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OPEN-TOP CHAMBER STUDY:
THE INFLUENCE OF AMBIENT CONCENTRATIONS OF AIR POLLUTANTS ON AGRICULTURAL CROPS IN THE UK

D. FOWLER, J.N. CAPE, I.S. PATERSON & I.D. LEITH

Edinburgh Research Station
Bush Estate
Penicuik
Midlothian

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1. INTRODUCTION

The objective of this study was to show whether concentrations of the air pollutants SO_2, NO_2 and O_3 typical of much of the cereal crop growing areas of the UK influence growth, development and yield of barley.

The annual average gas concentrations intended for the study were: SO_2, 10 to 15 ppbV and NO_2, 5 to 15 ppbV. Average concentrations of O_3 are probably less important than the number of occasions with peak concentrations in excess of 60 ppbV (episodes) which for an average UK summer is between 5 and 15.

The objective was therefore for a relatively simple experiment to investigate whether air pollutants are influencing crop growth without extrapolation from effects produced at much larger concentrations. In order to detect statistically significant yield differences as small as 10% (the detection limit designed into this study), adequate replication of treatments was a vital component of experimental design.

With the 4 replicates for each treatment chosen for this study and the decision to study both spring and winter sown crops, a site with 32 chambers was established, (16 filtered and 16 unfiltered) in western Glasgow.

Continuous monitoring of gas air composition in the different treatments was necessary throughout the study. The tables in Section ~~3.1~~ 2.2 show the mean concentrations for each ~~treatment and each experiment.~~ The concentrations of SO_2 were much smaller than those present during the early 1970s in Glasgow, and the concentrations of NO_2 were larger than those of SO_2.

Other studies at the site using the same equipment were included to help interpret any treatment differences revealed by the main experiment or included whenever 'spare' chambers became available to increase the output of information on crop effects generally.

These included:

1) detailed studies of the physical environment of the ITE open-top chamber.
2) effects of ambient ozone on the growth of radish.
3) studies of the efficiency of photosynthesis in filtered and polluted air.
4) studies of the exchange of CO_2, H_2O and the pollutant gases NO_2, NO and O_3 in open-top chambers.the growth of radish.
5) winter injury to Scots pine in a polluted environment.
6) effects of additional ozone on the growth and development of field benas.

This report summarizes results of the main experiments and the additional studies. More detailed information for these experiments may be found in the appendix.

2 MAIN EXPERIMENTS

2.1 Methods and results

A record of the crop management and site and soil characteristics is provided in the appendix.

Five main experiments were undertaken between autumn 1982 and summer 1985:

1. Winter barley, 2 varieties, planted ~~October~~ Sept 1982.
2. Spring barley, 2 varieties, planted March 1983.
3. Winter barley, 2 varieties, planted ~~October~~ Sept 1983.
4. Spring barley, 2 varieties, planted March 1984.
5. Winter barley, 1 variety, 2 fertilizer treatments, planted Sept ~~October~~ 1984.

Each of these experiments will be described briefly, with results.

Experiment 1. Winter barley.
Two varieties (Igri and Gerbel) were sown on a 10 cm grid in prepared plots in a split-plot statistical design using 4 randomised blocks. Additionally, 4 plots were sown with each variety as non-chambered plots for comparison of growth inside and outside chambers.

The chambers were placed on the overwintered barley in April, when the electricity supply was installed at the site. The treatment (filtered/unfiltered) was therefore only applied from April to harvest.

Visual observations of the plots were recorded weekly, as were leaf areas, leaf emergence and developmental data for selected plants taken within three quadrats randomly placed within the inner section of each plot. At final harvest, each quadrat was sampled separately from the main harvest for detailed measurements. The remainder of each plot was harvested in octants; the circular plot was divided into an inner and outer section, of approximately equal areas, and each section was harvested by quadrants (NW, NE, SE and SW) so that directional effects on growth in the chambers could be evaluated. All data were combined (including single plants from the quadrats) before analysis of variance of the data. Initial analysis was on the raw data as collected (i.e. head weights and shoot weights). The individual plants harvested from the quadrats gave average values for grain and chaff, which were applied to the measured data to estimate grain and straw weights. The statistical model used for analysis (using GENSTAT statistical package) was:

Y = block + block-airtype + block--airtype-section + block-airtype-section-quadrant + airtype * section * quadrant.

This model formula specifies the experimental layout and treatments with interactions. In addition to information on the effect of air filtration, the analysis also gave information on 'edge' effects (inner section vs. outer section) and directional effects (north-south or east-west). The results are shown in Table 1(a) for data on head weights and shoot weights expressed as mean grams/octant harvested (and dried). Table 1(b) shows the size of effect detectable using this experimental design with the amount of variation observed in this experiment. Note that for both varieties combined, a 6% effect on head weight would have been statistically significant. Analysis of single plant data for head weight/stem, grain weight/stem and grain weight/grain showed no significant differences with treatment, except for Igri (inner section), where grain weight per grain was significantly reduced in filtered air, by 8.5%.

Table 1(c) shows the results expressed as grain and straw weights per unit area, and harvest index. Although the experimental design would have detected small differences as a result of the treatments, significant

Table 1(a)

Significance of air type (filtered/unfiltered)

	Shoot (mean : g/octant)				Head (mean : g/octant			
	Filtered	Unfiltered	Diff	LSD at 5%	Filtered	Unfiltered	Diff	LSD at 5%
Igri	89.6	92.8	3.2	10.4	101.1	107.3	6.2	15.5
Gerbel	89.7	88.5	-1.2	5.5	104.6	114.8	10.2	11.1
Igri-Outer	86.4	88.8	2.4	14.5	98.1	104.0	5.9	24.6
Igri-Inner	92.8	96.8	4.0	9.0	104.0	110.6	6.6	10.6
Gerbel-Outer	84.0	82.5	-1.5	6.0	103.6	113.7	10.1	15.7
Gerbel-Inner	95.4	94.5	-0.9	5.3	105.7	115.9	10.2	11.2
Outer	85.2	85.6	0.4	5.4	100.9	108.8	7.9	11.9
Inner	94.1	95.7	1.6	4.1	104.8	113.2	8.4*	6.5

* significant difference at 5% level.

Table 1(b)

Size of effect detectable at 5% significance level, expressed as %, compared with observed effect

	Shoot		Head	
	Effect at 5%	Observed	Effect at 5%	Observed
Igri	11.4	3.5	14.9	6.0
Gerbel	6.2	-1.3	10.1	9.3
Igri-Outer	16.6	2.7	24.3	5.8
Igri-Inner	9.5	4.2	9.9	6.2
Gerbel-Outer	7.2	-1.8	14.5	9.3
Gerbel-Inner	5.6	-1.0	10.1	9.2
Outer	6.3	0.5	11.3	7.5
Inner	4.3	1.7	6.0	7.7*

Table 1(c)

Computed yield data expressed in g m^{-2}

	grain		straw		harvest index	
	filtered	unfiltered	filtered	unfiltered	filtered	unfiltered
Whole plot: Igri	648	687	789	820	0.450	0.455
Gerbel	673	738	791	794	0.457**	0.480
Both together	660 *	713	790	807	0.454**	0.467
Inner section: Igri	570	606	699	732	0.449	0.453
only Gerbel	579 *	635	717	722	0.446 *	0.467
Both together	575 *	621	708	727	0.448 *	0.460

Table 2(a)

Significance of airtype (filtered/unfiltered)

