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Calculating losses of crops in Denmark caused by high ozone levels

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In order to help guide air pollution legislation at the European level, harmful air pollution effects on agriculture crops and the consequent economic implications for policy have been studied for more than a decade. Ozone has been labeled as the most serious of the damaging air pollutants to agriculture, where growth rates and consequently yields are dramatically reduced. Quantifying the effects has formed a key factor in policymaking. Based on the widely held view that AOT40 (Accumulated exposure Over Threshold of 40 ppb) is a good indicator of ozone-induced damage, the Danish Eulerian Model (DEM) was used to compute reduced agriculture yields on a 50 km × 50 km grid over Europe. In one set of scenarios, a ten year meteorological time series was combined with realistic emission inventories. In another, various idealized emission reduction scenarios are applied to the same meteorological time series. The results show substantial inter-annual variability in economic losses, due in most part to meteorological conditions which varied much more substantially than the emissions during the same period. It is further shown that, taking all uncertainties into account, estimates of ozone-induced economic losses require that a long meteorological record is included in the analysis, for statistical significance to be improved to acceptable levels for use in policy analysis. In this study, calculations were made for Europe as a whole, though this paper presents results relevant for Denmark.

Keywords: air pollution models, AOT40 values for ozone, damaging effects, economical evaluations of losses

1. Damaging effects of high ozone concentrations on crops

Since political agendas began to embrace sustainable development as one of its strategic goals, industrial development was to be balanced by efforts to increasingly exploit alternative energy sources, improve the efficiency of food production, and invest in ways to reduce the pollution levels to prescribed acceptable levels and/or to keep them there. Anthropogenic emission reductions and environmentally friendly human practices were the generally accepted policies to pursue. Air pollution exposure has been labeled as one of the primary concerns in both the industrial and third worlds. Air pollution affects human health, water and soil quality, forests, ecosystems and food production. As part of an effort to quantify air pollution damages to a variety of sectors, i.e., with the hope to establish policies which are acceptable to both government authorities and stake-holders, many efforts were directed at quantifying the damages of air pollution exposures to, for example, agricultural crops. The key pollutant of concern to agricultural yield has been ozone.

It has long been recognized that high ozone concentrations induce damaging effects in agricultural crops, though little was known until 1990 of the extent of damages worldwide and/or of possible abatement options. During the past ten years, the scientific community expanded their efforts to conduct research on ozone exposure to specific types of crops. Newly designed open top chambers (OTC's) allowed systematic study, thus leading to quantifiable estimates for use in policy analysis. To report on early progress, a number of meetings were held during the 1990's, e.g., in Switzerland in 1993 [15], and in Finland in 1995 [22]. Among the recommendations from these meetings, a new parameter called AOT40 was introduced [15,22]. It was suggested that this parameter be applied to agricultural and economic assessments and the subsequent modelling of the benefits associated with reduced ozone exposure. The AOT40 parameter is commonly accepted now by the European experts studying damaging effects from high air pollution levels and is also recommended in the discussions of the forthcoming EU Ozone Directive (see, for example, [3,12,13]).

The selection of 40 ppb was a practical threshold value, below which agricultural damages due to ozone exposure were insignificant, and above which damages could be assumed to have a linear relation with increasing ozone concentration. The data which supported the AOT40 threshold and subsequent parameterizations were based on a large number of OTC experiments, both in Europe and in the United States. The results obtained in Europe are discussed in many papers of the proceedings [15,16,22]. In USA the efforts in this direction started earlier. The National Crop Loss Assessment Network (NCLAN) program was initiated in 1980 and finished in 1986. The number of species studied was 17. There were 38 field experiments (see more details in [20]). The results were used for economic assessment of the impact of high ozone levels on the USA agriculture [1]. The data collected during the work on the NCLAN program has also been used by many European scientists (see again [15,16,22]).

Policy analysis using agricultural land use practices, emission inventories, and meteorological time series, have generally been limited to average conditions extending over periods of, e.g., one year. Such limitations were imposed in most part due to costly computer resources and to the fact that the needed data bases were not available. However, with the recent explosion of computer power, combined with easily accessible data bases on high resolution European emission inventories (e.g., EMEP), it is possible now, by using modern and fast computers, to obtain answers to some key questions pertaining to shorter term episodes and variations, which were beyond reach only a few years ago:

- What are the effects on simulations of the short term exposure estimates, in particular during daytime hours of the primary growth season, from the beginning of May to the end of July?
- What are the impacts of strong inter-annual variability of meteorological variability, combined with existing emission inventories?
- What is the time span required in order to obtain statistically significant conclusions regarding ozone damage to crops and benefits of ozone abatement strategies?

Given that answers to such questions involve an extensive study in both modelling and simulation, we begin the process with the following objective: to evaluate the ozone-induced losses for one of the more important crops, i.e., wheat, where yield and economic costs are evaluated in terms of the model resolution. This objective requires sufficiently high spatial and temporal resolution of both meteorology and emissions, and a sufficiently long meteorological record. To provide a realistic assessment of the results of this study, Denmark was chosen as the study domain, due to its characteristic and systematic heterogeneous variability in agriculture, emissions, and meteorology. A detailed analysis of the statistical confidence of our results will be presented, on both the national level and for each of the Danish counties.

In this study, economic damages derived from AOT40 values were calculated over a period of ten years (from 1989 to 1998) using the Danish Eulerian Model. The following data files were required for the completion of this comprehensive task:

- the AOT40 values for Denmark for each year in the period from 1989 to 1998, based on previous studies carried out using the Danish Eulerian Model and verified by performing comparisons with measurements and with results obtained by other models (the accumulated AOT40 values for the three months, May, June and July, in which the crops are growing were actually used in this study, but data on a monthly basis for every year in the period 1989–1998 are also available in our data-base containing AOT40 values);
- the relationship between the AOT40 values and the crop losses, based on documentation of OTC results presented at meetings in Switzerland and Finland [15,22,25];
- information about the yield of crops in the different counties of Denmark for each of the ten years under consideration (derived from the Danish Statistical Bulletins, see [31–40]; also data from [7] was used); and
- the average market prices of the crops in Denmark for the ten years used in our study (this information is also taken from the Danish Statistical Bulletins; see again [31–40]).

As is perhaps apparent due to the limited number of available data files, an important assumption was invoked, i.e., that the environmental controls which affect crop yield are independent. Controls, such as drought, extreme heat, insufficient solar radiation, and ozone, are not necessarily independent and may act together to nonlinearly affect crop yield. The degree of independence is variable, year by year. In this study, we did not have access to such environmental details during the ten year period of study, and all conclusions will therefore be in reference to the assumption that ozone can act as an independent parameter affecting yield and economic costing.

From a computational point of view, the most demanding part of this study was the calculation of the complicated mix of atmospheric chemistry and meteorological transport patterns, which are used to derive high resolution maps of the AOT40 values. Such computations are extremely demanding, and can successfully be handled only if large modern computers are available and, moreover, if the numerical methods implemented in the model are running in an optimal (or, at least, nearly optimal) way. In this study, four powerful supercomputers were used. These were: a vector machine FUJITSU; a shared memory parallel SGI ORIGIN 2000 computer with up to 32 processors; a distributed memory IBM SP computer with up to 32 processors and a mixed shared-distributed memory architecture; an IBM SMP, containing two nodes working in a distributed memory mode with four processors on each node working in a shared memory mode. After making the numerical calculations of gridded AOT40, the model results were transmitted from the supercomputers to several workstations at the National Environmental Research Institute (NERI). All further calculations, including economic costing and visualizations were carried out on the NERI work-stations. The sequence of steps, i.e., using four parallel supercomputers and performing subsequent calculations on NERI workstations, was the optimum approach in addressing computer demanding questions, and required a large number of scenarios to achieve statistical significance. Additional details of the computational methods and/or optimization procedures for use in air pollution modelling may be found in the following references [2,4,18,27,29,42,45,46].

The paper is organized as follows. The definition of the way of measuring long-term exposures to high ozone concentrations in connection of crops is given in section 2. This is followed in section 3 with additional details of the computation techniques for AOT40, including statistical certainty of the results. The calculation of the agricultural losses in terms of differential yield is summarized in section 4, both for individual Danish counties as well as for the whole of Denmark.

