions and for the whole country. The data given in Table 1 consists of official information for the yield received from the Ministry of Agriculture and Forestry of Bulgaria.

| **Annual yield of some crops in Bulgaria** ($\times 10^3$ **tons**) | | | | | | |
|---|---|---|---|---|---|---|
| **Region** | wheat | | corn | | sunflower | |
| | 1996 | 1997 | 1996 | 1997 | 1996 | 1997 |
| 1. Sofia City | 8 | 23 | 2 | 2 | 0 | 1 |
| 2. Burgas | 365 | 491 | 64 | 80 | 61 | 64 |
| 3. Varna | 473 | 960 | 221 | 434 | 145 | 117 |
| 4. Lovech | 131 | 450 | 223 | 362 | 105 | 76 |
| 5. Montana | 118 | 326 | 182 | 205 | 63 | 57 |
| 6. Plovdiv | 122 | 221 | 75 | 88 | 15 | 15 |
| 7. Russe | 243 | 590 | 241 | 408 | 94 | 83 |
| 8. Sofia | 66 | 142 | 36 | 40 | 2 | 2 |
| 9. Haskovo | 260 | 353 | 45 | 77 | 45 | 31 |
| **Total** | 1786 | 3556 | 1089 | 1696 | 530 | 446 |

**Table 1** The yield (in thousand tons) of wheat, corn and sunflower in the nine regions of Bulgaria and for the whole country

## 5 Calculating the losses from the yield of crops in Bulgaria

The EMEP grid has to be mapped on the regional division of Bulgaria. This has been done by preparing a rectangular matrix $A$. The rows of $A$ correspond to the nine Bulgarian regions, while the columns correspond to the Bulgarian cells of the EMEP grid (their total number is 143). Let $V_i$ be the area of the $i$th Bulgarian region. Let $v_{ij}$ be the part of the $i$th Bulgarian region contained in the $j$th cell ($i = 1,2,\ldots,9, \quad j = 1,2,\ldots,143$). Then $a_{ij} = v_{ij}/V_i$. This implies that the sum of the elements in each row is equal to one.

Let us assume that the yield over each region is evenly distributed over the entire area of the region. Then it is clear that having calculated matrix $A$ (a special program which does this has been prepared) and having the AOT40 values, we can calculate the losses by using a relationship obtained by linear regression. Provided that $y$ is the actual yield, $y + z$ is the expected yield without any ozone exposure, $\xi$ is the AOT40 in ppb.hours, the following formula is actually used to calculate the losses:

$$100\,y/(y+z) = \alpha\xi + \beta \quad (\alpha < 0\,,\ \beta \approx 100) \tag{5.2}$$

where $\alpha$ and $\beta$ are statistically determined coefficients. The values $\alpha = -0.00177$ and $\beta = 99.6$ have been used to calculate the results in Table 2 and in Table 3. Similar values are used in Pleijel [8]. They are determined by analyzing a large amount of experimental data, which is representative for Europe ([4]).

Instead of using the experimental data from [4], one can use the data from the Nordic countries. This leads to a slightly different regression function (see again [8]), based on North European countries' statistics, which gives a little bit lower losses.

| **Estimated yield losses in 1996 in Bulgaria** | | | | | | |
|---|---|---|---|---|---|---|
| **Region** | Losses (in thousand tons and %) of | | | | | |
| | wheat | | corn | | sunflower | |
| 1.Sofia City | 7 | (46.0%) | 2 | (46.0%) | 0 | |
| 2.Burgas | 292 | (44.4%) | 51 | (44.4%) | 49 | (44.4%) |
| 3.Varna | 310 | (39.6%) | 145 | (39.6%) | 95 | (39.6%) |
| 4.Lovech | 110 | (45.7%) | 188 | (45.7%) | 88 | (45.7%) |
| 5.Montana | 89 | (43.0%) | 137 | (43.0%) | 48 | (43.0%) |
| 6.Plovdiv | 115 | (48.5%) | 71 | (48.5%) | 14 | (48.5%) |
| 7.Russe | 169 | (41.0%) | 168 | (41.0%) | 65 | (41.0%) |
| 8.Sofia | 58 | (46.7%) | 32 | (46.7%) | 2 | (46.7%) |
| 9.Haskovo | 238 | (47.8%) | 41 | (47.8%) | 41 | (47.8%) |
| **Total** | 1388 | (43.7%) | 834 | (43.4%) | 402 | (43.1%) |

