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Yield and Grain Quality of Spring Wheat (*Triticum aestivum* L., cv. Drabant) Exposed to Different Concentrations of Ozone in Open-Top Chambers

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ABSTRACT

*Spring wheat (*Triticum aestivum *L., cv. Drabant) was exposed to different concentrations of ozone in open-top chambers for two growing seasons, 1987 and 1988, at a site located in south-west Sweden. The chambers were placed in a field of commercially grown spring wheat. The treatments were charcoal-filtered air (CF), non-filtered air (NF) and non-filtered air plus extra ozone (NF^+). In 1988, one additional ozone concentration (NF^{++}) was used. Grain yield was affected by the ozone concentration of the air. Air filtration resulted in an increase in grain yield of about 7% in both years, compared to NF. The addition of ozone (NF^+, NF^{++}) reduced grain yield and increased the content of crude protein of the grain in both years. Filtration of the air had no significant effect on the content of crude protein, compared to NF. The results showed a strong positive chamber effect on grain yield in the cold and wet summer of 1987. In 1988, there was no net chamber effect on grain yield. The relative differences between the CF, NF and NF^+ treatments with respect to grain yield were of the same magnitude in the two years, despite the very different weather conditions.*

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INTRODUCTION

Several studies in the United States, within the National Crop Loss Assessment Network (NCLAN), have shown that ambient concentrations of ozone over large areas of the country are high enough to reduce the yield of field-grown crops (Heck *et al.*, 1983). In these, and other studies, wheat was found to be sensitive to ozone (Heagle *et al.*, 1979; Kress *et al.*, 1985; Amundson *et al.*, 1987; Kohut *et al.*, 1987). Information regarding the impact of ambient concentrations of ozone on the yield of important crops in Europe is scarce compared to the US. However, to assess the effect of ambient concentrations of ozone on crops, spring wheat (cv. Albis) has been used in a Swiss open-top chamber study. The results suggested that it was sensitive (Lehnherr *et al.*, 1987), as grain yield and net photosynthesis decreased with increasing ozone concentration. These results, together with negative results on yield of spinach and potatoes exposed to elevated concentrations of ozone in open-top chambers in southern Sweden (Skärby & Jönsson, 1988), raised the question whether negative effects of ambient concentrations of ozone on the yield of crops occur also in Sweden.

The concentrations of ozone in southern Sweden are in the same range as in the NCLAN and Swiss studies. However, caution must be exercised, if results concerning effects of air pollutants on plants are to be extrapolated from one geographical region to another, e.g. from North America to Europe. The wheat cultivars grown in North America are not the same as those used in Europe and different cultivars of wheat have been shown to respond differently to ozone exposure under similar conditions, in the laboratory (Shannon & Mulchi, 1974) as well as in the field (Heagle *et al.*, 1979). Furthermore, while little information regarding how weather conditions influence plant response to ozone is available, the NCLAN data show that the effect of ozone on yield can vary from year to year (Heagle *et al.*, 1988).

We consider ozone to be the most important air pollutant for field grown crops in southern Sweden. The occurrence of major phytotoxic gases in rural areas of southern Sweden is characterized by low sulphur dioxide and nitrogen dioxide levels compared to ozone. In 1985–87, the 24-h monthly means for ambient ozone concentration on the Swedish west coast were in the range of 27 to 48 nl litre^{-1} during April to September. Episodes reaching 100 to 125 nl litre^{-1} (1-h means) may occur in spring and summer. During 1985–87, from April to September the 24-h monthly means for sulphur dioxide and nitrogen dioxide were $3{\cdot}6 \pm 1{\cdot}5$ and $3{\cdot}2 \pm 1{\cdot}0\ \mu g\ m^{-3}$, respectively (Lövblad *et al.*, 1985; Lövblad *et al.*, 1986; Dahlberg *et al.*, 1987).

In 1984, The Commission of the European Communities (CEC) initiated an experimental programme to evaluate crop loss due to air pollution in

Europe. The co-operative programme (COST 612) mandates the use of open-top chambers, with filtered and non-filtered air, sited in field-grown crops. Spring-sown cereals or legumes are strongly recommended. The present study is a part of that programme. Wheat was chosen since it is of great agricultural importance in southern Sweden. The study was conducted in south-west Sweden in 1987 and 1988, and was designed to follow the common programme of the CEC co-operation. The aim was to evaluate the impact of ambient and elevated ozone concentrations on grain yield and quality of an important spring wheat cultivar in southern Sweden.

MATERIALS AND METHODS

Open-top chambers

The open-top chambers were 1·24 m in diameter and 1·60 m tall, including the frustum. The chambers and fans were obtained from the Institute of Terrestrial Ecology, Edinburgh, UK and are described in detail by Fowler *et al.* (1988). Air was blown, day and night, through a circular perforated annulus situated about 0·1 m above the canopy. The flow rate in our experiments corresponded to approximately three air changes per minute of the full chamber volume. The coefficient of variation in the air flow between the chambers was about 6%.