2. Definition of the critical ozone levels for crops

Based on OTC results, it has for practical reasons been assumed that the critical exposure level for crops is 3000 ppb.hours, and losses of crops will be avoided if the AOT40 values do not exceed this level. Model calculations however show that for most regions of Europe, AOT40 values are on the order of 15000–25000 ppb.hours, and there is enormous inter-annual variability. Statistical variability will therefore include a significant spatial and temporal character. In addition, the selection of 40 ppb as the practical accepted threshold, rather than a small deviation from this value such as 39 ppb or 41 ppb, for example, adds an additional level of uncertainty which must be accounted for in this analysis.

We generalize the threshold value by considering the concentration as a variable, c, such that ozone induced damage to crops is a function of $AOT(c)$. Note for reference that AOT40 values are equivalent to $AOT(c)$ when the parameter $c = 40$ ppb. The function $AOT(c)$ may be extended to a practical form if defined by the sum:

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

where N is the number of day-time 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 $AOT(c)$ function given by (1) is based on the use of discrete values of the concentrations (hourly mean values). Often this function is defined by using a continuous representation of the concentrations; see, for example, [30]. The continuous representation given below is a slight generalization of the definition which is commonly used (see again [30] for the commonly used definition):

$$AOT\big(c(t)\big) = \sum_{i=1}^{M} \left\{ \int_{t_i}^{T_i} \max\big[c(t) - c, 0\big]\, \mathrm{d}t \right\}, \qquad (2)$$

where M is the number of days in the period under consideration (in this study this period contains the three months May, June and July; i.e., $M = 92$), while the independent variable t varies in the interval from sunrise t_i to sunset T_i for the day i, $i = 1, 2, \ldots, M$. We reiterate here that $c = 40$ ppb is used as the threshold in this study.

Some computations were carried out in an attempt to evaluate the error which appears when the continuous representation (2) is replaced with the discrete formula (1). Indeed, the discrete formula can be considered as a first-order numerical method (the Mid-point Rule, see section 2.1 in [8]) for the computation of an approximation of the integral in (2) with $\Delta t = 1$ hour. A higher order numerical algorithm (the Simpson's Rule, see again [8]) has also be applied with the same value of Δt in connection with a few runs. These additional calculations indicate that the error is relatively small, about 6%, assuming here that the discrepancy between the results obtained by these two formulae gives us an evaluation of the error. This is why the discrete formula (1) is used in this study. It should repeated here that the discrete formula (1) is commonly used for calculating AOT40 values.

2.1. *Difficulties in the computation of AOT40 values*

As mentioned in the previous sections, the Danish Eulerian Model (DEM) has been used to compute AOT40 values in the Danish grid cells for a period of ten years (1989–1998) and for different scenarios.

In fact, this model calculates AOT40 values for the whole of Europe, but only the results for the Danish cells are reported in this study. The results for the other parts of Europe are, however, stored and will be used in subsequent studies of other particular regions of Europe.

DEM is fully described in [42]. The numerical methods in DEM are discussed in [2,43–46]. Information about the model and results obtained by the model are also given in the web-site for the model [41].

Before starting to use the AOT40 values calculated by DEM for evaluating the losses of crops, it is necessary (i) to discuss the sensitivity of the AOT40 values to the (unavoidable) errors made in the process of computations and (ii) to try to verify the calculated by DEM AOT40 values by comparing them with AOT40 values measured at appropriate stations (in our study, at stations located either in Denmark or close to the borders of Denmark).

2.2. *Sensitivity of the AOT40 values to errors*

The process of computation of AOT40 values is rather unstable in the sense that small errors, which are caused either by the numerical methods used in the model or by uncertainties of the input data and/or the physical and chemical mechanisms implemented in different parts of the model, can lead to large errors in the AOT40 values. A direct implication of this kind of instability is the fact that the model can produce very poor quality AOT40 values even when the ozone concentrations, which are calculated by the same model, are rather accurate. This can be illustrated by the following example.

Denote by c_i^{exact} the exact ozone concentration at hour i, where $i = 1, 2, \ldots, N$. Assume that the corresponding calculated and measured ozone concentrations are denoted by $c_i^{\text{calculated}}$ and c_i^{measured}, respectively. If the values of these three quantities (measured as usual in ppb) are

$$c_i^{\text{exact}} = 41, \qquad c_i^{\text{calculated}} = c_i^{\text{measured}} = 42, \qquad (3)$$

then the value of the relative error of the calculated ozone concentration (in percent) is given by

$$\frac{100|c_i^{\text{exact}} - c_i^{\text{calculated}}|}{c_i^{\text{exact}}} \approx 2.44, \tag{4}$$

which is as a rule considered an excellent result. Of course, the value of the relative error of the measured ozone concentration is in this case precisely the same.

Let us calculate now the relative errors of the calculated and measured contribution to the AOT40 value for the hour i. It is clear that the result for the contribution to the relative error in the calculated AOT40 value for hour i (assuming as always in this paper that $c = 40$ ppb) is given by the expression

$$\frac{100|c_i^{\text{exact}} - c_i^{\text{calculated}}|}{|c_i^{\text{exact}} - c|} = 100, \tag{5}$$

which is a very bad result. Again the same result can be obtained for the contribution to the relative error in the measured AOT40 value for hour i.

Two important conclusions can easily be drawn from this simple but illustrative example:

- The sensitivity of the results to errors is a consequence of the definition of the AOT40 and, therefore, it depends only on the accuracy of the achieved results but not on the way of producing the results (i.e., the AOT40 values calculated both by using a model or by measurements will necessarily be very sensitive to errors and uncertainties).
- As mentioned above, the model or the measurements can give very poor AOT40 values even if the calculated (or measured) ozone concentrations are rather accurate.

The numerical example given above indicates also that the critical regions, where the uncertainties in the calculations of the AOT40 values will normally be very large, are the regions where the AOT40 values are in the neighborhood of the critical level of 3000 ppb.hours. Indeed, in such cases the ozone concentrations will quite often be in the neighborhood of the threshold of 40 ppb and, thus, the error of the contributions to the AOT40 values will be, as shown by the above example, very sensitive to errors. In regions where the AOT40 values are exceeded by a large amount, such as 5–7 times, usually the contributions to the AOT40 values will be large. The experiments show that very often the major contributions are given by concentrations greater than 80 ppb, and the numerical uncertainty is reduced considerably when this is so. Indeed, if $c_i^{\text{exact}} = 82$ and $c_i^{\text{calculated}} = c_i^{\text{measured}} = 84$, then the relative errors of the calculated and measured concentrations are precisely the same, about 2.44%, as in (4), while the relative errors of the contributions to both the calculated and the measured AOT40 values at hour i are reduced from 100% in (5) to about 4.76%.

Similarly, no problems arise in the regions where the AOT40 values are generally under 3000 ppb.hours because in this case the calculated concentrations will often be under 40 ppb and, thus, will not contribute to the AOT40 values.

Denmark is in a region where a sharp north–south gradient of AOT40 is observed. This is illustrated by data which show AOT40 north of Scandinavia are generally below the critical value of 3000 ppb.hours, while south of Denmark the AOT40 values are often two or three times this critical values. An example is provided in figure 1 for 1998. It should be noted that 1998 is one of the "good years" within the ten-year period studied in this paper (with relatively small AOT40 values in Denmark). It should also be noted that 1998 is, in some sense, not very typical. Normally, the AOT40 values in Germany, the Netherlands, Belgium and Northern France are rather high (see, for example, [5]), most likely due to some combination of the emissions and meteorological variability for that given year.

It is clear from this discussion that it is necessary to carry out some special, for the area of Denmark, verification of the results. This will be done in the next section.

2.3. Verification tests of the model results

The ability of this model to produce reliable AOT40 values has been validated in [5,47], where the AOT40 values calculated by the model over the whole of Europe were compared with the corresponding measured values at more than 90 measurement stations located in different European countries. Something more is needed in this study. Indeed, most of the stations that have been used in [5,47] are located in highly polluted areas. In this paper we are interested in studying the economical losses in Denmark, which are caused by high AOT40 values. The ozone pollution levels in Denmark are normally not very high. The analysis given in the previous subsection indicates that it is crucial to compare the AOT40 results calculated by DEM with measurements taken in stations located in Denmark or, at least, close to the Danish borders. Therefore, we located eight such stations (see figure 2) and compared models results with measurements taken at the selected stations.