	Shoot (mean: g/octant)				Head (mean: g/octant)			
	Filtered	Unfiltered	Diff.	LSD at 5%	Filtered	Unfiltered	Diff	LSD at 5%
Golf	42.5	41.6	0.9	6.8	68.6	64.4	4.3	18.7
Golden Promise	35.7	35.2	0.5	4.5	52.9	50.3	2.6	5.6
Golf - Outer	38.2	37.7	0.5	13.2	66.3	62.2	4.1	29.4
Golf - Inner	46.9	45.5	1.4	2.1	71.0	66.6	3.4	10.1
G. Prom - Outer	30.2	29.3	0.9	4.1	46.4	42.7	3.7	7.5
G. Prom - Inner	41.2	41.1	0.1	6.5	59.3	57.9	1.4	3.8
Outer	34.2	33.5	0.7	4.9	56.4	52.4	4.0	11.9
Inner	44.1	43.3	0.7	3.7	65.1	62.3	2.9	5.1

Table 2(b)

Size of effect detectable at 5% level, expressed as percentage, compared with observed differences

	Shoot		Head	
	Effect at 5%	Observed	Effect at 5%	Observed
Golf	16.2	2.1	28.1	6.5
Golden Promise	12.7	1.4	10.9	5.0
Golf - Outer	34.8	1.3	45.8	6.4
Golf - Inner	4.5	3.0	14.7	4.9
G. Prom. - Outer	13.8	3.0	16.8	8.3
G. Prom. - Inner	15.8	0.2	6.5	2.4
Outer	14.5	2.1	21.9	7.4
Inner	8.4	1.7	8.0	4.5

Table 2(c)

Computed yield data expressed in g m^{-2}

	grain		straw		harvest index	
	filtered	unfiltered	filtered	unfiltered	filtered	unfiltered
Whole plot: Golf	440	412	395	383	0.524	0.517
Golden Promise	334	317	323	316	0.508	0.500
both together	387	364	359	350	0.516	0.508
Inner section Golf	389	365	371	358	0.511	0.505
only: Golden Promise	325	318	323	321	0.502	0.497
both together	357	341	347	340	0.507	0.501

differences were in general only observed by combining varieties. Barley grown from April in filtered air gave lower head and grain weights than in unfiltered air, and the harvest index was also smaller in filtered air, for both varieties taken together and also for Gerbel alone. There were also significant differences in growth within a plot, with each variety showing a significant increase in shoot weights (but not head weights) in the inner section compared with the outer section. For Igri, both head and shoot weights were significantly lower in the North half of the plot relative to the South half, and head weights were lower in the West than in the East. Gerbel showed no North-South differences, but head weights were also lower in the West. The inner section showed a smaller variability, with the only significant difference being for Igri head weights between North and South. When both varieties were considered together, this difference was also significant (at 1% level).

There was therefore a pronounced directional influence on growth, presumably related to light interception and shading of the northern half of the chambers. Differences between East and West were small, but may be related to shading or to variations in water availability.

Experiment 2 Spring barley

Two varieties (Golf and Golden Promise) were sown on a 10 cm grid in prepared plots using the same statistical design as Experiment 1. The chambers were placed on the plots shortly after emergence (in April) and left until harvest in July. Measurements were recorded as for Experiment 1, and the final harvest followed the same procedures. The statistical analysis was identical; mean values of head weight and shoot weight per octant are shown in Table 2(a), and in Table 2(b) are given the changes detectable at the 5% level, compared to observed differences. Table 2(c) lists the results for grain, straw and harvest index calculated from the samples. There were no significant differences between filtered and unfiltered plots, but the variety Golf gave significantly larger yields (of both grain and straw) than Golden Promise. There was much less variability in the inner section than the outer section, but the only significant effect of airtype was observed in the outer section of Golden Promise, where the head/shoot ratio was 5% larger in filtered air than in unfiltered air. Analysis of the individual plant data showed (for the outer section only) that the head weight was 16% greater and number of grains per stem was 9% higher in filtered air. The varietal differences were expressed in significantly larger grain wt/stem and grain wt/grain for Golf, but a smaller number of grains per stem, compared with Golden Promise. There were also significant directional differences in growth, with higher head and shoot yields in the North half than in the South (in contrast to winter barley). However, the inner section showed no directional differences other than an increased shoot weight in the West compared to East.

Experiment 3 Winter barley

Two varieties (Igri and Gerbel) were sown as in Experiment 1. Chambers were placed on the plots after shoot emergence, and observations and measurements recorded as for Experiment 1. During the growth of this crop, there was a severe mildew infection in December which preferentially damaged unfiltered plots. Although this was controlled by application of a spray, one plot was totally destroyed (Gerbel, filtered air), which necessarily made the analysis of the yield data more complex. The harvest was made as before, with separate sampling of octants and groups of individual plants from 3 randomly-placed quadrats in the inner section. The results for head and shoot weights in each octant are shown in Table 3(a). Calculated values for grain, straw and harvest index are given in Table 3(b). There were no significant effects of airtype on data from individual plants, but grain no./stem and grain wt/stem was greater for Gerbel than Igri, while Igri had heavier grains, but fewer than Gerbel. Directional differences were similar to Experiment 1, with lower head and total weights in the north than in the south, and lower in the east than in the west. This was true for both sections (inner and outer), as well as for the whole chamber. The overall effect of filtering the air was to increase the grain yield, in contrast to Experiment 1, where filtration from April to harvest reduced grain yield.

Experiment 4 Spring barley

This experiment was identical to experiment 2, with the varieties Golf and Golden Promise. Results on head and shoot weights are given in Table 4(a). Computed grain and straw weights, and harvest index, are shown in Table 4(b). As in Experiment 2, there were no effects of filtering the air, and the only significant difference was between varieties, with Golf yielding a greater straw weight than Golden Promise.

Experiment 5 Winter barley

This experiment, sown in late September 1984, used only a single variety (Gerbel) but two different fertilizer treatments, designated as N1 and N2. Table 5(a) shows the amounts applied to each treatment and the timing of the applications. The head and shoot weights are given in Table 5(b) and calculated grain and straw weights, and harvest index, in Table 5(c). The yields of both grain and straw were significantly greater for the higher nitrogen treatment (by 13% and 15% respectively).

Table 3(a)

Significance of air type (filtered/unfiltered)

	Shoot (mean g/octant)				Head (mean g/octant)			
	Filtered	Unfiltered	Diff	LSD at 5%	Filtered	Unfiltered	Diff	LSD at 5%
Igri	53.2	47.7	5.5	8.3	100.4	83.9	16.5	22.2
Gerbel	47.6	47.5	0.1	15.3	102.0	93.0	9.0	34.7
Igri - Outer	37.8	29.9	7.9	10.7	71.6	56.8	14.8	16.1
Igri - Inner	68.5	65.5	4.0	9.1	129.3	111.0	18.3	28.5
Gerbel - Outer	31.3	28.9	2.4	11.1	71.7	59.3	12.4	28.4
Gerbel - inner	63.8	66.1	-2.3	20.1	132.2	126.7	5.5	44.4
Outer	34.5	29.4	5.1	5.7	71.2	58.0	13.2*	10.0
Inner	67.3	65.8	1.5	5.5	131.5	118.8	12.7	13.0

*significant difference at 5% level

Table 3(b)

Computed yield data expressed in g m^{-2}

	grain		straw		harvest index	
	filtered	unfiltered	filtered	unfiltered	filtered	unfiltered
Whole plot: Igri	577	485*	403	360	0.591	0.576
Gerbel	602	539	370	365	0.622	0.597*
both together	590	512*	387	363	0.607	0.586*
Inner section: Igri	667	578	477	445	0.583	0.565
only Gerbel	699	663	445	462	0.612	0.589
both together	683	621	461	454	0.598	0.577*

Table 4(a)

Significance of air type (filtered/unfiltered)