Experimental site

The experiment was conducted in a wheat field at Östad, 50 km north-east of Göteborg, Sweden (N 57°54′, E 12°24′) (Fig. 1). The site was about 60 m above sea level and the soil is rich in clay with a pH-value slightly above 6. No significant variation in soil pH was found within the experimental area. No major air pollutant sources are located in the vicinity of the investigation area.

Cultural practices

In both years, a spring wheat cultivar (*Triticum aestivum* L., cv. Drabant) was sown with 12·5-cm row-spacing (240 kg seeds ha^{-1}). The fertilizers contained nitrogen (120 kg ha^{-1}), phosphorus (22 kg ha^{-1}) and potassium (22 kg ha^{-1}). The chambers were occasionally removed to allow the experimental area to be treated with an insecticide and/or a fungicide in the same way and at the same time as the rest of the field. Further details on agricultural practices are given in Table 1.

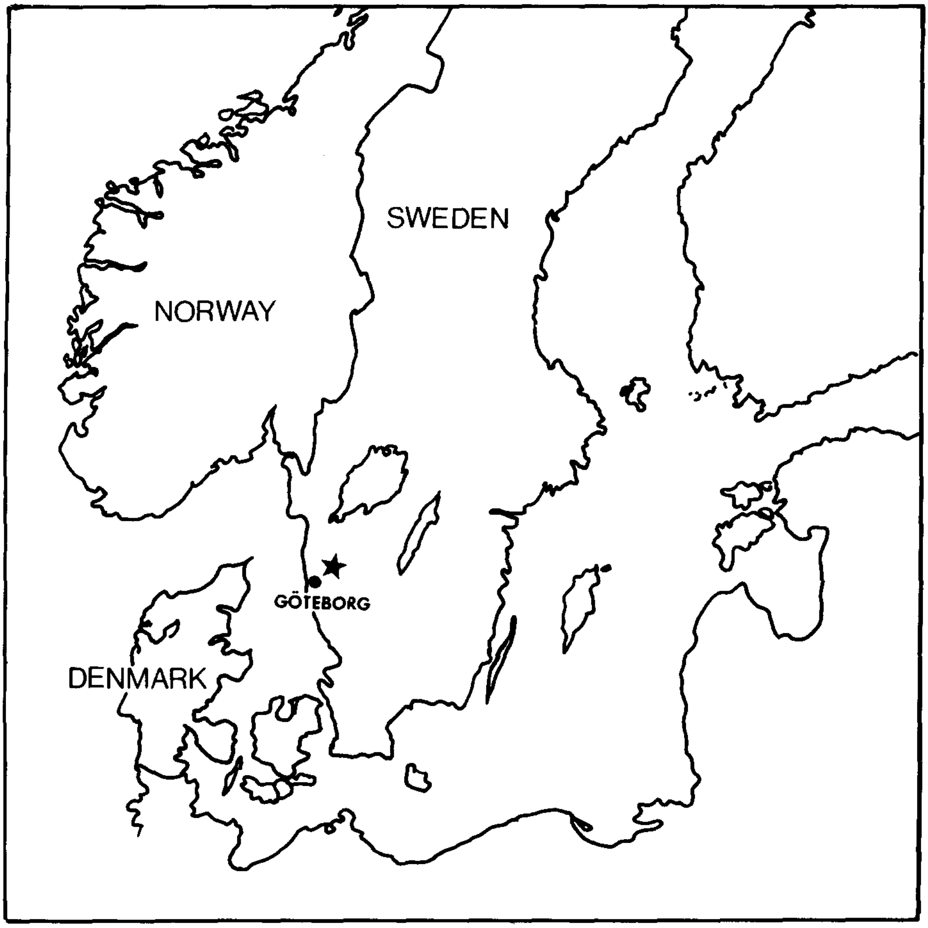

Fig. 1. Location of the experimental station at Östad, Sweden (N 57°54′, E 12°24′).

Experimental design

The following treatments were used:

AA—ambient air plots without chambers
CF—chambers with charcoal-filtered air
NF—chambers with non-filtered air
NF^{+}—chambers with non-filtered air + about 25 nl $litre^{-1}$ ozone
NF^{++}—chambers with non-filtered air + about 35 nl $litre^{-1}$ ozone.

The NF^{++} treatment was used in 1988 only. In 1987, there were seven replicates in each treatment. The treatments were distributed in a randomized complete block design, the blocks being arranged along a

TABLE 1
Timetable of Events during the Experiments in 1987 and 1988

Event	*1987*	*1988*
PK fertilization[a]	Autumn 1986	Autumn 1987
Planting	1 May	29 April
N fertilization[b]	15 May	12 May
Herbicide[c]	25 May	23 May
Installation of chambers	25 June	27 May
Insecticide[d] and Mn[e]	—	9 June
Insecticide[f] and fungicide[g]	—	29 June
Start of ozone fumigation	16 July	6 July
Fungicide[g]	21 July	—
End of ozone fumigation	15 Sept.	30 Aug.
Removal of chambers	28 Sept.	31 Aug.
Harvest of all plots	—	31 Aug.
Harvest of NF^+ treatment	30 Sept.	—
Harvest of CF, NF, and AA treatments	9 Oct.	—

[a] PK 8:8 (Hydro-Supra)
[b] Nitrate of lime (Hydro-Supra)
[c] 1987: Glin (Dupont), 1988: Actril (ICI)
[d] Metacystox R100 (Bayer)
[e] $MnSO_4$ (Hydro-Supra)
[f] Sumicidin (Dupont)
[g] Tilt (Ciba-Geigy)

weak slope. In 1988, a completely randomized design was used, with five replicates in each treatment.