If a given station provides measurements for each day-time hour of the period from the beginning of May to the end of July, then the AOT40 value for this station can be calculated by applying (1), in the same way as the AOT40 values are calculated by using model results. Unfortunately, there are always missing measurements. If all missing measurements are taken in cases where the ozone concentrations are less than 40 ppb, then the missing concentrations have no effect on the resulting AOT40 value. It is clear, however, that this will normally not be the case. Thus, in the case of missing measurements, approximations of the AOT40 values will in general be obtained (even in the ideal case where there are no errors in the measurements).

Approximations to the AOT40 values were calculated (for each year of the period from 1989 to 1997, the measurements for 1998 are not yet available) at the eight selected stations by using the hourly measurements at day-time and formula (1). The averaged AOT40 values (over the nine-year

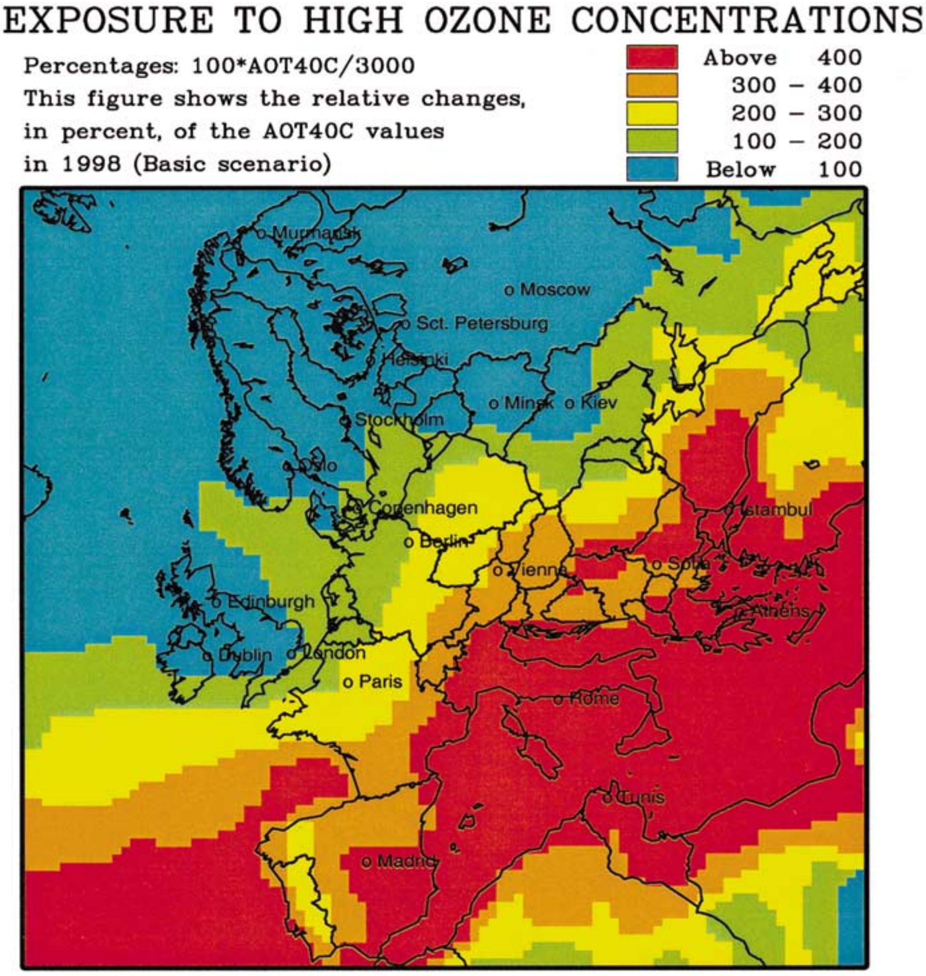


Figure 1. The distribution of the AOT40 values in Europe in 1998.

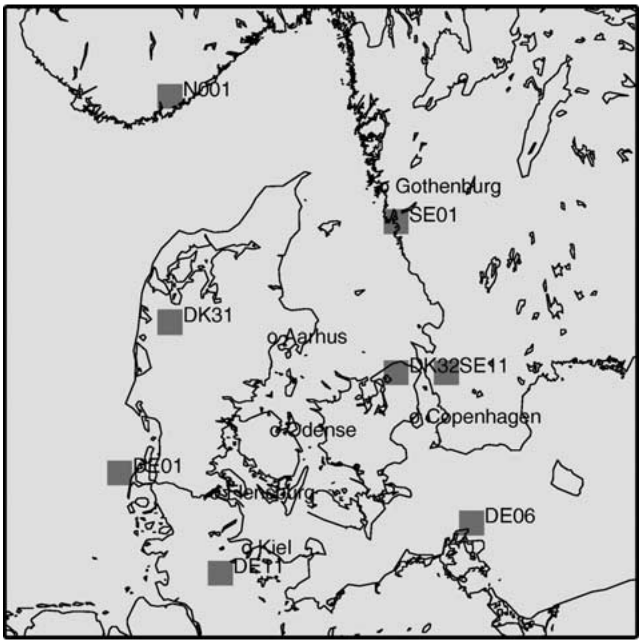


Figure 2. Measurement stations used in the verification tests.

period) are compared with the corresponding model results in table 1.

The following remarks are needed in order to facilitate the interpretation of the results presented in table 1:

- There are only measurements for 1989 at Arkona. These measurements are compared with model results for 1989.
- "Missing" refers to the total number of missing measurements for the nine-year period (for each year only in day-time hours from the beginning of May to the end of July, i.e., the total number of day-time hours in the three months under consideration during the nine-year period is about 12 000 for Denmark and its surroundings). For Arkona, "Missing" is giving the number of missed measurements in 1989.
- "Discrepancy" refers to the quantity:

$$\frac{|\text{Measured AOT40} - \text{Calculated AOT40}|}{\text{Calculated AOT40}}.$$

It is seen (the numbers given in brackets in the fourth and fifth columns in table 1) that the exceedances over the critical limit of 3000 ppb.hours vary in the interval [1.2, 3.3] for the measured AOT40 values, while the variation is in the interval [1.3, 2.5] for the calculated AOT40 values. The dis-

Table 1
Comparison of averaged (over the nine-year period) measured and calculated AOT40 values. The figures in brackets show by how much the critical value of 3000 ppb.hours is exceeded.

Station	Country	Code	Measured	Calculated	Discrepancy	Missing
Ulborg	Denmark	DK31	4328 (1.4)	6100 (2.0)	29%	2123
Frederiksborg	Denmark	DK32	4812 (1.6)	4811 (1.6)	0%	1362
Rörvik	Sweden	SE1	5866 (2.0)	4667 (1.6)	26%	816
Vavihill	Sweden	SE11	7232 (2.4)	5140 (1.7)	41%	686
Birkenes	Norway	NO1	3677 (1.2)	3806 (1.3)	3%	447
Westerland	Germany	DE1	5971 (2.0)	7480 (2.5)	20%	672
Arkona	Germany	DE6	9889 (3.3)	7410 (2.5)	33%	18
Hohenwestedt	Germany	DE11	4969 (1.7)	6533 (2.2)	24%	686

crepancies between measured and calculated AOT40 values vary in the interval [0%, 41%] (see the numbers in the sixth column of table 1). There are several reasons for these discrepancies. Three of them are very important:

- The AOT40 values at a given point are evaluated when measurements are used, while a mean AOT40 value at the grid-square (50 km × 50 km = 2500 km^2), in which the station under consideration is located, is calculated by the model.
- The model calculations rely heavily on the anthropogenic emission inventories used. The uncertainties of the anthropogenic emission inventories are evaluated to be about 30%. These uncertainties increase when the anthropogenic emissions are actually used in the models (because only annual values are available for every grid-square and it is necessary to simulate some temporal variations).
- The uncertainties of the biogenic emissions are even greater than the uncertainties of the anthropogenic emissions.

Taking into account the above short discussion of the uncertainties, one could consider the calculated discrepancies as an indication that the results are “good” (in the sense that the calculated discrepancies are comparable with the uncertainties of the most important input data and/or the uncertainties caused by comparing representative mean values on rather large grid-cells with measurements at given points within the cells).

If the discrepancies are compared on annual basis, then they vary on a wider interval, but can still be considered as acceptable (taking into account both the large numbers of missing measurements and the uncertainties in the input data used in the model). It should be emphasized here that the number of missing measurements at Ulborg seems to be very high (for some years). The results obtained for the Danish measurement station Ulborg, year by year, are shown in table 2. While is not very clear why the results produced by the model for 1990 and 1997 differ so much from the corresponding measurements, we suspect that there may be local subgrid scale processes (caused by specific meteorological conditions in 1990 and 1997). It is well known that this can take place, and this is one of the reasons to recommend taking mean AOT40 values over a period of five years (see, for example, [3,5,15,22]).