**Table 2** Yield losses for 1996 computed for the nine regions of Bulgaria and for the whole country

| Estimated yield losses in 1997 in Bulgaria | | | | | | |
|---|---|---|---|---|---|---|
| **Region** | Losses (in thousand tons and %) of | | | | | |
| | wheat | | corn | | sunflower | |
| 1.Sofia City | 14 | (37.9%) | 1 | (37.9%) | 1 | (37.9%) |
| 2.Burgas | 351 | (41.7%) | 57 | (41.7%) | 46 | (41.7%) |
| 3.Varna | 511 | (34.8%) | 231 | (34.8%) | 62 | (34.8%) |
| 4.Lovech | 283 | (38.6%) | 227 | (38.6%) | 48 | (38.6%) |
| 5.Montana | 190 | (36.9%) | 120 | (36.9%) | 33 | (36.9%) |
| 6.Plovdiv | 154 | (41.0%) | 61 | (41.0%) | 10 | (41.0%) |
| 7.Russe | 320 | (35.1%) | 221 | (35.1%) | 45 | (35.1%) |
| 8.Sofia | 88 | (38.1%) | 25 | (38.1%) | 1 | (38.1%) |
| 9.Haskovo | 266 | (43.0%) | 58 | (43.0%) | 23 | (43.0%) |
| Total | 2176 | (38.0%) | 1001 | (37.1%) | 270 | (37.7%) |

**Table 3** Yield losses for 1997 computed for the nine regions of Bulgaria and for the whole country

## 6 Runs with the scenario for 2010

There exist several scenarios for the variations of the emissions in the future (scenarios for years 2000, 2005, 2010 can be found in the EMEP report [7]). The scenario for 2010 has been used in this study. Results are given in Table 4. The results do not change too much (comparing with the corresponding results in Table 3). The reason for this can be explain as follows. The scenario 2010 have been created by using some assumptions for emission reductions related to the emission levels in 1990. However, in many countries the emissions in 1996 are already on the level which have been assumed for 2010 (and sometimes even below the level for 2010). As a matter of fact, the $NO_x$ emissions in Bulgaria (according to the EMEP inventories) are 376 in 1990 and 259 in 1996, while the figure is expected to be 290 in 2010 (the units being 1000 tons per year).

The results indicate that the harmful effects from long-term exposures to high ozone concentrations will remain in the future unless some measures are urgently taken.

It should be mentioned that the results for Scenario 2010, which are used in Table 4, are calculated by using the meteorological data for 1997. The meteorological conditions vary significantly from one year to another.

## 7 Calculating the price of the losses

The annual crop losses in a given country can be very significant. It has been estimated that the losses due to high ozone pollution levels in the rural areas of USA are more than a billion dollars [10]. That is why it is quite important for each country to study its own losses. An evaluation of the price of the losses shown in Table 2 - Table 4 can easily be calculated by using the results from these tables and the prices in 1996 and 1997.

Total prices (the sums of the prices for the wheat, corn and sunflower) corresponding to the losses given in Table 2 - Table 4 are shown in Table 5. The results for Scenario 2010 are calculated