Pollutant exposure

Filtration of the air in the CF treatment was started as soon as the chambers were installed. Ozone generation was started at anthesis in both years. Ozone addition lasted daily from 11·00 until 18·00, local time. Further information concerning experimental practices is given in Table 1.

The plants were exposed to ozone, produced by air-operated electric discharge ozonators (Sonozaire 630). In 1987, one generator was used, in 1988, two generators. The air into the ozonators was not dried prior to ozonation. The ozone from the generators was distributed to the chambers via manifolds and aluminium tubes with a minimum length of 5 m. There is evidence that a certain amount of N_2O_5 is produced in such a system (Brown & Roberts, 1988). However, when the relative humidity of the air is above 50%, N_2O_5 reacts very rapidly with water to form HNO_3 (Tuazon *et al.*, 1983; Platt *et al.*, 1984). As the relative humidity of the air was below 50% only on rare occasions and as HNO_3 is rapidly deposited on wet surfaces (aluminum tubes and plastic manifolds), we believe that neither N_2O_5 nor HNO_3 was deposited to the plants. Measurements from a similar study on conifers carried out by our group confirms this suggestion.

Pollutant and climate monitoring

Air samples were drawn through 5-m-long Teflon (PTFE) tubes (6 mm in diameter). All Teflon tubes were continuously ventilated and connected to a time-share system with PTFE solenoid valves. Air was sampled 0·1 m above the canopy in the centre of all chambers where ozone was added (NF^+ and NF^{++}), in one CF chamber, one NF chamber, one AA plot and at 3 m above ground level. Ozone concentrations were monitored using a UV absorption ozone analyzer (Model 8810, Monitor Labs Inc., San Diego, CA, USA). The monitor was calibrated once a month using a portable ozone generator (Model 8500, Monitor Labs Inc., USA).

Air temperature and relative humidity were monitored with Rotronic YA-100 hygrometer/thermometers at 0·1 m above canopy. Soil temperature was measured with Pt-100-sensors at 0·10 m soil depth. These parameters were measured inside one NF-chamber and in one AA plot. Ozone and climate data, were collected with a data logger (Campbell Scientific CR 10). Precipitation was recorded with a standardized precipitation collector at one location in the vicinity of the experimental area.

Harvest and analysis of plant material

To facilitate the harvest, each circular plot was marked by a plastic strip, with a diameter of 1·10 m and a height of 6 cm. The strips were installed when the plants were about 10 cm high. In 1987, the plants inside the entire circular plot were harvested. In 1988, the plants in the northern half of the circular plot were used for studies of production and the other plants were used for physiological studies. All heads were cut and then all the straw of each plot. The grain of each plot was carefully threshed by hand. The dry weight of three subsamples from each plot (5–10 g fresh weight) was determined by drying three samples at 70°C until constant weight was achieved. The rest of the grain was sent to an authorized agricultural laboratory for determination of crude protein content, 1000-grain weight and cadmium content (atomic absorption spectroscopy, graphite oven). Crude protein content was estimated by determination of the nitrogen content (Kjeldahl) and multiplying the nitrogen content by 6·25. The entire straw from each plot was dried at about 33°C and 15% relative humidity until constant weight.

Statistical analysis

For the harvest data of 1987 and 1988, a two-way-analysis of variance and a one-way-analysis of variance were performed, respectively. Least Significant Differences (LSD) were calculated when the F-test was significant ($P = 0.05$) (Snedecor & Cochran, 1967).

RESULTS

Weather conditions

The weather conditions in south-west Sweden differed markedly between the two years (Table 2). 1987 was characterized by unusually cold and rainy May and June, while in 1988, May and June were hot and very dry, making irrigation of all chamber plots necessary to avoid drought stress. All AA plots were also irrigated. On the other hand, July became an extremely rainy month in 1988, with a monthly precipitation of 193 mm at Östad; 69 mm fell within half an hour in one day in July, causing damage to the crop.

TABLE 2
Monthly Mean Temperatures (°C) at Landvetter Airport, 30 km East of Göteborg, Sweden

	May	*June*	*July*	*Aug.*	*Sept.*	*Oct.*
1987	8·7	11·0	14·7	13·0	10·7	8·2
1988	12·5	16·8	15·5	14·6	12·4	6·4

Climate and ozone concentrations

Monthly means of the temperatures of the air and the soil, and the relative humidity of the air, inside one chamber and at one ambient air plot in August 1987 and 1988, are presented in Table 3. During both years, the air temperature was about 1°C higher inside the chamber than outside, and soil temperature about 0·2°C higher. In August 1987 and 1988, the monthly means of the relative humidity inside the chamber and outside did not differ significantly.