Table 2
Comparison of measured and calculated annual AOT40 values at Ulborg (Denmark, DK31). The figures in brackets show by how much the critical value of 3000 ppb.hours is exceeded.

Year	Measured	Calculated	Discrepancy	Missing
1989	7340 (2.4)	7770 (2.6)	6%	116
1990	1361 (0.5)	7650 (2.6)	82%	347
1991	4356 (1.5)	4920 (1.6)	11%	637
1992	8619 (2.9)	7290 (2.4)	18%	421
1993	4675 (1.6)	5400 (1.8)	13%	279
1994	5588 (1.9)	8250 (2.8)	32%	52
1995	3340 (1.1)	6780 (2.3)	51%	176
1996	2198 (0.7)	2700 (0.9)	19%	46
1997	1473 (0.5)	4140 (1.4)	64%	49
Average	4328 (1.4)	6100 (2.0)	29%	2123

Table 3
Comparison of measured and calculated averaged (for years 1989, 1990, 1992, 1993 and 1994) AOT40 values at Ulborg (Denmark, DK31). The figures in brackets show by how much the critical value of 3000 ppb.hours is exceeded. The IIASA results are taken from [3, table 2.8].

Source	Averaged AOT40 value	Discrepancy
Measured (Ulborg)	5517 (1.8)	–
Computed (DEM)	7272 (2.4)	24%
Computed (IIASA)	8000 (2.7)	31%

The model results calculated with the Danish Eulerian Model have also been compared with results given in the Seventh Interim IIASA Report (see [3, table 2.8]). AOT40 values, which are averaged for the years 1989, 1990, 1992, 1993 and 1994, are given in [3, table 2.8]. Some results from the comparison with the the AOT40 values from [3] are given in table 3.

3. Calculating the losses from the yield of crops in Denmark

If AOT40 exceeds 3000 ppb.hours, then a linear relationship, which is discussed in Pleijel [25], can be applied to evaluate the loss from the yield of crops due to the high ozone pollution levels. The implementation of this linear relationship is described in this section.

The EMEP grid has to be mapped on the regional division of Denmark. This has been done by preparing a rectangular matrix A. The rows of A correspond to the fourteen Danish counties, while the columns correspond to (10×7) sub-grid of the EMEP grid (this sub-grid contains 70 cells and covers the whole of Denmark together with some surrounding areas). Let V_i be the area of the ith Danish region. Let v_{ij} be the part of the ith Danish region contained in the jth cell $(i = 1, 2, \dots, 14,\ j = 1, 2, \dots, 70)$. 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 run to calculate and store for future use matrix A) 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, ξ is the AOT40 in ppb.hours, the following formula is actually used to calculate the losses:

$$100y/(y+z) = \alpha\xi + \beta \quad (\alpha < 0,\ \beta \approx 100), \qquad (6)$$

where α and β are statistically determined coefficients. The values $\alpha = -0.00151$ and $\beta = 99.5$ have been used to calculate the losses from the yield of crops in each Danish county as well as for the whole country in the time period from 1989 to 1998. These values of $\alpha = -0.00151$ and $\beta = 99.5$ are recommended for wheat and for Scandinavian conditions in Pleijel [25]. In the same paper Pleijel uses other values for the rest of Europe ($\alpha = -0.00177$ and $\beta = 99.6$). The values of the first pair (α, β) are determined by analyzing a large amount of experimental data taken in the Scandinavian countries, while the values of the second pair (α, β) are derived by using experimental data which are representative for the whole of Europe ([25], see also [14,17,21]).

4. Calculating the cost of the losses

The market prices for the years in the period from 1989 to 1998 have been taken from the official Danish statistics. Having the losses from the yields of crops and the prices of the crops for the years under consideration, it is not difficult to evaluate the cost of the losses under an assumption that the prices will remain the same for the expected yield (i.e., the yield which will be obtained if the critical ozone levels were not exceeded). This has been done for each year in the studied period. The results obtained in these calculations will be presented in section 6.

It would probably be more beneficial to apply some strategies for dynamical evaluation of the prices as a function of both the amount of the yield and the international economical conjuncture. Such a study requires some more advanced economical models. There are plans to carry out such a study in the future.

5. Selection of different scenarios

It is not sufficient to calculate results concerning losses of yield from crops caused by the actual emissions. It is also necessary to attempt to give an answer to any of the following questions:

1. Is it at all possible to avoid the exceedance of the critical level of 3000 ppb.hours in Denmark and/or in Europe?
2. Will the critical level of 3000 ppb.hours be exceeded if the reduction of the appropriate emissions is very substantial?
3. What will happen if the traffic emissions are drastically reduced?

The Danish Eulerian Model has been run with all anthropogenic emissions in Europe reduced to zero (but keeping the biogenic emissions in the whole of Europe unchanged) in order to obtain an answer to the first question. The runs with this scenario, the Zero Scenario, indicate that the answer to the first question is positive. The AOT40 values calculated by using this removal were under the critical level of 3000 ppb.hours for the whole of Europe. The mean values of the ozone concentrations in Denmark were between 8–15 ppb. While the removal of all anthropogenic emissions is not a solution which can be used in practice, the results obtained by using this scenario are indicating that the exceedances of the AOT40 values over the critical level of 3000 ppb.hours are due to anthropogenic emissions.

The Big Reductions Scenario, with large reductions of the anthropogenic emissions in Europe (again keeping the biogenic emissions unchanged), was run to address the second question. The anthropogenic NO_x, VOC and CO emissions were reduced to 15% of the 1989 levels. Also, in this case, the calculated AOT40 values were under the critical level of 3000 ppb.hour in the whole of Europe. The mean values of the ozone concentrations in Denmark were between 19 and 23 ppb.

The emissions due to traffic were reduced by a big amount, 90%, in the attempt to answer the third question (information about the traffic emissions given in the Seventh Interim Report of IIASA [3] has been used to perform the

Table 4

Comparison of the total anthropogenic NO_x emissions in Europe obtained by three scenarios. (The emissions of Scenario 2010 do not change from one year to another, they are calculated from the emissions for 1990 by using specific factors for each country.) The units are 1000 tonnes N per year.

Year	Basic Scenario	Traffic Scenario	Scenario 2010
1989	23752	10688	14980
1990	23277	10475	14980
1991	22564	10154	14980
1992	21614	9726	14980
1993	20664	9299	14980
1994	20189	9085	14980
1995	19714	8871	14980
1996	19239	8658	14980