| Estimated yield losses in 1997 for Scenario 2010 | | | | | | |
|---|---|---|---|---|---|---|
| **Region** | Losses (in thousand tons and %) of | | | | | |
| | wheat | | corn | | sunflower | |
| 1.Sofia City | 13 | (36.9%) | 1 | (36.9%) | 1 | (36.9%) |
| 2.Burgas | 336 | (40.6%) | 55 | (40.6%) | 44 | (40.6%) |
| 3.Varna | 487 | (33.7%) | 220 | (33.7%) | 59 | (33.7%) |
| 4.Lovech | 272 | (37.7%) | 219 | (37.7%) | 46 | (37.7%) |
| 5.Montana | 183 | (35.9%) | 115 | (35.9%) | 32 | (35.9%) |
| 6.Plovdiv | 148 | (40.2%) | 59 | (40.2%) | 10 | (40.2%) |
| 7.Russe | 304 | (34.0%) | 211 | (34.0%) | 43 | (34.0%) |
| 8.Sofia | 84 | (37.3%) | 24 | (37.3%) | 1 | (37.3%) |
| 9.Haskovo | 256 | (42.0%) | 56 | (42.0%) | 22 | (42.0%) |
| Total | 2084 | (37.0%) | 959 | (36.1%) | 258 | (36.7%) |

**Table 4** Yield losses in 1997 computed under Scenario 2010 for the nine regions of Bulgaria and for the whole country

by using the yields and the prices for 1997. If the results are to be used by decision makers, then much more careful analysis of the future development of the agriculture and of the prices in Bulgaria is needed.

The prices of the losses given in Table 5 are obtained by using the advanced procedure based on linear regression of large sets of carefully prepared experimental data. One can use a much more simplified approach in which it is assumed that all losses are always equal to 10% when the AOT40 values exceed the critical exposure of 3000 ppb.hours. Under this assumption the results for the three scenarios are: 55.000, 72.046 and 70.908 millions US dollars for 1996, 1997 and Scenario 2010. These numbers should be compared with the numbers given in the last line of Table 5; i.e. with 236.501, 266.571 and 255.269 respectively. Of course, this is a very optimistic estimation, but also the figures obtained by using such a simplifying assumption are very high. It should also be mentioned that estimation of about 10.5% for the losses in Bulgaria, which are due to the exposures to high ozone levels, can be found in [9].

## 8 Plans for future work

- It would be better to use the data for the counties instead of the data for the regions (which are perhaps too large in comparison with the grid used in DEM. This can be done by using the same principles. Matrix $A$ from Section 5 will now have larger dimensions. The task of preparing this finer mapping will be solved in the near future.
- The basic ideas used to obtain the results in this paper can be applied for other European countries (or even groups of countries). This is another task which will be solved in the next two-three years.
- The AOT40 function could (and probably should) be adjusted for the countries in Southern Europe. The growing period for the crops in these countries starts earlier than the growing period for the crops in the countries in Central and Northern Europe. Therefore the period which is used

| Price of losses for crops | | | |
|---|---|---|---|
| **Region** | Prices in million US dollars | | |
| | 1996 | 1997 | 2010 |
| 1.Sofia City | 0.519 | 0.958 | 0.921 |
| 2.Burgas | 29.894 | 32.861 | 31.481 |
| 3.Varna | 49.712 | 62.022 | 59.070 |
| 4.Lovech | 42.512 | 47.047 | 45.270 |
| 5.Montana | 28.116 | 28.529 | 27.399 |
| 6.Plovdiv | 15.833 | 16.135 | 15.548 |
| 7.Russe | 38.805 | 47.724 | 45.476 |
| 8.Sofia | 6.498 | 7.191 | 6.931 |
| 9.Haskovo | 24.613 | 24.103 | 23.173 |
| Total | 236.501 | 266.571 | 255.269 |

**Table 5** Price of losses for crops (wheat, corn and sunflower) for the nine regions of Bulgaria and for the whole country (the results for Scenario 2010 are calculated with meteorological data for 1997)

in the definition should be shifted (for example, April-May-June could be used instead of May-June-July). Moreover, it may be worthwhile to adjust the length of this period in connection with the specific growing period of the sorts of crops, typical for the countries in Southern Europe (the loss occurs precisely in the growing period).

- An attempt to evaluate the price of the loss due to high AOT40 values has been described in this paper. It is also important to evaluate the prices that have to be paid to perform the needed reductions of the emissions by which the loss will be avoided (or, at least, reduced). Having this two estimates a cost-benefit analysis can be carried out in an attempt to find an optimal solution of the problems. Such a study has to be carried out by multidisciplinary teams from many European countries.

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