The diurnal variation of the temperature of the air inside the chamber

TABLE 3

Monthly Means of Climatic Parameters during August 1987 and 1988 Inside a Chamber (NF) and at an Ambient Air Plot (AA)

Parameter	*1987* NF	*1987* AA	Δ	*1988* NF	*1988* AA	Δ
Air temperature[a] (°C)	12·6	11·6	1·0	14·9	13·8	1·1
Soil temperature[b] (°C)	12·1	11·9	0·2	13·4	13·2	0·2
Relative humidity[a](%)	91·4	90·7	0·7	84·8	84·8	0·0

[a] Measured 0·1 m above canopy.
[b] Measured 0·1 m depth.
Δ Difference between NF and AA.

during August was greater in 1988 than in 1987 (Figs 2 and 3). The diurnal variation of the relative humidity of the air during this month was also different in the two years. In August 1987, the relative humidity was higher inside the chamber during the daytime, and lower during the night (Fig. 2). In 1988, the difference in relative humidity inside and outside the chamber was small (Fig. 3).

The average diurnal variations in ozone concentrations in the different treatments in August 1987 and 1988 are presented in Figs 4 and 5, respectively. A similar pattern was observed in both years. 24-h and 7-h (11·00–18·00, local time) seasonal means of ozone concentrations in the different treatments are presented in Table 4. In 1987, addition of ozone was

TABLE 4

7-h (11.00–18.00, Local Time) and 24-h Seasonal Means of Ozone Concentrations in the Different Treatments

Treatment	*Ozone concentration (nl litre^{-1})* 7-h seasonal mean 1987[e]	7-h seasonal mean 1988[f]	24-h seasonal mean 1987[e]	24-h seasonal mean 1988[f]
NF[a]	15	22	10	16
CF[b]	3	6	2	5
NF+[c]	42	44	19	23
NF++[c]	—	56	—	26
AA[d]	21	32	14	22
3 m	27	36	19	26

[a] Non-filtered air chamber.
[b] Charcoal-filtered air chamber.
[c] Non-filtered air + ozone chambers.
[d] Ambient air plots.
[e] 28 July–14 Sept., 2 days missing.
[f] 9 July–18 Aug., 6 days missing.

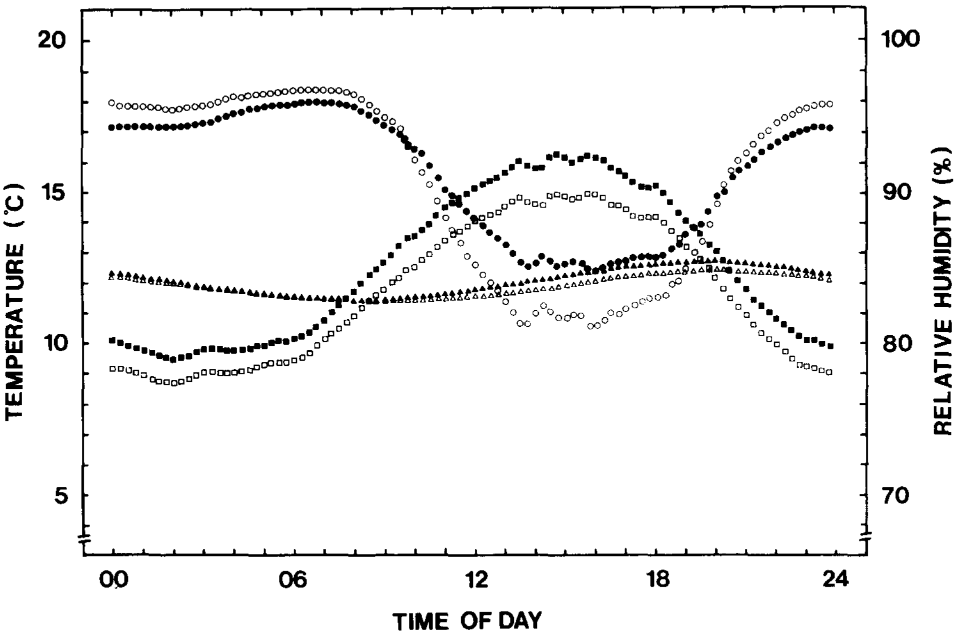

Fig. 2. Monthly means of air and soil temperature and relative humidity during August 1987. Temperature and relative humidity of the air was measured 0·1 m above the canopy and soil temperature at a depth of 0·1 m. ■ = air temperature, ▲ = soil temperature, ● = relative humidity. Solid symbols = inside chamber (NF), open symbols = ambient air plot (AA).