	Shoot (mean g/octant)				Head (mean g/octant)			
	filtered	unfiltered	diff	LSD at 5%	filtered	unfiltered	diff	LSD at 5%
Golf	29.3	30.5	-1.2	3.0	78.4	76.8	1.6	15.0
Golden Promise	26.9	26.2	+0.7	3.0	69.9	65.8	4.1	15.0
Both together	28.1	28.4	-0.3	2.8	74.1	71.3	2.8	13.8
Golf - inner	31.0	34.0	-3.0	3.4	79.5	82.5	-3.0	18.8
G.Prom - inner	31.9	32.0	-0.1	3.4	81.0	78.4	2.6	18.8
both - inner	31.5	33.0	-1.5	3.1	80.3	80.4	-0.1	17.3

Table 4(b)

Computed yield data expressed in g m^{-2}

	grain		straw		harvest index	
	filtered	unfiltered	filtered	unfiltered	filtered	unfiltered
Whole plot: Golf	476	469	322	326	0.597	0.590
Golden Promise	441	412	276	270	0.616	0.597
both together	459	441	299	298	0.606	0.593
Inner section Golf	424	437	289	314	0.594	0.583
only: G. Prom	445	424	284	287	0.593	0.593
both together	434	431	286	301	0.602	0.588

Table 5(a)

Fertilizer treatments on winter barley

Date	N1	N2	type
22.9.84	10 kg N ha^{-1}	30 kg N ha^{-1}	NH_4NO_3
	100 kg 8 ha^{-1} P & K	100 kg ha^{-1} P & K	compound
15.3.85	40 kg N ha^{-1}	60 N ha^{-1}	NH_4NO_3
16/17.4.85	60 kg N ha^{-1}	90 kg N ha^{-1}	NH_4NO_3
24.4.85	5 kg ha^{-1} $MnSO_4$	5 kg ha^{-1} $MnSO_4$	
Total N applied	110 kg ha^{-1}	180 kg ha^{-1}	

Table 5(b)

Significance of air type (filtered/unfiltered) variety Gerbel

	Shoot (mean g/octant)				head (mean g/octant)			
	filtered	unfiltered	diff	LSD at 5%	filtered	unfiltered	diff	LSD at 5%
N1	40.5	45.4	4.9)	5.7	87.5	92.3	4.8)	9.5
N2	45.7	54.8	9.1**)		97.3	106.4	9.1)	
both	43.1	50.1	7.0**	4.0	92.5	99.4	6.9*	6.7
N1 - inner	51.8	55.2	3.4)	7.1	105.2	101.6	3.6)	12.6
N2 - inner	56.6	64.0	7.4*)		111.5	114.2	2.7)	
both - inner	54.2	59.6	5.4*	5.0	108.3	107.9	0.4	8.9

Table 5(c)

Computer yield data expressed in g m^{-2}

	grain		straw		harvest index	
	filtered	unfiltered	filtered	unfiltered	filtered	unfiltered
Whole plot: N1	573	611	376	409	0.607	0.599
N2	642	705	418	490**	0.607	0.590*
both	607	658*	397	449**	0.607	0.595*
Inner only: N1	600	587	412	425	0.592	0.580
N2	637	660	448	489	0.587	0.574
both	619	624	430	457	0.590	0.577

2.2 DISCUSSIION

The objective of the experiments, to detect treatment differences as small as 10% was achieved for 4 out of the 5 main experiments, and the average least significant difference for the inner section of the chambers for all 5 experiments was 9.8%.

Spring Barley

The two spring barley experiments showed no significant differences between treatments. Grain yield per unit area for the varieties Golden Promise and Golf were consistently (ie both experiments) about 5% smaller in the polluted air treatments but these were not significant at the 5% probability level. The experiments therefore produced almost identical results in subsequent years, and the overall dry matter yield per treatment for polluted and clean air differed by only about 1%.

The two years provided similar concentrations of NO_2 and SO_2 though both were small, generally less than 20 ppbV NO_2 and 5 ppbV SO_2. The two years did differ in the number of photochemical ozone episodes:-
44 hours with hourly average O_3 exceeding 60 ppbV in 1983
22 " " " " " " 60 ppbV in 1984.

TABLE 6.

Spring barley pollutant gas concentrations (1984)

SO_2 ppbV		NO_2 ppbV		O_3 ppbV	
F	UF	F	UF	F	UF
0.7	5.4	3.9	15.7	3.3	24.1

F = Filtered
UF = Unfiltered

There is no evidence therefore of a significant effect of the air pollutants SO_2, NO_2 and O_3 at these concentrations on growth or yield of spring barley. If we examine the concentrations of SO_2 and NO_2 in the cereal crop growing areas of the UK then for the summer months, concentrations are 6 to 18 ppbV for SO_2 and 10-15 ppbV for NO_2 for Bottesford and Stoke Ferry in Eastern England. The concentrations are therefore of the same order as those experienced in the Glasgow experiment.

Winter barley

Results of the winter sown barley experiments differ considerably from those of the spring sown experiments. Although differences are small, each of the three experiments show statistically significant effects of air-type (i.e. filtration).

The three experiments differed a little in experimental design, the first experiment (1982-1983) was not subjected to the air filtration treatment until April 1983 but sequential harvest data shows that more than 90% of the dry matter fixed was during the treatment period April-August 1983. The growing conditions were good (no significant pest or pathogen problems and no significant water stress conditions during the main period of growth and development) and the main effects were increased grain yield and a larger harvest index (significant at the 1% level) in the polluted treatment. The grain yield difference at 8.4% shows that in these experimental conditions the presence of the air pollutants may be regarded as beneficial to crop yield at these concentrations.

Table 7. Average gas concentrations for winter barley experiments October-July.

SO_2 ppbV		NO_2 ppbV		O_3 ppbV	
F	UF	F	UF	F	UF
0.8	5.4	3.5	16.5	3.4	23.9

F Filtered
UF Unfiltered (Ambient)

The observation of improved growth and/or yield at small pollutant concentrations is not uncommon and may arise for a number of reasons.

The very small concentrations (up to 20 ppbV) of substances containing major plant nutrients (S and N) may be regarded as potential fertilizers. However, a more probable cause of this observation is that as the pollutant concentration decreases from acute injury concentrations, the plant's metabolic functioning is still influenced by the pollutant but in more subtle ways. For example the root/shoot ratio may be changed by a re-partitioning of assimilate as has been seen in many of the NO_2 effects experiments at Lancaster. This may for example lead to a result similar to these observed in the winter barley 1982-1983 experiment where the pollutant caused a redistribution of assimilate favouring the growth of above ground parts (straw and grain) but especially grain.

In the 1984-1985 winter barley experiment using just one of the varieties (Gerbel) but introducing two fertilizer treatments a similar result was obtained, increased above-ground yield of both straw and grain in polluted air. The effect was largest for the largest fertilizer treatment. This growing season like that of 1982-1983 was not significantly influenced by pests, pathogens or water stress.

In the remaining winter barley experiment (1983-1984) growing conditions conditions and the results were rather different. In this experiment the crop was subject to a mildew attack during the winter, but largely recovered during the spring. However by early May, the soil withincrop had become very dry (14 mm rain in 7 weeks to 18 May). Limited irrigation water was applied to alleviate water stress during this experiment, to have applied no water might have led to larger differences (but the crop might have failed completely!).

The final harvest showed a large reduction in grain yield of the polluted treatment. For both varieties (Gerbel and Igri) the grain yield in polluted air was less than in clean air, but variability between replicates was considerable and only by combining the results of both varieties did the yield reduction appear significant at the 5% level. The difference in yield between air-type treatments was large and represented a yield loss of 20%.

This result, while in the opposite direction to the results of the 1982-1983 and 1984-1985 experiments, is consistent with the interpretation above, that the presence of pollutants has influenced the dry matter partitioning. In this year the crop in polluted air was less able to withstand moderate water stress during May and June.

The results are not easily interpreted in terms of ozone episodes over 60 ppb (57 hours in 1983, 22 hours in 1984, 15 hours in 1985), but the timing of such episodes is likekly to be very important.