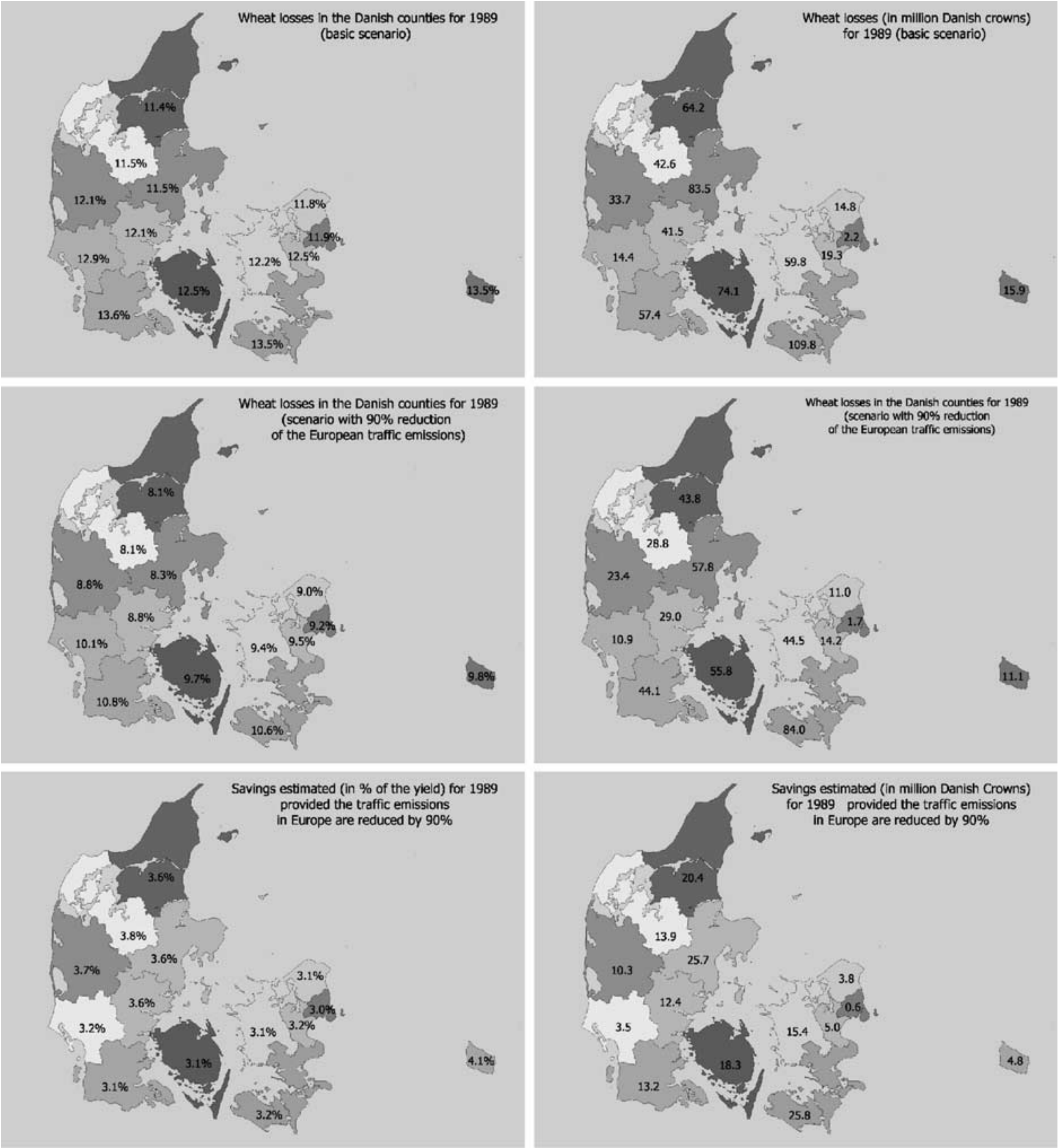


Figure 3. Losses (in percent) and prices (in millions of Danish crowns) of losses for 1989 in Denmark by counties.

reductions). This resulted in the following total reductions of the anthropogenic European emissions:

- the anthropogenic NO_x emissions were reduced by 45%,
- the anthropogenic VOC emissions were reduced by 40%,
- the anthropogenic CO emissions were reduced by 54%,
- the anthropogenic SO_2 and NH_3 emissions as well as the biogenic emissions were kept unchanged.

The scenario obtained by these reductions will be called the Traffic Scenario. It should be noted here, however, that the Traffic Scenario for 1989–1991 is close to Scenario 2010 (Scenario 2010 is discussed in several places, in this paper we have used the factors for reducing the emissions, in every European country, which are given in [3]). For the other years, the above reductions give total emissions that are considerably less than the emissions for Scenario 2010, because the reductions are applied for the actual emissions for the year under consideration and the actual emissions have been reduced in the period 1989–1998. This situation is clearly seen from table 4, where the total anthropogenic NO_x emissions in Europe for three scenar-

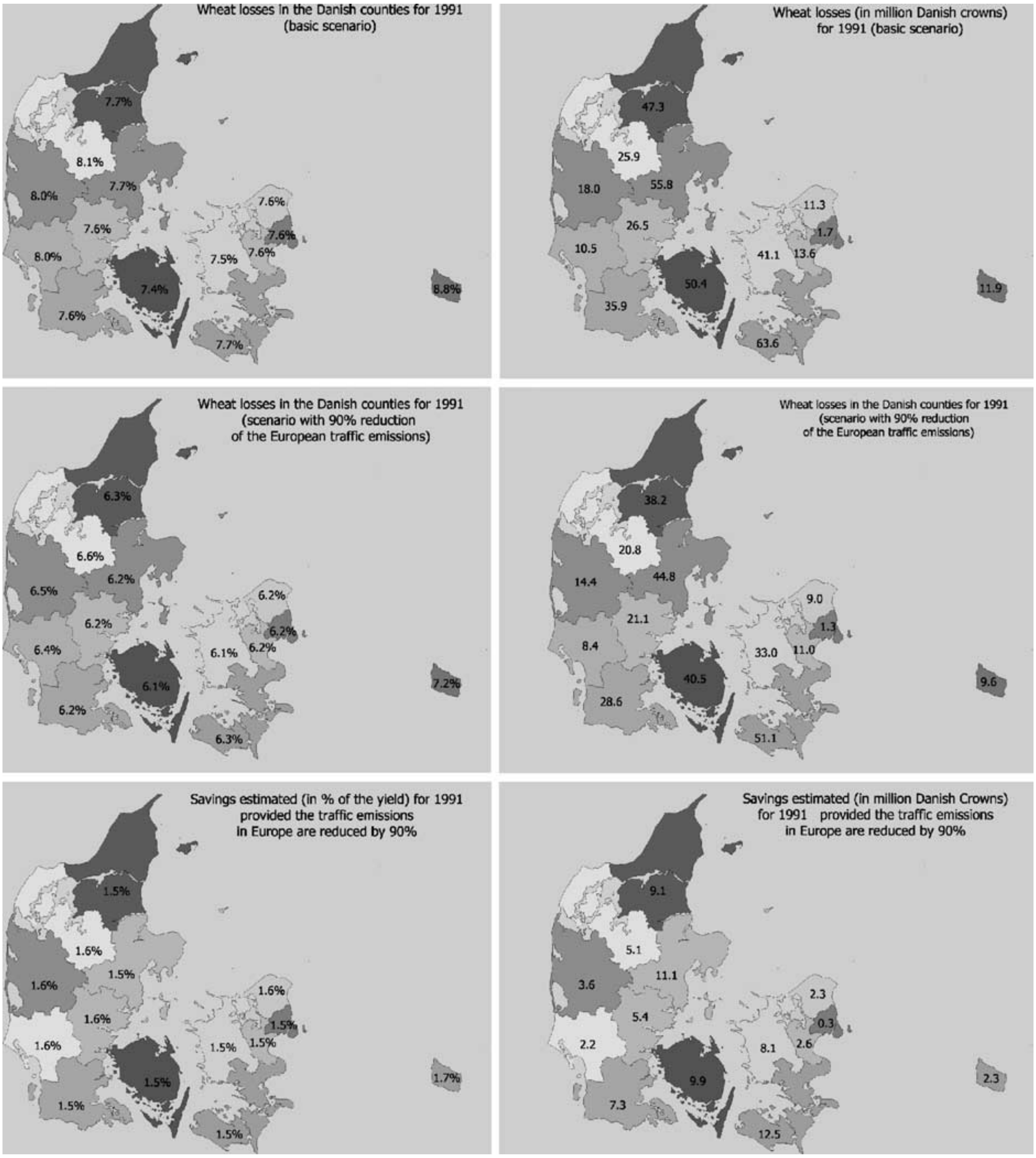
Figure 4. Losses (in percent) and prices of losses (in millions of Danish crowns) for 1990 in Denmark by counties.

ios are given for each year in the period 1989–1996 (the emission inventories for 1997 and 1998 are still not available, the 1996 emissions are used also for years 1997 and 1998).

The results concerning losses of yield from crops in the Danish counties and in the whole of Denmark, which are obtained with the Traffic Scenario, will be compared in the next section with the corresponding results found by the Basic Scenario (table 4).

6. Results from runs with the selected scenarios

Losses of yield from wheat have been calculated for the years 1989–1998 by using the Basic Scenario, in which the Danish Eulerian Model has been run by using the actual EMEP emissions for these years. By using the losses and the prices of wheat, the economical losses were also calculated. The same procedure was then repeated for the Traffic Scenario. The results are shown in figures 3–12. Six plots are given in each figure:


Wheat losses in the Danish counties for 1991 (basic scenario)

Wheat losses (in million Danish crowns) for 1991 (basic scenario)

Wheat losses in the Danish counties for 1991 (scenario with 90% reduction of the European traffic emissions)

Wheat losses in the Danish counties for 1991 (scenario with 90% reduction of the European traffic emissions)

Savings estimated (in % of the yield) for 1991 provided the traffic emissions in Europe are reduced by 90%

Savings estimated (in million Danish Crowns) for 1991 provided the traffic emissions in Europe are reduced by 90%

Figure 5. Losses (in percent) and prices of losses (in millions of Danish crowns) for 1991 in Denmark by counties.