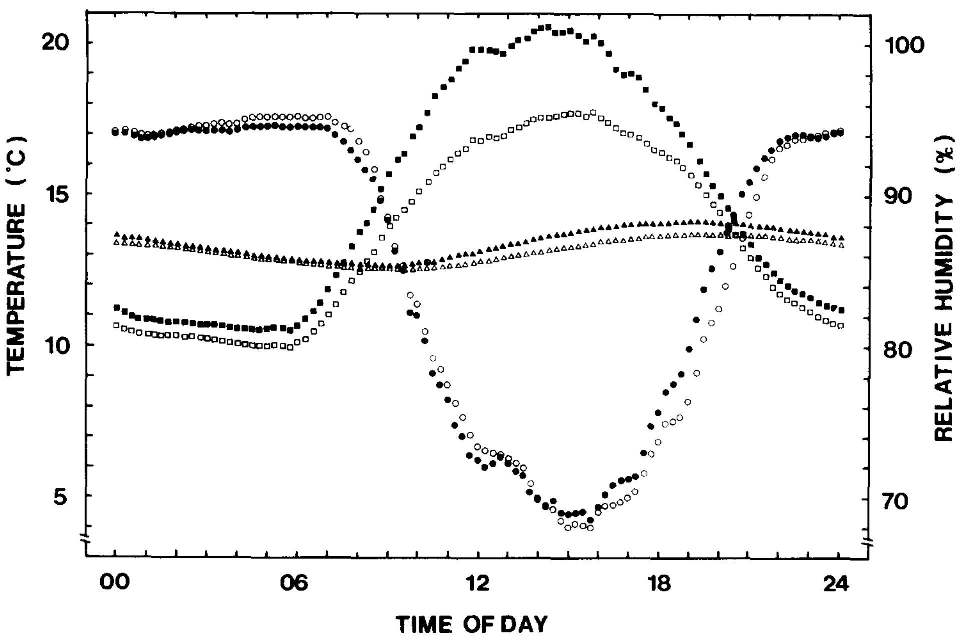

Fig. 3. Monthly means of air and soil temperature and relative humidity during August 1988. Temperature and relative humidity of the air was measured 0·1 m above the canopy and soil temperature at a depth of 0·1 m. ■ = air temperature, ▲ = soil temperature, ● = relative humidity. Solid symbols = inside chamber (NF), open symbols = ambient air plot (AA).

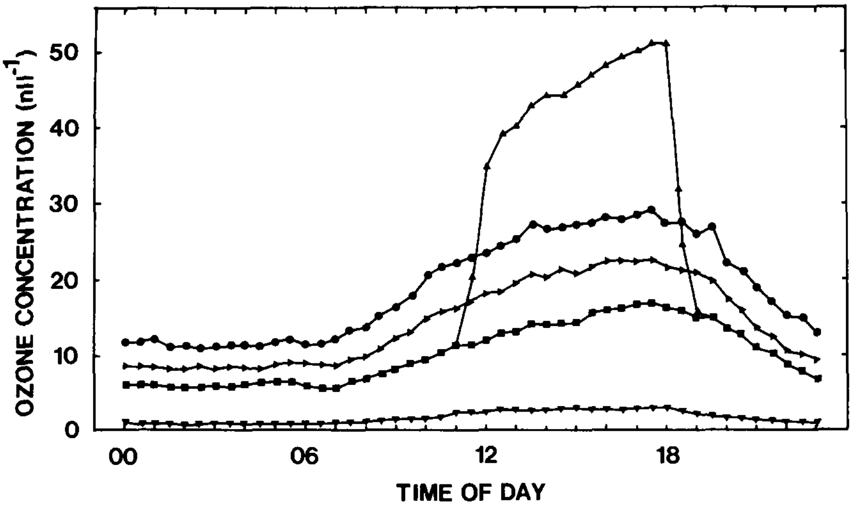

Fig. 4. Average diurnal variation of ozone concentrations in the different treatments during August 1987. ■ = chambers with non-filtered air (NF), ▼ = chambers with charcoal-filtered air (CF), ▲ = chambers with non-filtered air + ozone (NF^+), ▶ = ambient air plot (AA), ● = 3 m above ground level.

started on 16 July. However, because of breaks in data collection due to adjustments of the ozone fumigation, the seasonal mean for 1987 was calculated for the period 28 July to 14 September. In 1988, the seasonal mean is based on the period 9 July to 18 August. The ozone concentration of the ambient air was considerably lower in 1987 compared to that in 1988. The ozone concentration of the CF treatment was also lower in 1987, while that of the NF^+ treatment was similar to that in 1988. The daily variation in the ozone concentration of the ambient air at 3 m above ground level during 1987 and 1988 is presented in Figs 6 and 7, respectively. From 2 July until 30 September 1987, an ozone concentration exceeding 50 nl litre^{-1} was recorded on seven different days. The corresponding number for 12 June until 30 August 1988 was 20 days.

Visible foliar injury and senescence

Observations of visible injury were made in both years. Chlorotic and necrotic spots on leaves were observed in the treatments where ozone was added. These changes were observed in both years in the NF^+ treatment, about two weeks after the fumigation was started. In the NF^{++} treatment, they appeared after about one week. In both years, the plants in the CF treatment were still partly green by the time of harvest, while the plants in the NF and AA treatments were entirely yellowed.