Other crops which show a much greater sensitivity to O_3 (e.g. field beans) may be expected to show yield loss in response to ozone episodes. The number of episodes required to produce a 10% reduction in yield may not readily be estimated from published work so far.

The additional summer experiment with O_3 injection and field beans was used to show whether a limited number of episodes (10 days) could significantly influence growth and development of a sensitive crop. The experiment is described in some detail later but shows a pronounced effect on leaf area and dry matter in the different treatments.

These may be summarized as follows:

TABLE 8

	average leaf area per plant cm^2	Treatment (± SD)
1. filtered air (2 ppbV O_3)	201	± 50
2. ambient air (20 ppbV O_3)	195	± 45
3. 100 ppbV episodes*	164	± 49
4. 200 ppbV episodes*	131	± 41

* ambient + additional O_3 for 6 hours (1000-1600) for each of 10 days.

Other differences including plants above ground, dry weights and the degree of acute injury are described later.

Chamber aspect and edge effects

The results of these experiments contain much more detail than has been shown in this summary, and this includes information on the interquadrant differences within chambers and "north" v "south" differences within chambers, all as part of a study of the influence of chambers on plant growth and development.

An example of the analysis of results according to different chamber sections has been included as figures 1 to 6 from the winter barley experiment of 1982-1983. The data are presented in diagrammatic form for one variety and for 'head', shoot, and total weights and for head/shoot ratio. Broadly these show a small effect of aspect on yield within the chamber, the 'southern' half of the chamber yielding slightly more total dry matter than the 'northern' half. The differences vary from 2 to 12% and are not statistically significant in all cases but it is a sufficiently consistent effect to be confident of a real effect at about the 5% level.

The analysis of yield in concentric circles was to examine the influence of 'edge'. In theory the small chamber could cause considerable edge effects due to solar radiation absorption by the edge plants that would not be available to the plants in the centre. The harvest areas within a chamber were designed with 50% of the crop area as 'INNER' and 50% as 'OUTER', and the main results are taken from an analysis for the inner section. However, the use of a shading material on the walls of the chamber below crop height appears to have largely eliminated the solar-radiation edge effect. The remaining problems of edge are concerned with damage of edge plants by frequent removal of the chamber from the plot for crop development study, and with water and nutrient availability. The differences between yields in the outer and inner sections are less consistent than the north v south, but is again in the range 3 to 10% and is statistically significant for the shoot yield of variety Igri in the example provided.

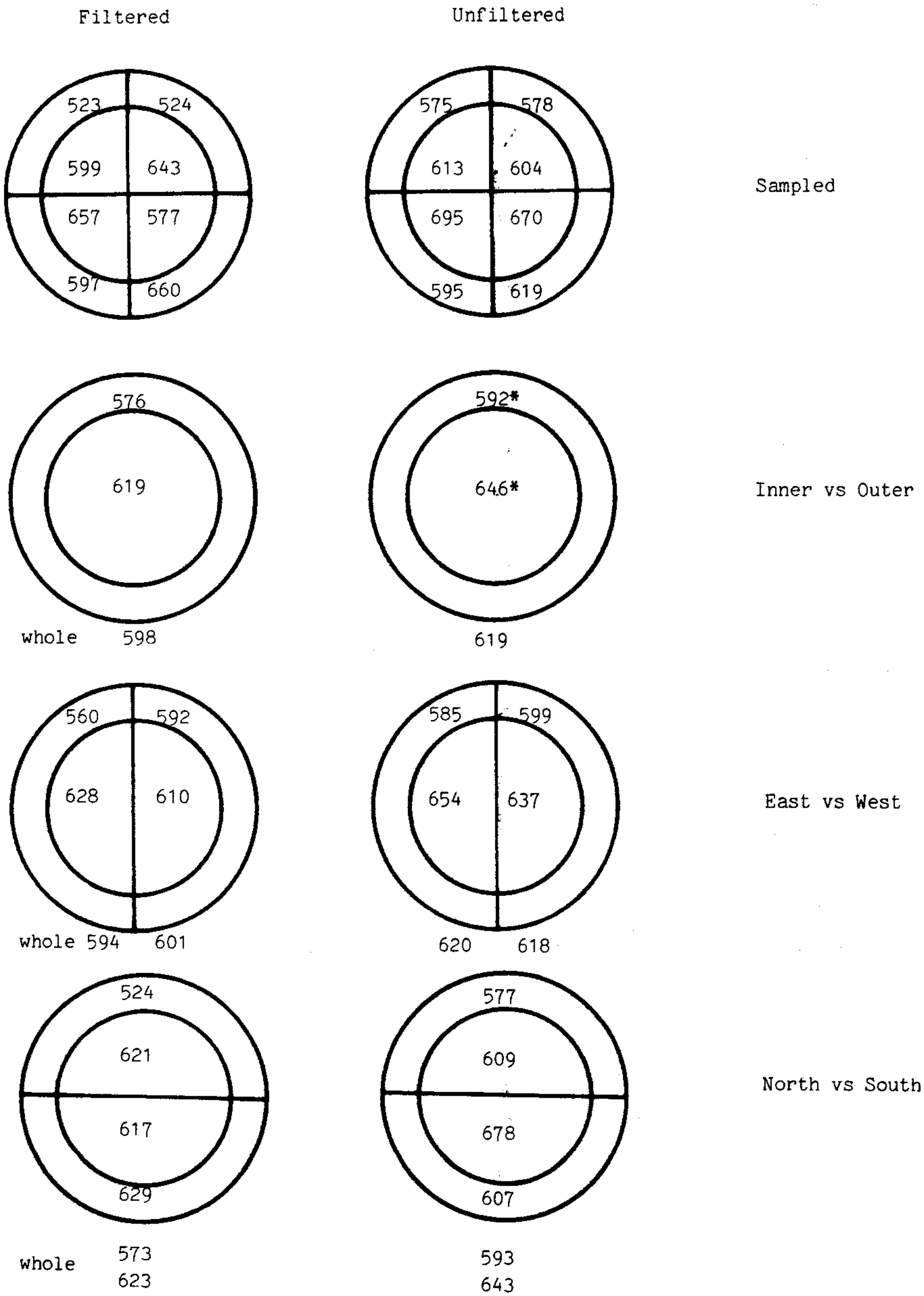
These data are available for each of the 5 experiments and for each variety and for combined treatments (providing 90 pages of this type of information in all).

Fig. 1. Within-chamber differences in yield.