- upper left plot: the losses of the yield from wheat obtained with the Basic Scenario,
- centre left plot: the losses of the yield from wheat obtained with the Traffic Scenario,
- lower left plot: the difference between the losses of the yield from wheat obtained with the two scenarios divided by the actual yield from wheat,
- upper right plot: the prices (in millions of Danish crowns) of the losses of the yield from wheat obtained with the Basic Scenario,
- centre right plot: the prices (in millions of Danish crowns) of the losses of the yield from wheat obtained with the Traffic Scenario,
- lower right plot: the difference between the prices of the losses of the yield from wheat obtained with the two scenarios.

Average results over the studied period of ten years have also been calculated. These results are shown in figure 13. The six plots in figure 13 are as the plots displayed in figures 2–12. The results given in figures 2–12 indicate that

Wheat losses in the Danish counties for 1992 (basic scenario)

Wheat losses (in million Danish crowns) for 1992 (basic scenario)

Wheat losses in the Danish counties for 1992 (scenario with 90% reduction of the European traffic emissions)

Wheat losses in the Danish counties for 1992 (scenario with 90% reduction of the European traffic emissions)

Savings estimated (in % of the yield) for 1992 provided the traffic emissions in Europe are reduced by 90%

Savings estimated (in million Danish Crowns) for 1992 provided the traffic emissions in Europe are reduced by 90%

Figure 6. Losses (in percent) and prices of losses (in millions of Danish crowns) for 1992 in Denmark by counties.

the AOT40 values vary considerably both from one year to another and from one sub-region of Denmark to another. This is due to the fact that the growing period for crops is rather short (three months only) and, therefore, the meteorological conditions may play an important role on the production of ozone during these periods, even in two consecutive years (see, for example, the results for 1996 and 1997).

Results for the whole of Denmark were also prepared. The temporal variation of the losses of yield from wheat for the whole of Denmark over the ten-year interval is shown in figure 14. Similar results, about the prices of the losses, are given in figure 15.

The results given in figures 3–15 can be viewed as upper bounds of the losses (cost of the losses) from the yield of wheat. Some lower bounds can be calculated under the simple assumption that if the critical level of 3000 ppb.hours is exceeded, then the losses from the yield of wheat are always 5%. The lower and the upper bounds for the whole of Denmark (averaged over the period of ten years) can be seen in


Wheat losses in the Danish counties for 1993 (basic scenario)

Wheat losses (in million Danish crowns) for 1993 (basic scenario)

Wheat losses in the Danish counties for 1993 (scenario with 90% reduction of the European traffic emissions)

Wheat losses in the Danish counties for 1993 (scenario with 90% reduction of the European traffic emissions)

Savings estimated (in % of the yield) for 1993 provided the traffic emissions in Europe are reduced by 90%

Savings estimated (in million Danish Crowns) for 1993 provided the traffic emissions in Europe are reduced by 90%

Figure 7. Losses (in percent) and prices of losses (in millions of Danish crowns) for 1993 in Denmark by counties.

Table 5
Lower and upper bounds for the averaged (per year) losses and prices of the losses in Denmark (the averaged losses are given in percent, while the averaged prices are given in millions of Danish crowns).

Bound	Losses in percent	Prices in Danish crowns
Lower	4.2	202
Upper	7.7	396

table 5. It should be pointed out that the lower bounds are similar to those obtained in [28].

7. Concluding remarks and plans for future work

The results presented in this study are based on the use of the more or less settled Level I concept. Detailed information about this concept can be found in the papers included in [15,22]. Recent research indicates that economical evaluation should be based on the more advanced Level II concept. This topic has been discussed by many scientists from the European community during their last workshop in Switzerland ([16]; see also Emberson et al. [9–11] and Karlsson et al. [23]). However, it was also stressed in [16]

Figure 8. Losses (in percent) and prices of losses (in millions of Danish crowns) for 1994 in Denmark by counties.

that there are still many unresolved problems in connection with the practical implementation of the Level II approach ("*development is still in progress and many research issues remain*" [16, p. 18]). As an interim solution, it is proposed to use a modified AOT40 approach using a set of factors for variables influencing ozone uptake by the plants. However, there are still open questions related also to this interim solution. First attempts in this direction were made in [19,26]. It would be interesting to first apply the interim solution and then the complete Level II approach (when all problems with its practical implementation are resolved) and to investigate the differences between the results obtained in this paper and the results that are based on the use of more advanced approaches. We are planning to carry out this comparison in the near future.

It has been emphasized in the beginning of this paper that the uncertainties connected with the evaluations of the losses and costs of the losses due to high ozone levels are very large. Moreover, the experience gained after many trials indicates that some changes of the methodology are needed

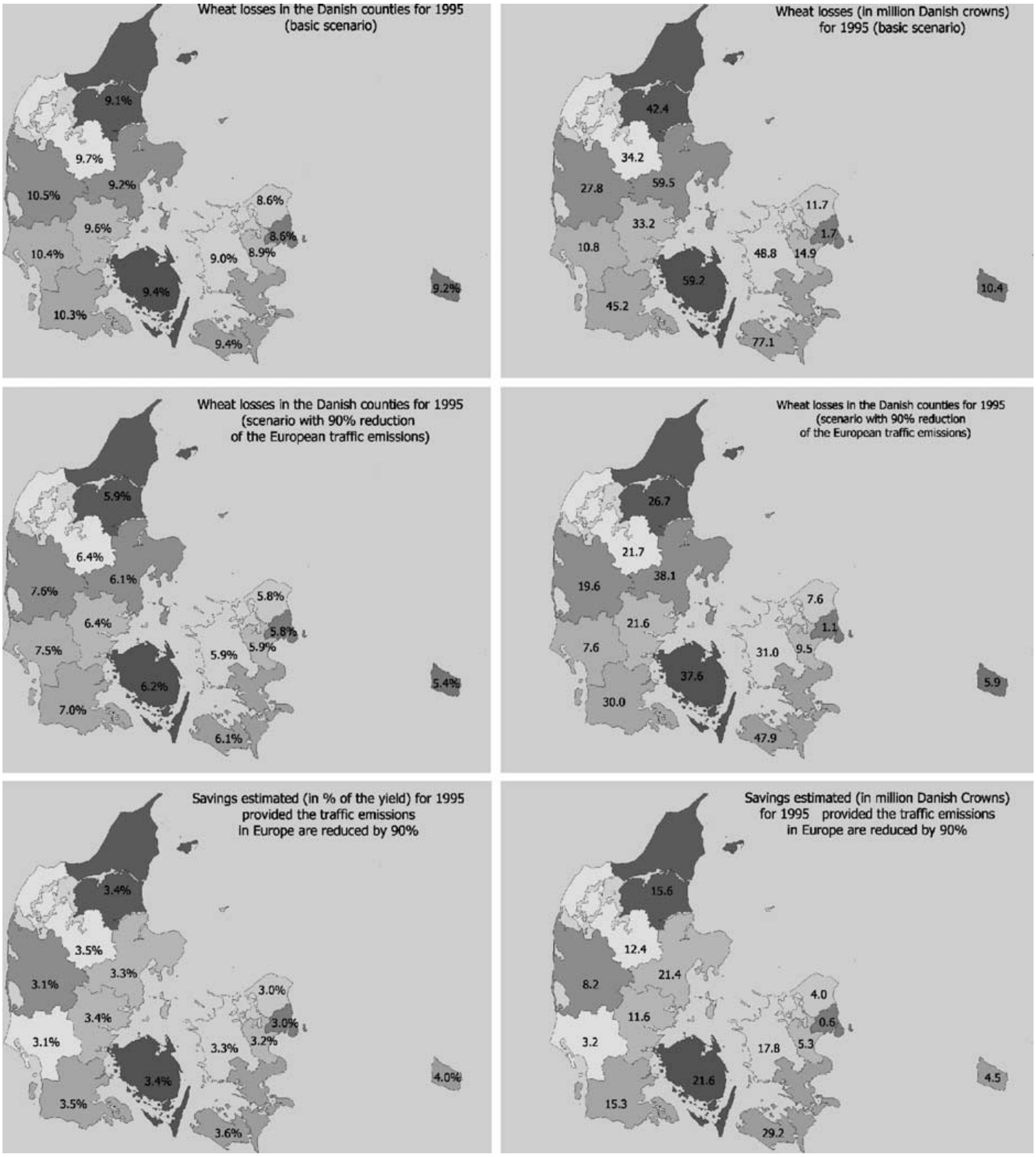


Figure 9. Losses (in percent) and prices of losses (in millions of Danish crowns) for 1995 in Denmark by counties.