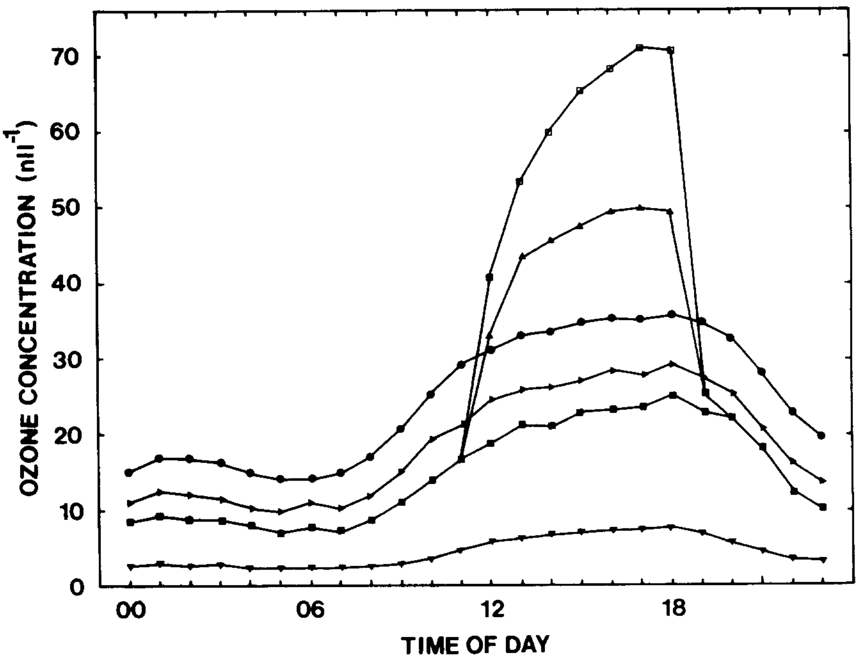

Fig. 5. Average diurnal variation of ozone concentrations in the different treatments during August 1988. ■ = chambers with non-filtered air (NF). ▼ = chambers with charcoal-filtered air (CF), ▲ = chambers with non-filtered air + ozone (NF^+), □ = chambers with non-filtered air + ozone (NF^{++}), ▶ = ambient air plot, ● = 3 m above ground level.

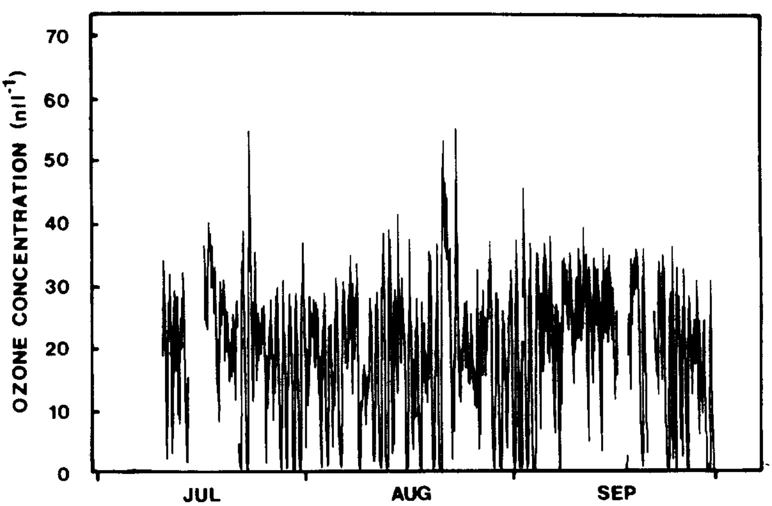

Fig. 6. Variation in ozone concentration in the ambient air at 3 m above ground level during 1987. From 2 July until 30 September 1987, an ozone concentration of 50 nl litre^{-1} was exceeded on seven different days.

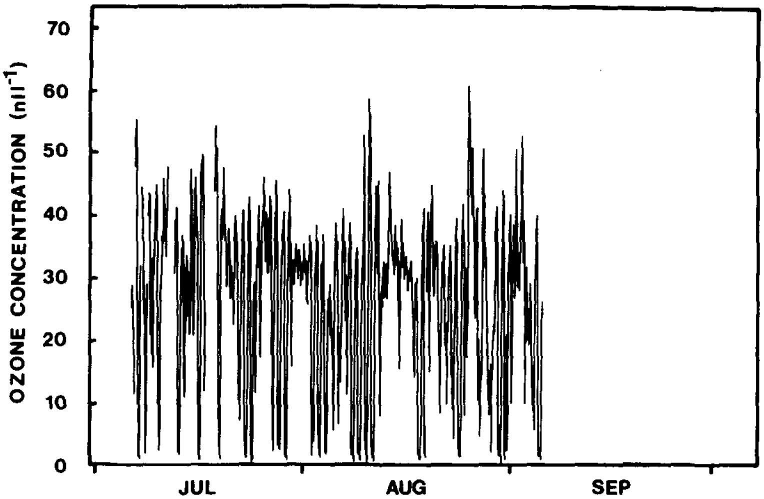

Fig. 7. Variation in ozone concentration in the ambient air at 3 m above ground level during 1988. From 12 June to 30 August 1988, an ozone concentration of 50 nl litre^{-1} was exceeded on 20 different days.

Yield and grain quality

In 1987, the plant material in four chambers became heavily infested with aphids. Neither the field as a whole, nor any other plot showed any sign of infestation. The three blocks with the four infested plots were left out of the data. Consequently, four blocks remained for analysis. In 1988, no plots were left out of the data.