Experiment 1

Winter barley 1982-83

Variety: Igri Shoot weight gm^{-2}



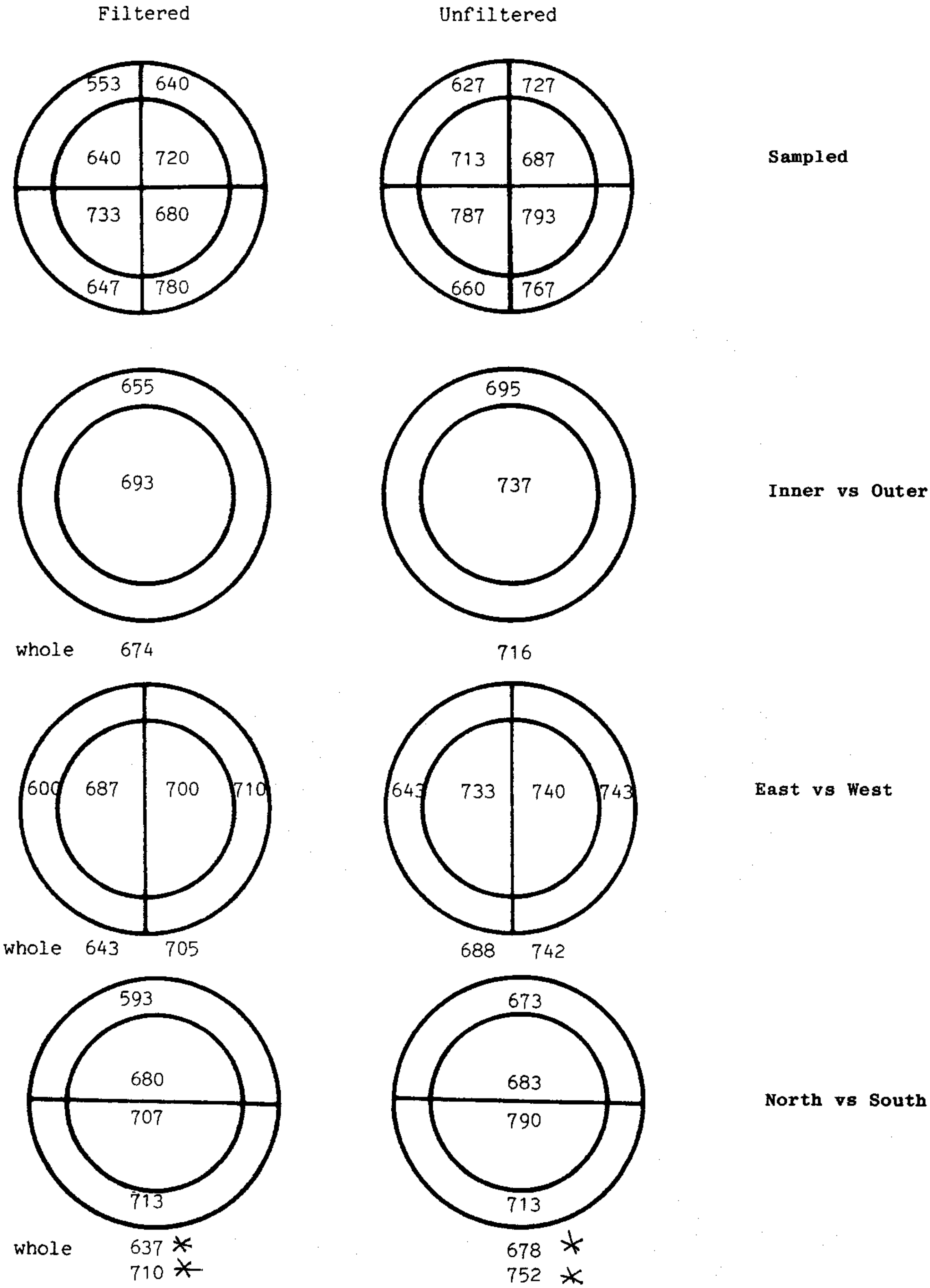
Note: * difference significant at 5% level, ** at 1% level.

Fig. 2.

Experiment 1

Winter barley 1982-83

Variety: Igri Head weight gm^{-2}



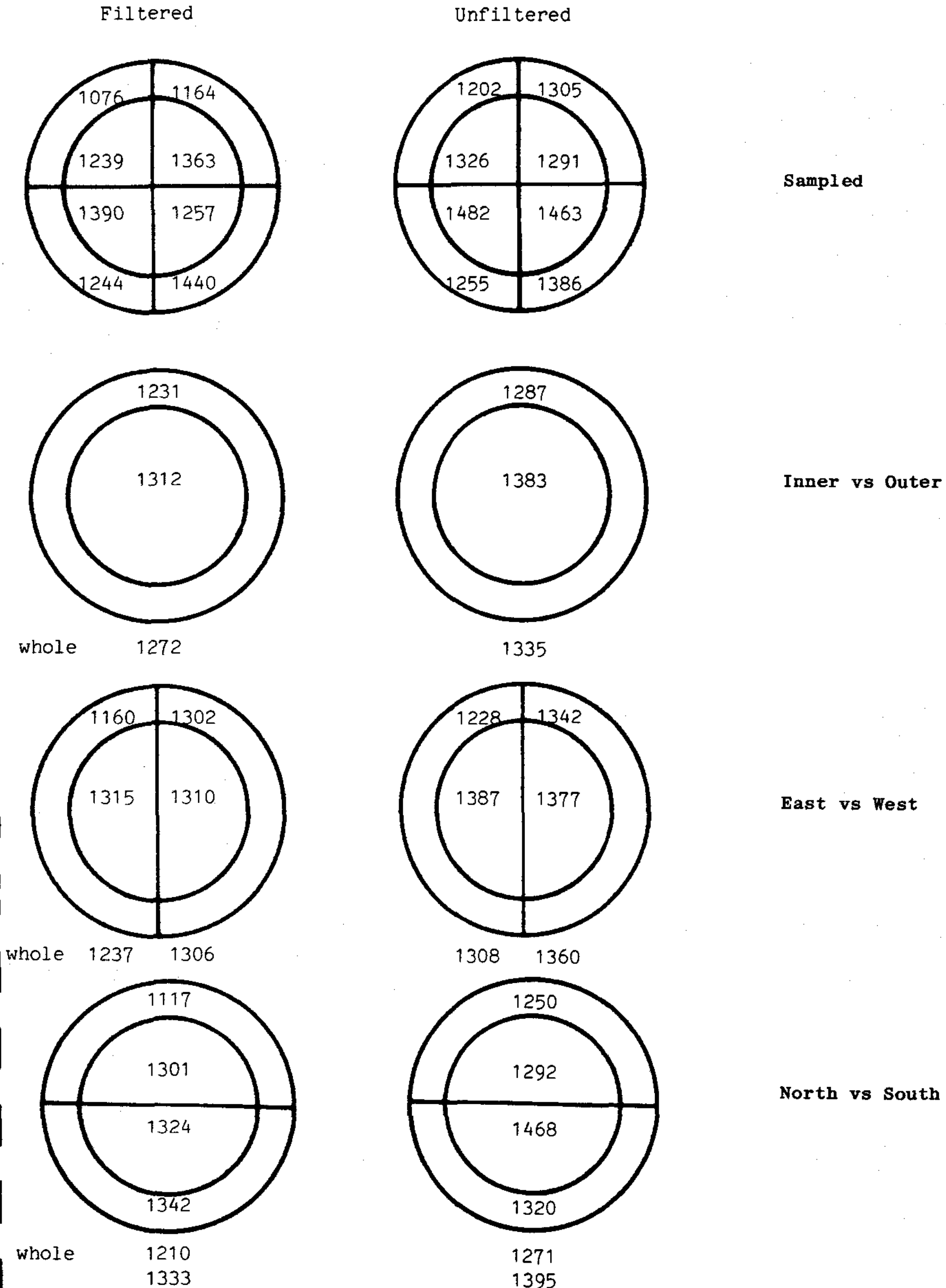
Note: * difference significant at 5% level, ** at 1% level.

Fig. 3.