(see the previous paragraph). Therefore one should be careful when the results presented in this paper are interpreted. Three important conclusions can be drawn in spite of the difficulties due to the uncertainties discussed in this paragraph:

- The results given in the figures and tables indicate that the losses due to high ozone levels are significant.
- The results obtained with different scenarios indicate that the losses can be fully avoided only if unrealistically high emission reductions are performed.
- The results indicate also that the losses can be reduced significantly (but not avoided) if very large reductions of the traffic emissions are made. It should be pointed out that it is hard to believe that such big reductions of the traffic emissions can be achieved. However, the total emissions in Europe can be reduced approximately to the same level by reducing not only the traffic emissions, but also the emissions from other sectors (it has been pointed out in section 7 that the total European emissions for the Traffic Scenario do not differ too much from the emis-

Figure 10. Losses (in percent) and prices of losses (in millions of Danish crowns) for 1996 in Denmark by counties.

sions in Scenario 2010 proposed by IIASA, see table 4 and [3]).

Although there are still many uncertainties, the results in this paper indicate that high AOT40 values are causing rather big losses of the yield of crops in Denmark. The study has been carried out over a very long time-interval: ten years (1989–1998). The value of the losses varies from one year to another. The variations are caused both by the fact that the meteorological conditions are changing from one year to another and by the fact that the European anthropogenic emissions were gradually reduced in the studied period.

Several scenarios were also performed. The two scenarios with dramatic reductions of the anthropogenic emissions, the Zero Scenario and the Big Reduction Scenario, show that *it is theoretically possible* to avoid losses caused by high AOT40 values. These reductions are, however, quite unrealistic and, therefore, cannot be carried out in practice with today's technology and/or policy frameworks. On the other hand, the experiments with such scenarios indicate

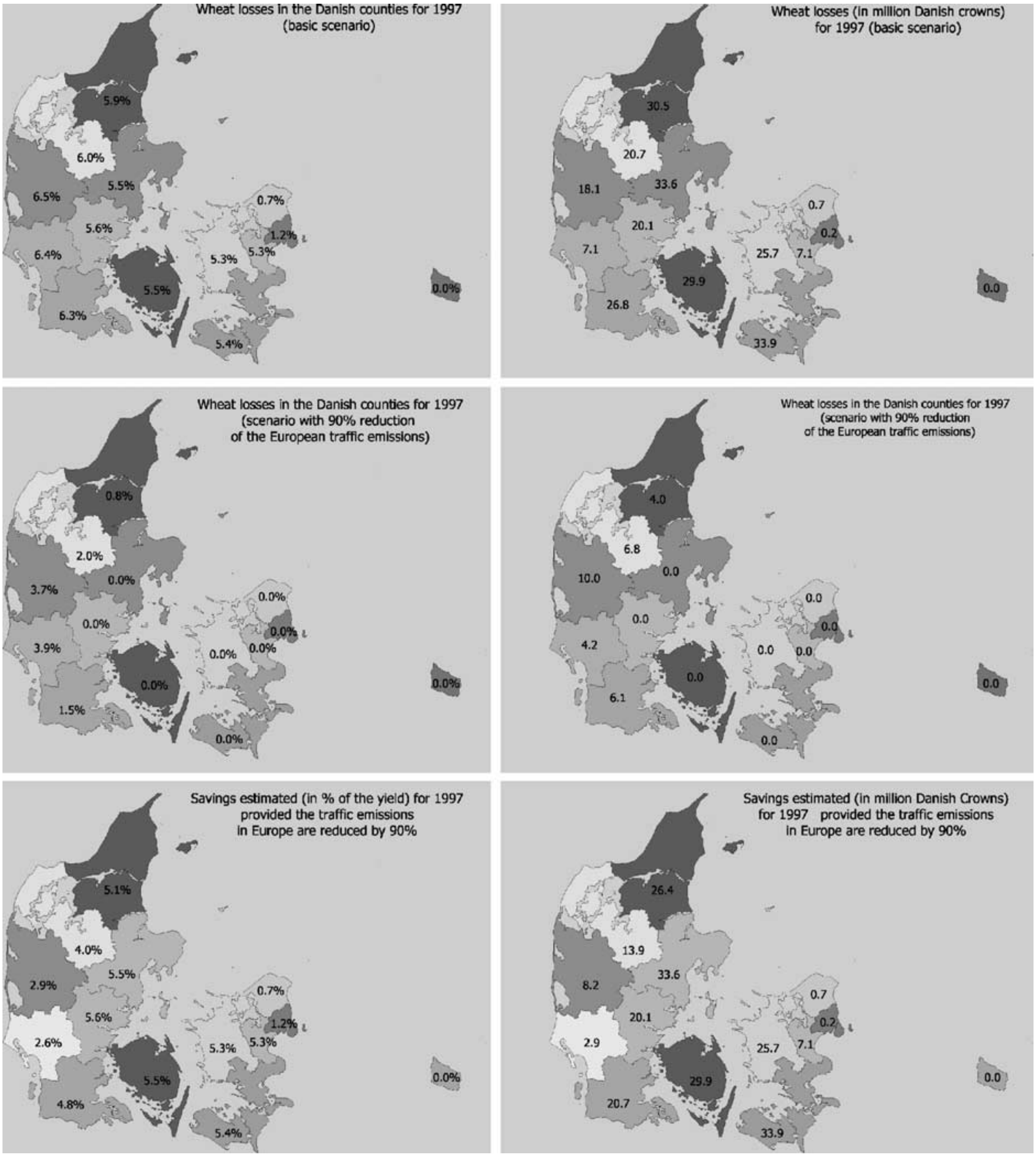


Figure 11. Losses (in percent) and prices of losses (in millions of Danish crowns) for 1997 in Denmark by counties.

that the exceedances are entirely due to anthropogenic emissions.

The runs with the Traffic Scenario indicate that reductions of the emissions which are less than those suggested in the well-known Scenario 2010 (but comparable with it) will reduce the amount of losses due to high AOT40 values. However, the losses will in general not be avoided, even in the Danish area. On the other hand, the results in this paper are important to the assessment of benefits associated with traffic emissions reduction policy.

The question of finding the optimal (which in this context means, roughly speaking, the smallest) reductions for the European emissions by which the critical value of 3000 ppb.hours will not be exceeded is still open. Probably, it will not be possible to implement in practice such optimal reductions when these are found (these reductions will still be too big, which is indicated from the previous conclusion about the Traffic Scenario).

Finally, the question of identifying the emission sources, which are most important for the ozone levels in Denmark, is

Wheat losses in the Danish counties for 1998 (basic scenario)

Wheat losses (in million Danish crowns) for 1998 (basic scenario)

Wheat losses in the Danish counties for 1998 (scenario with 90% reduction of the European traffic emissions)

Wheat losses in the Danish counties for 1998 (scenario with 90% reduction of the European traffic emissions)

Savings estimated (in % of the yield) for 1998 provided the traffic emissions in Europe are reduced by 90%

Savings estimated (in million Danish Crowns) for 1998 provided the traffic emissions in Europe are reduced by 90%

Figure 12. Losses (in percent) and prices of losses (in millions of Danish crowns) for 1998 in Denmark by counties.

important. The answer to this question is not an easy one, because of the non-linearity of the chemical reactions in which ozone is involved. Indeed, some results presented in [6] indicate that setting the Danish emissions to zero will in some cases lead to an increase of the ozone levels in Denmark (see [6, figure 8]). This fact indicates that

- the problem of identifying the sources, which are most responsible for the high ozone levels in Denmark, is very complex

and, which is even more important,

- further research in this direction is highly desirable.

The conclusion is that reductions of the emissions in an area, which is much bigger than Denmark (perhaps, the whole of Europe), are needed in the attempt to reduce the ozone pollution levels in Denmark. We plan to continue our work in this direction in the near future.