Results from yield and quality measurements are presented in Table 5. The number of heads was influenced neither by ozone nor by the enclosure of the plants inside the chambers. Exposure to filtered air, compared to non-filtered air, resulted in an increase in grain yield of approximately 7% in both years. This effect, however, was significant only in 1987. Treatments with extra ozone resulted in significantly lower grain yields compared to non-filtered air in both years. The reduction due to the NF^+ treatment compared to the NF treatment was approximately 7% in 1987, as well as in 1988. In 1988, the corresponding reduction due to the NF^{++} treatment was about 22%. A significant positive net chamber effect of about 40% on grain yield was obtained in 1987. In 1988, the corresponding figure was close to zero.

The 1000-grain weight values show the same pattern as grain production. The positive filter effect on 1000-grain weight compared to NF was about 6% in 1987 and about 4% in 1988; however, this was not significant in either of the years. The negative effect of the NF^+ treatment compared to NF was 11% in 1987 and 6% in 1988, significant in 1987 only. Thus, effects of the chamber and the ozone treatment on 1000-grain weight was generally

TABLE 5
Plant Growth Parameters for the Different Treatments

Year	*Treatment*[a]	*Heads m*$^{-2}$	*Grain, dw (ton ha*$^{-1}$*)*	*1000-grain weight*	*Harvest index*	*Protein (% dw)*	*Cadmium (µg kg*$^{-1}$ *dw)*
1987	AA	502 ± 13	2·81 ± 0·18 a	25·3 ± 1·7 a	0·30 ± 0·02 a	12·6 ± 0·5 a	—
	CF	485 ± 36	4·23 ± 0·17 b	39·0 ± 3·2 b	0·43 ± 0·03 b	12·6 ± 0·5 a	—
	NF	477 ± 33	3·96 ± 0·34 c	36·8 ± 1·8 b	0·42 ± 0·02 b	12·2 ± 0·2 a	—
	NF^{+}	505 ± 25	3·68 ± 0·07 d	32·6 ± 1·1 c	0·41 ± 0·01 b	13·8 ± 0·4 b	—
	F	0·91 NS	60·1	39·3	34·8	7·2	
	LSD	—	0·25	3·1	0·04	0·8	
1988	AA	642 ± 100	5·72 ± 0·37 ab	35·9 ± 1·1 a	0·45 ± 0·01 a	12·6 ± 0·9 a	47·2 ± 3·6 a
	CF	646 ± 52	6·15 ± 0·58 a	41·2 ± 1·3 b	0·50 ± 0·01 b	13·6 ± 0·5 b	57·0 ± 4·2 b
	NF	653 ± 45	5·77 ± 0·73 ab	39·6 ± 1·4 bc	0·50 ± 0·01 b	13·7 ± 0·2 b	56·2 ± 4·5 b
	NF^{+}	697 ± 60	5·35 ± 0·60 b	37·3 ± 3·7 c	0·48 ± 0·02 b	14·2 ± 0·8 b	56·6 ± 4·0 b
	NF^{++}	697 ± 60	4·48 ± 0·44 c	30·0 ± 1·6 d	0·43 ± 0·02 a	15·2 ± 0·6 c	54·2 ± 4·7 b
	F	0·66 NS	6·4	22·3	28·5	11·0	4·7
	LSD	—	0·74	2·7	0·02	0·8	5·5

[a] Treatment abbreviations as for Table 4.
Values followed by different letters within columns and years are significantly different at $p = 0.05$.

greater in 1987 than in 1988. The effect of NF^{++} treatment compared to NF on 1000-grain weight was about 24%. The positive chamber effect on this parameter was statistically significant in both years: about 31% in 1987 and about 9% in 1988.

The variation in harvest index (proportion of total above-ground dry matter assimilated which is distributed to the grain) within each treatment was very small. In 1987, the differences in harvest index between the CF, NF and NF^{+} treatments were very small. The positive chamber effect on this parameter was about 43% and statistically significant. In 1988, the corresponding figure was 11%. However, the harvest index of the NF^{++} treatment was significantly lower than that of the other chamber treatments.

In 1987, there were no significant differences in the content of crude protein in grain among the AA, CF and NF treatments. In 1988, however, there was a significant positive chamber effect of about 8% on this parameter. Crude protein content tended to be higher in the treatments with extra ozone than in the others. In the NF^{+} treatment the positive effect compared to NF was 13% and 4% in 1987 and 1988, respectively. In 1988, the positive effect of the NF^{++} treatment, compared to NF, was about 11%. The effects of the NF^{+} treatment in 1987 and of the NF^{++} treatment in 1988 on crude protein content were statistically significant.

Bread baked from wheat is considered an important source of cadmium intake. Thus, the cadmium content of the grain is a quality parameter of interest, because of the human health risks connected with cadmium. It has been suggested that ozone fumigation may lead to an increased uptake of cadmium (Czuba & Ormrod, 1981). However, the cadmium content of the grain was not affected by ozone, but was significantly lower outside chambers than inside (Table 5). This parameter was measured only in 1988.