Experiment 1

Winter barley 1982-83

Variety: Igri   Total weight gm^{-2}



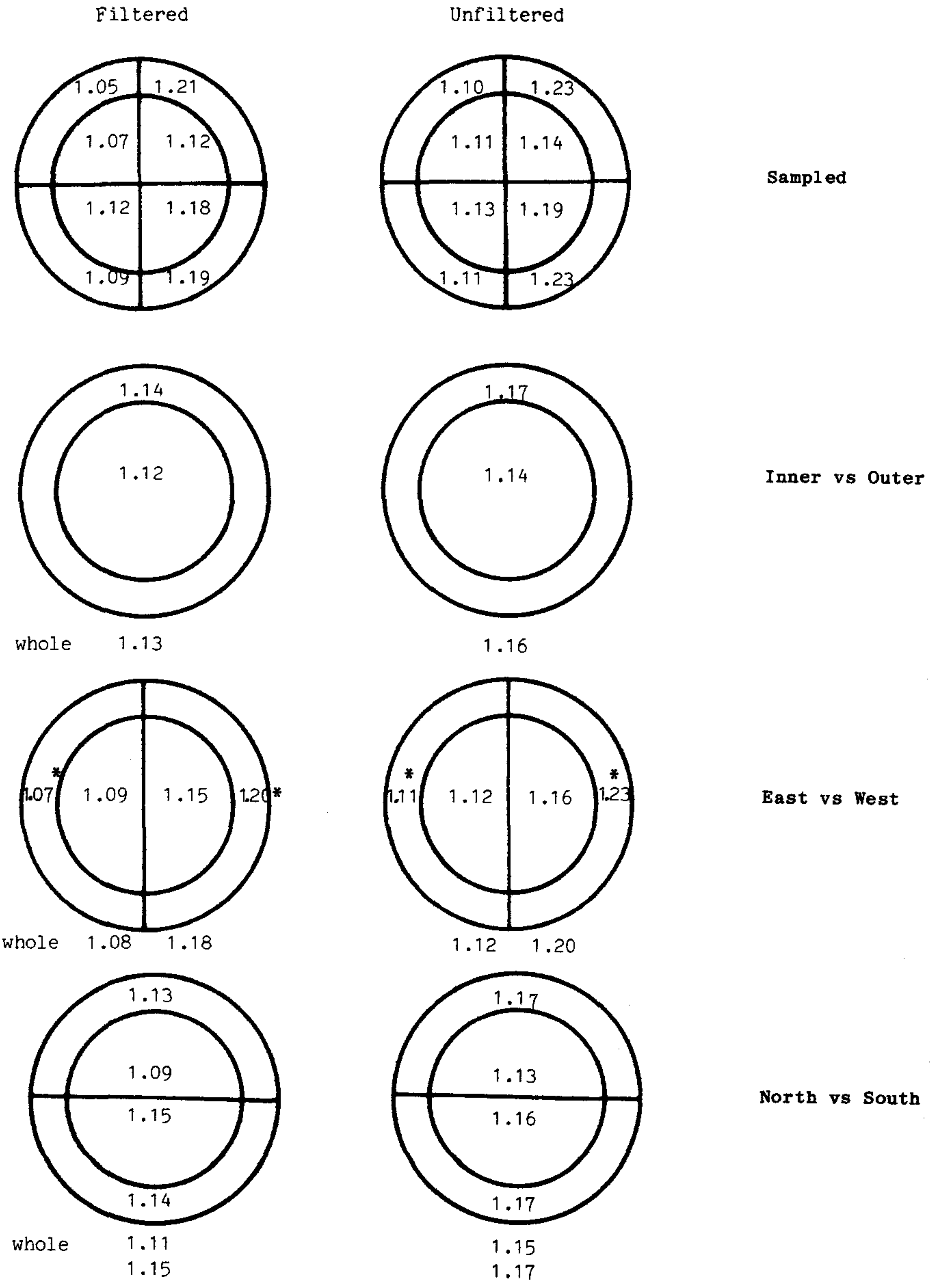
Note: * difference significant at 5% level, ** at 1% level.

Fig. 4.

Experiment 1

Winter barley 1982-83

Variety: Igri   Head/shoot ratio



Note: * difference significant at 5% level, ** at 1% level.

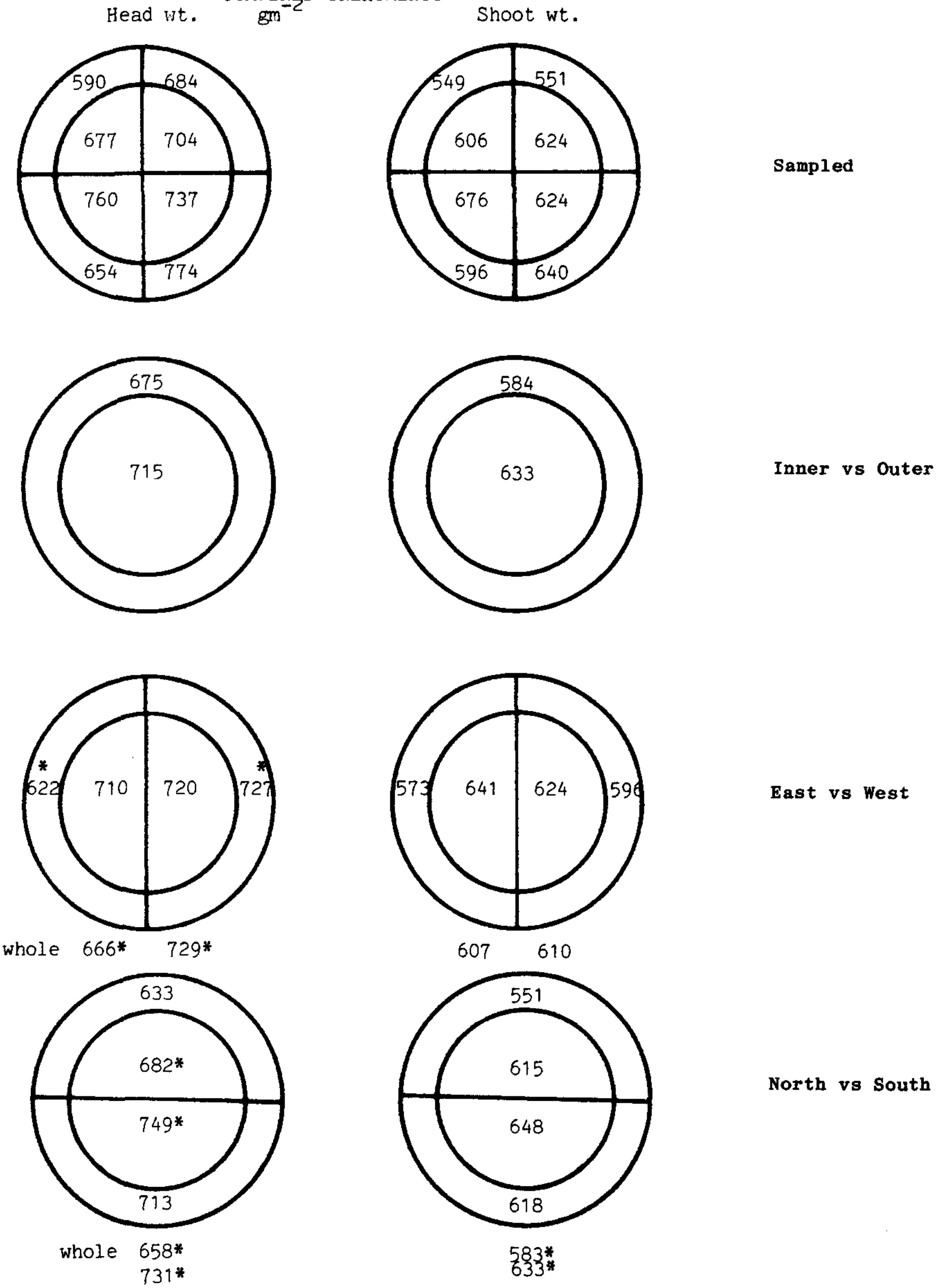
Fig. 5.