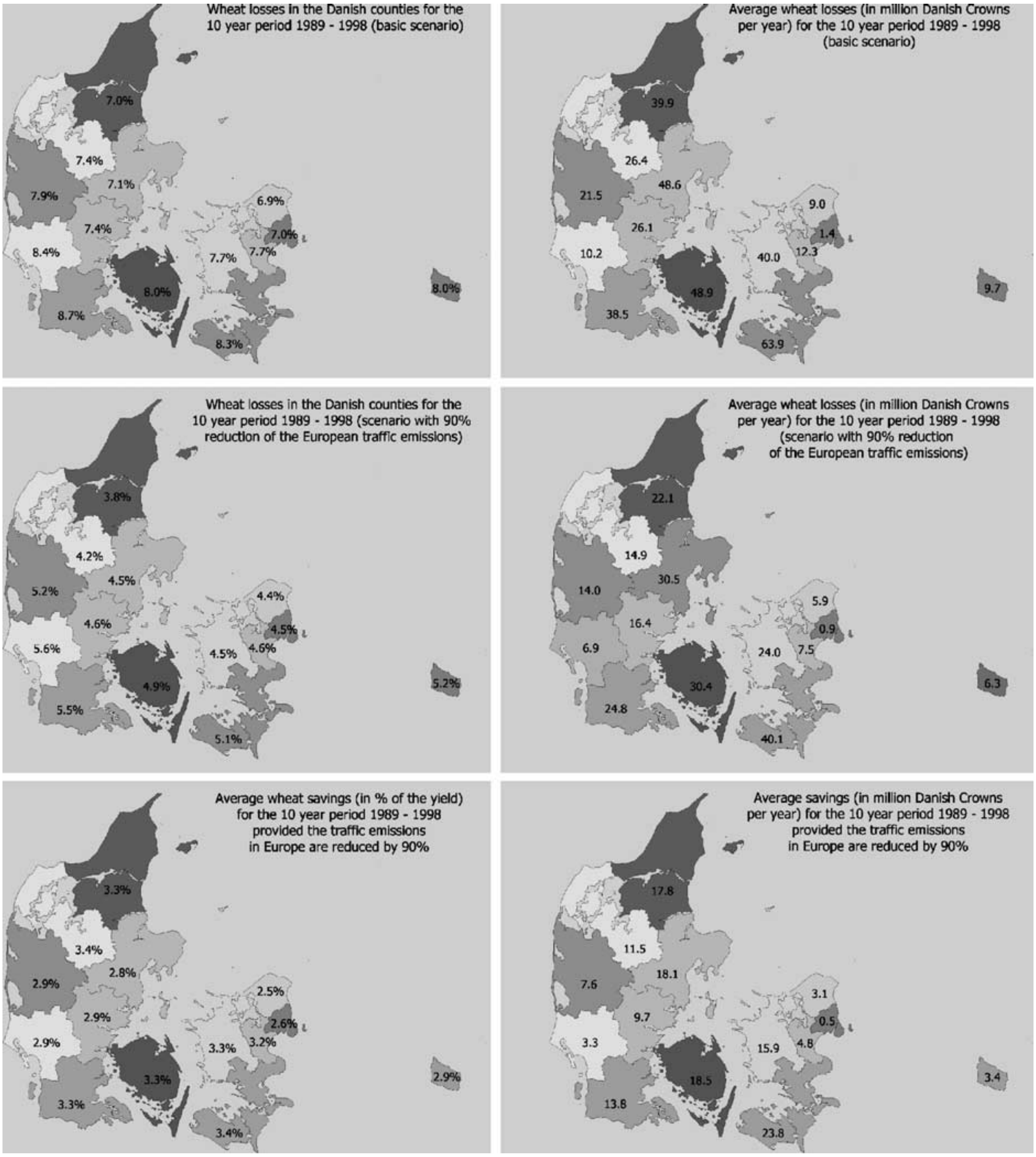


Figure 13. Averaged, over the period of ten years, losses (in percent) and prices of losses (in millions of Danish crowns) in Denmark.

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It should also be pointed out that the presentation of the results was improved considerably by following the constructive suggestions made by two unknown referees on a previous version of this paper.

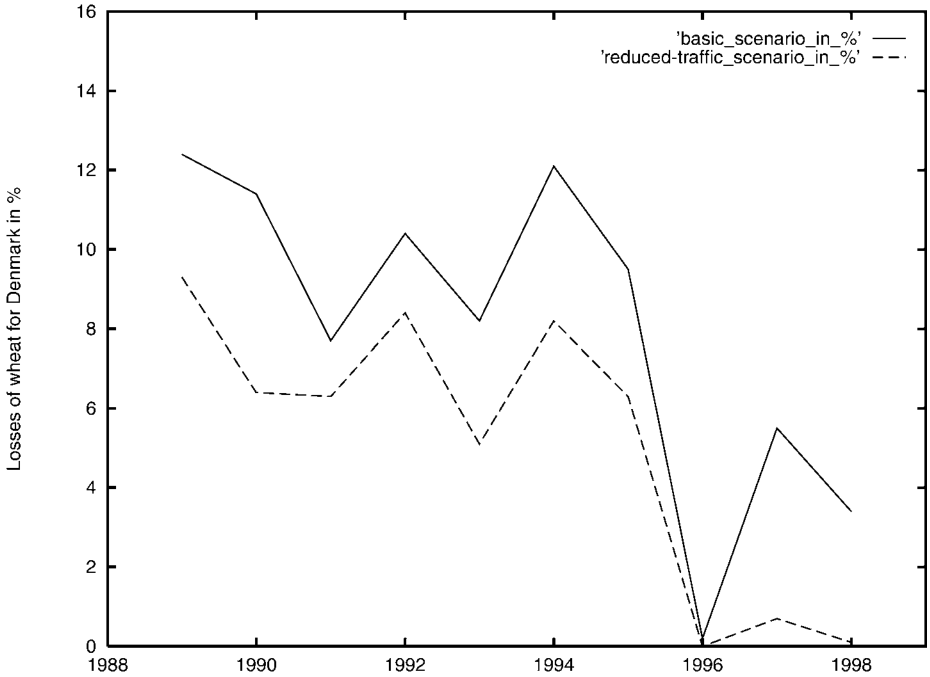

Figure 14. Comparison of the losses which are obtained with the two scenarios.

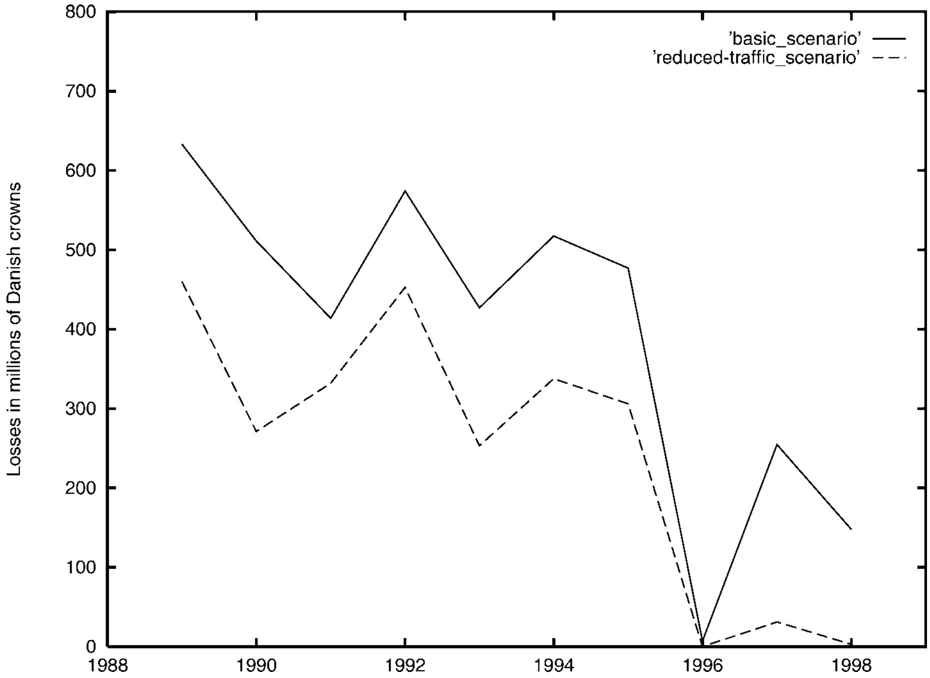

Figure 15. Comparison of the cost of the losses which are obtained with the two scenarios.

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