DISCUSSION

Exposure of spring wheat to elevated concentrations of ozone, starting at anthesis, resulted in a reduction in the grain yield in two subsequent years. The reduction was dependent on the ozone concentration, increasing with increasing ozone concentration. Thus, the response of this spring wheat cultivar to ozone exposure was similar to that of the spring wheat cultivar tested in Switzerland (Fuhrer *et al.*, 1989) and to the winter wheat cultivars used in the North American open-top chamber studies (Heagle *et al.*, 1979; Kress *et al.*, 1985; Amundson *et al.*, 1987; Kohut *et al.*, 1987).

The results of the present study indicate also that ambient concentrations of ozone in south-west Sweden are high enough to cause yield loss in spring wheat as the grain yield of wheat exposed to charcoal-filtered air was higher than that of wheat exposed to non-filtered air in both years, though only statistically significant in 1987. A larger variation in grain yield within treatments was obtained in 1988 compared with 1987. The larger variation was probably caused by a combination of smaller sampling area in each chamber in 1988, making random errors larger, and unevenly distributed damage to the crop caused by drought stress in June 1988 and by an extremely heavy rainfall incident one day in July 1988.

The results further show that the variation in yield due to ozone treatment, when using realistic ozone concentrations, is smaller than the possible variation in yield caused by differences in weather conditions between years. In 1987, the farmer's yield (15% water content) was slightly above 3 tons per hectare and in 1988, about 6 tons per hectare. The grain yield in the AA plots, 2·8 and 5·7 tons per hectare (dry weight) in 1987 and 1988, respectively, corresponds very well to the yield reported by the farmer.

The harvest index values of 1987 show that the plants outside the chambers were much less efficient in converting above-ground biomass into grain. The corresponding difference in 1988 was small. The lower 1000-grain weights of NF^{+} and NF^{++} show that the grains in these treatments are, on average, smaller than in CF and NF. Since the grain was harvested and threshed by hand, the yield loss estimates are probably conservative, as many of the small, dry seeds would have been lost during machine threshing (Kress *et al.*, 1985). This means that the yield loss due to ozone would have been larger if the threshing had been done by machine. In 1987, the variation between treatments in 1000-grain weight accounted for a larger proportion of the variation in yield than in 1988, indicating that seed number was more influenced by the ozone treatment in 1988.

A normal value of crude protein content in wheat in southern Sweden is 13·0% with a coefficient of variation of 12·6% (Åman, 1988). This means that the values achieved in this study are normal. It is, however, notable that the treatments which received extra ozone had a higher crude protein content. A similar increase in protein content was observed in another spring wheat study (Fuhrer *et al.*, 1989) as well as in one out of two years in a study where winter wheat was exposed to a simulated ozone episode during anthesis (Mulchi *et al.*, 1985).

The open-top chamber technique was developed to allow field fumigation of crops without major changes in the microclimate (Heagle *et al.*, 1973). However, compared to field situations, all types of chambers used to manipulate concentrations of air pollutants lead to changes in the microclimate (Colls & Baker, 1988; Heagle *et al.*, 1988; Jäger, 1988; Roberts *et al.*, 1988). The temperature of the air and the soil is increased and the movement of the air is changed. The amount and distribution of rain, and the intensity and spectrum of solar radiation are also different. The influence of the chamber on grain yield was very different in the two years. In the cold and wet summer of 1987, the influence on grain yield was large and positive, probably due to the higher temperatures inside the chambers. In 1988, the difference in grain yield between the AA and NF treatments was almost absent, although the effect of the chamber on grain production would most likely have been negative due to drought stress, if the plots had not been irrigated during the latter part of the very dry period in June.

Little information on how weather conditions influence a plant's response to ozone is available. However, the stable response of the plants to ozone from one year to the next year obtained in this experiment indicates that variation of abiotic factors, such as temperature and light, of this magnitude is of secondary importance for the response of the plants to ozone. Similar results were also obtained in the Swiss study (Fuhrer *et al.*, 1989); despite large differences in weather conditions, the effect of ozone on yield was similar from year to year.

In a crop field, the deposition of ozone, and thus the dose, is restricted by a number of resistances (Leuning *et al.*, 1979). In open-top chambers these resistances may be different from those in the field (Unsworth *et al.*, 1984*a*,*b*). If the boundary layer resistance inside the chamber is significantly different from that of the open field, this could lead to either a greater or a lesser uptake of pollutants like ozone, and hence an over- or underestimation of yield loss. It has been suggested by Reich (1987) that ozone uptake by plants may be a more suitable parameter to which to relate effects than ozone concentration. At present little information is available on whether or not the ozone uptake in open-top chambers is of the same magnitude as in the open field. A particular concentration of ozone in the chamber, causing a particular decrease in grain yield, does not necessarily correspond to the same decrease in grain yield in ambient air when the ambient ozone concentration is the same as in the chamber. The lack of knowledge concerning ozone uptake in chambers seriously limits the predictive capacity of the open-top chamber as a test system for quantitative estimations of crop loss due to air pollutants. However, from the present study we suggest that the impact of ozone on cereals is a relevant problem in southern Sweden.

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