Experiment 1

Winter barley 1982-83

Variety: Igri

COMBINED TREATMENTS



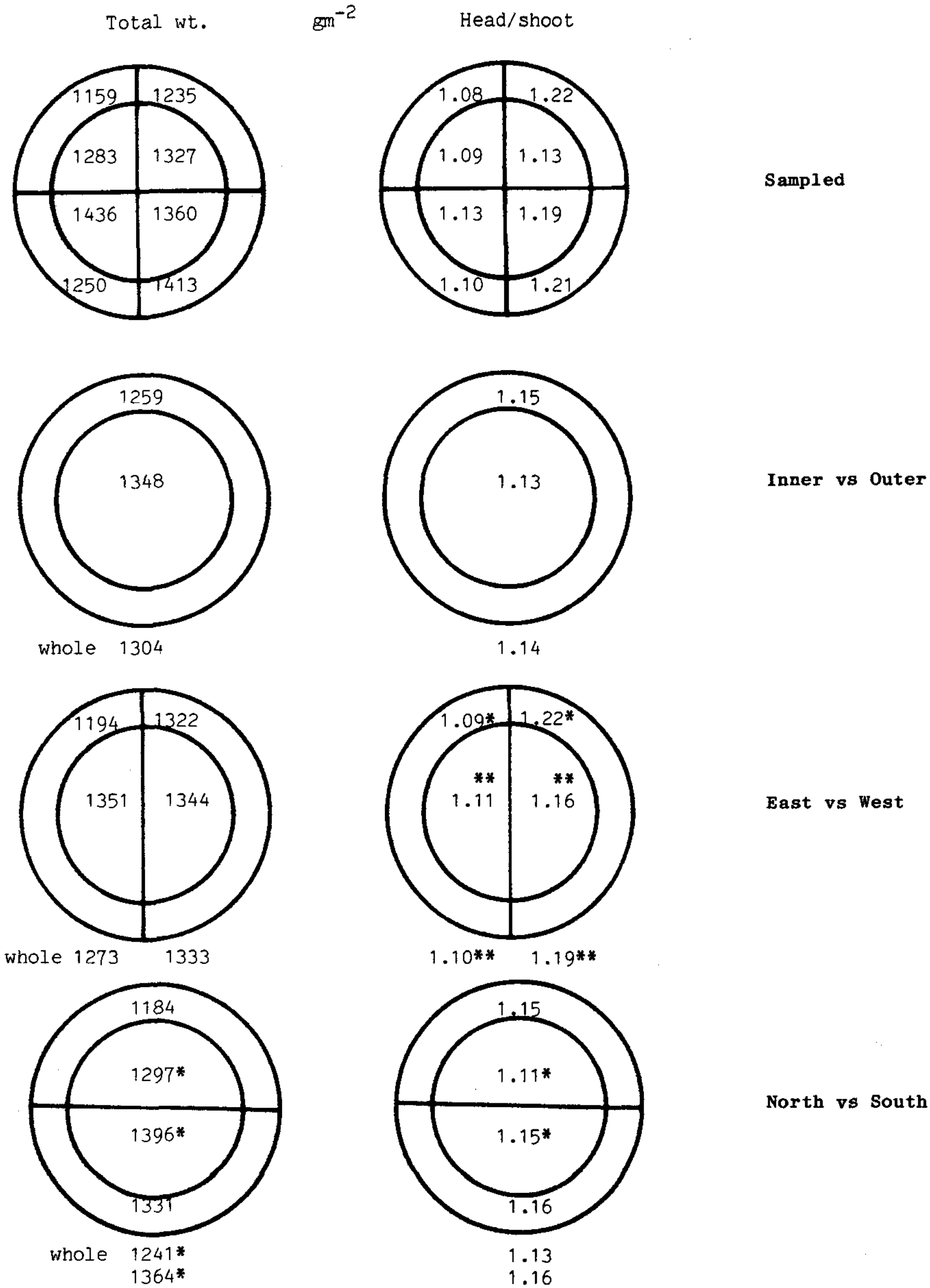
Note: * difference significant at 5% level, ** at 1% level.

Fig. 6.

Experiment 1

Winter barley 1982-83

Variety: Igri   Combined treatments



Note: * difference significant at 5% level, ** at 1% level.

3 OTHER STUDIES

3.1 Specifications of Open top chambers used in the barley studies

Chamber dimensions (See Figure 7)

Height	1.6 m		
Diameter	1.24 m		
Open diameter	0.9 m	Inlet pipe diam.	10 cm
Ground area	1.21 m^2	Annulus diam.	10 cm
Volume	1.93 m^3		

Materials & equipment

Walls -	Corrugated transparent sheeting - 'Super Corolux' riveted together to form cylinder.
Frame -	No frame, except for rectangular section aluminium rings, one at top and one at bottom, to which 'Corolux' is fixed with bolts.
Frustum -	PVC sheeting riveted together and attached to upper aluminium support ring.
Air distribution-	Air supply pipe enters close to base of chamber. Distribution within the chamber is effected through a plastic pipe (with verticle adjustment) supplying a perforated polythene annulus.
Pump -	Maximum flow 12 m^3 min^{-1}. In a chamber-filter system the range of flow rates available with the pump used (500 W motor) is 1-9 m^3 min^{-1}. The actual flow is determined by the desired residence time of air in the filter. Flow rates into chambers are matched to within 5%.
Air filter -	An activated carbon filter impregnated with chemicals to absorb SO_2 and NO_2. O_3 is removed readily by the activated carbon by itself. The granular filter material is contained in sealed fabric-coated filtered elements, each 80 cm x 80 cm x 4 cm, four of which are contained in each filter unit with pump attached beneath the filter, bolted to a steel frame.

Chamber characteristics

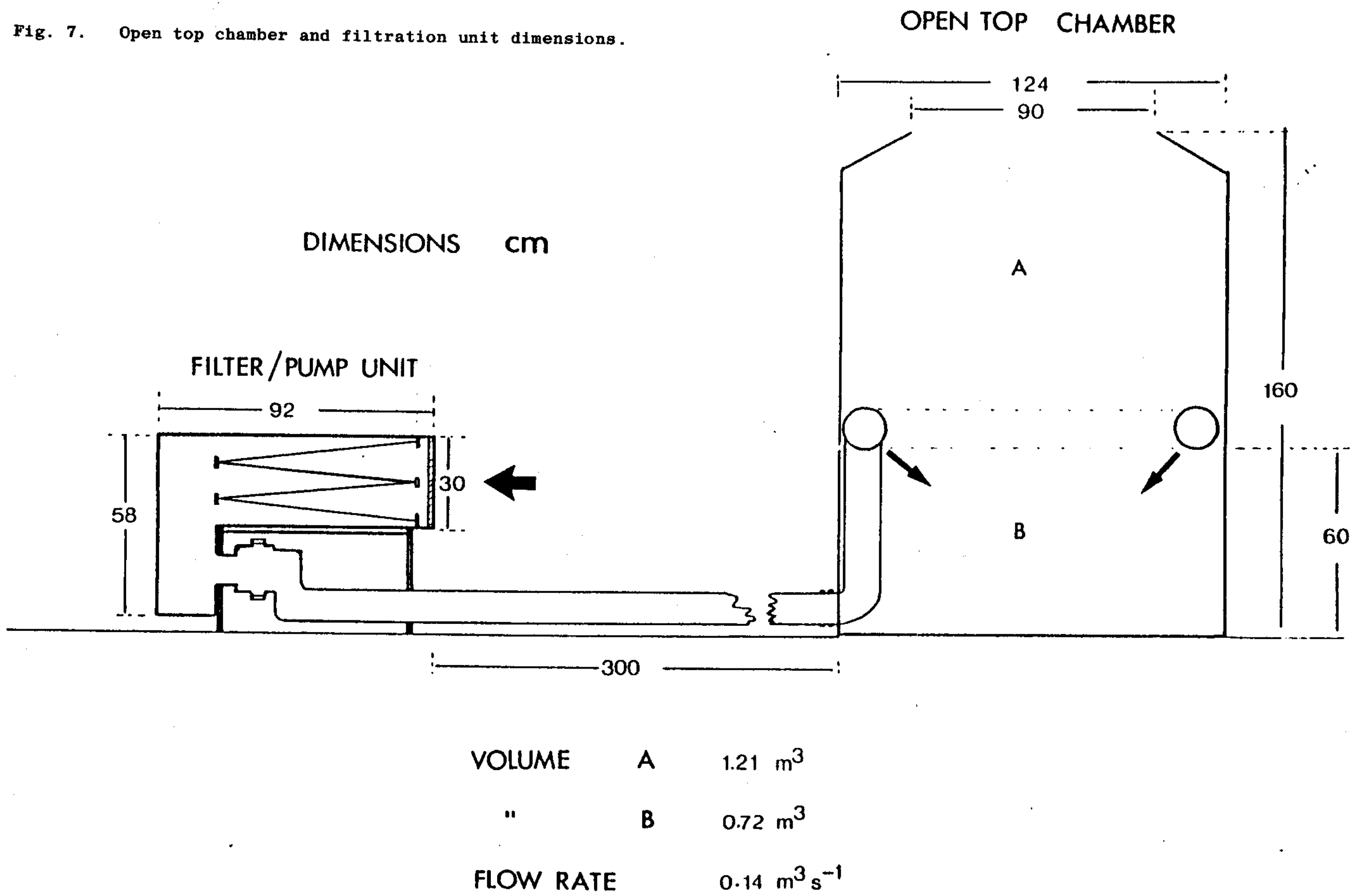
The flow rates used so far have bceen 6 m^3 $minute^{-1}$ (0.1 m^3s^{-1})$minute^{-1}$ which provides about 10 air changes per minute in the air space between crop and annulus (area B in diagram).

Filter efficiency -

Gas	$\mu g\ m^{-3}$	% removal
SO_2	10-100	95
NO_2	20-120	90
NO	20-140	0
O_3	8- 60	95

Residence time 0.35 s — Means of 20-100 values

Fig. 7. Open top chamber and filtration unit dimensions.



The filtration properties and their dependence on windspeed are shown diagrammatically in figure 8.

Note: (i) Final conc. depends upon amount of ambient air entering the chamber.
(ii) Removal of NO from airstream would be very expensive.

These filter efficiency values enable air concentrations in the chamber at windspeeds less than 2 m s^{-1} to be predicted. When wind speed is greater, significant incursions of air through the top of the chamber occur and overall filter efficiency is decreased. At 4 m s^{-1} air concentrations inside the chamber reach 33% of ambient values for SO_2 and NO_2 and O_3. Good performance of the chamber is assisted in conditions of large air concentrations and small wind speeds so that except for natural (O_3) the average overall efficiency of the chamber for SO_2 and NO_2 (and photochemical O_3 events) should exceed 80%.

Light - 'Corolux' walls transmit 80% of total short wave radiation. A similar percentage transmission is found for Photosynthetically Active Radiation. The diffuse component of incoming short-wave radiation is increased inside the chamber by refraction and internal reflections from the chamber walls.

The transmission characteristics of the chamber walls for short wave radiation on a sunny day are summarized in figure 9.

Air temperature- Air temperatures inside the chamber exceed those outside by 0.1°C for short-wave radiation flux (St) of 50 W m^{-2}. For St in the range 200-700 W m^{-2}, the temperature difference is between 0.2°C and 1.0°C. The effect of these temperatures of leaf temperatures is modified by air turbulence in the chambers.

The turbulent regime within the lower section of the chamber provides an efficient mechanism for the loss of sensible heat from foliage surfaces so that even though chamber air temperatures may exceed those of the air outside on a bright sunny day by between 1 and 2°C (see figure 10 the leaf temperature inside the chamber may be lower than in the field, depending on the windspeed over the field crop. The argument and assumptions are shown diagrammatically in figure 11.

An important feature of the small but persistent temperature difference between the chamber air and the 'field' is that at low temperatures 'developmental time' of the crop is strongly influenced. Taking a base temperature of 4°C above which growth and development occur, the cumulative degree-days within the chamber (which is on average between 0.3 and 0.5°C higher than field temperatures) generates a difference in

Fig. 8. Changes in chamber gas concentrations as a function of windspeed.

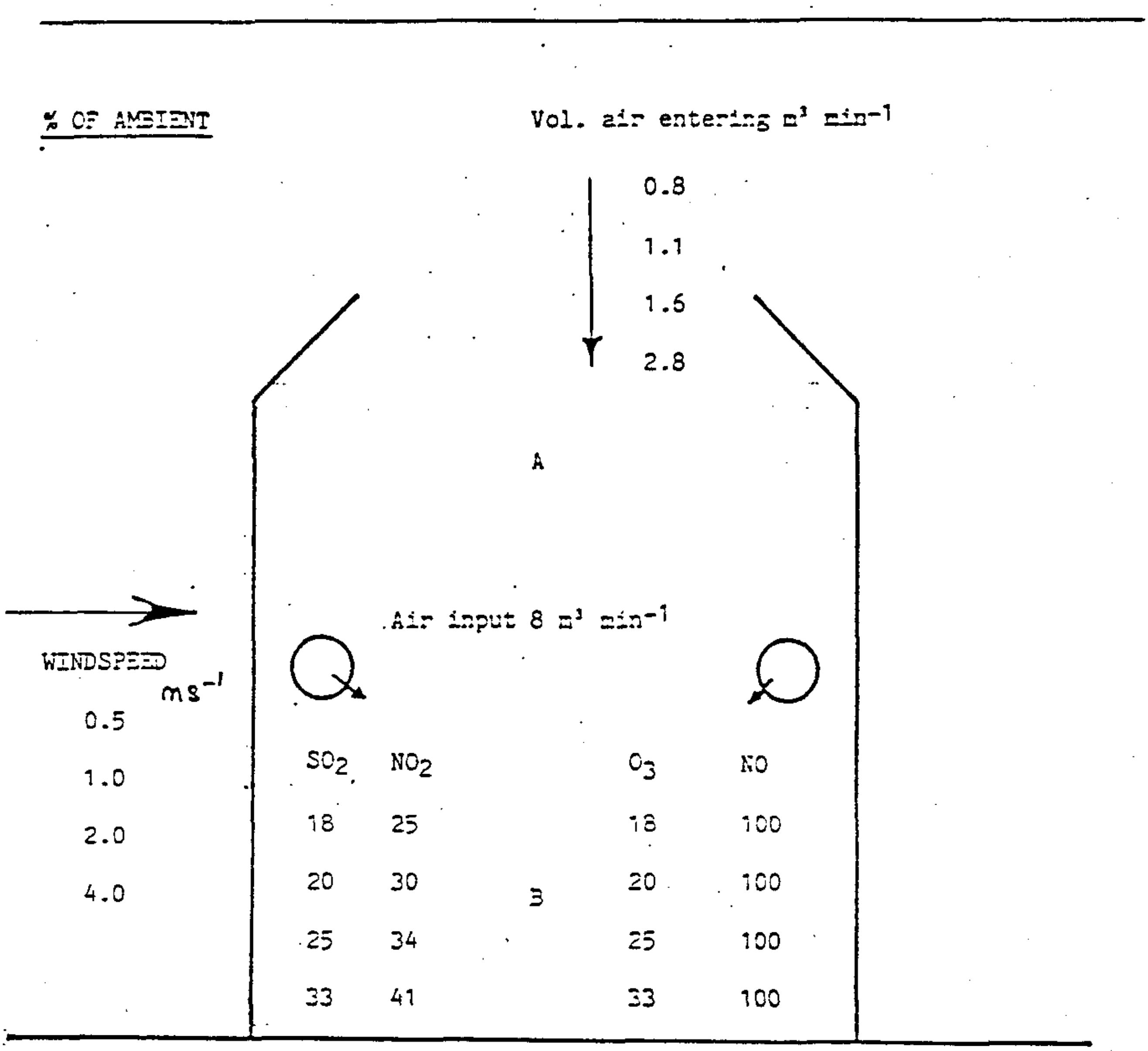
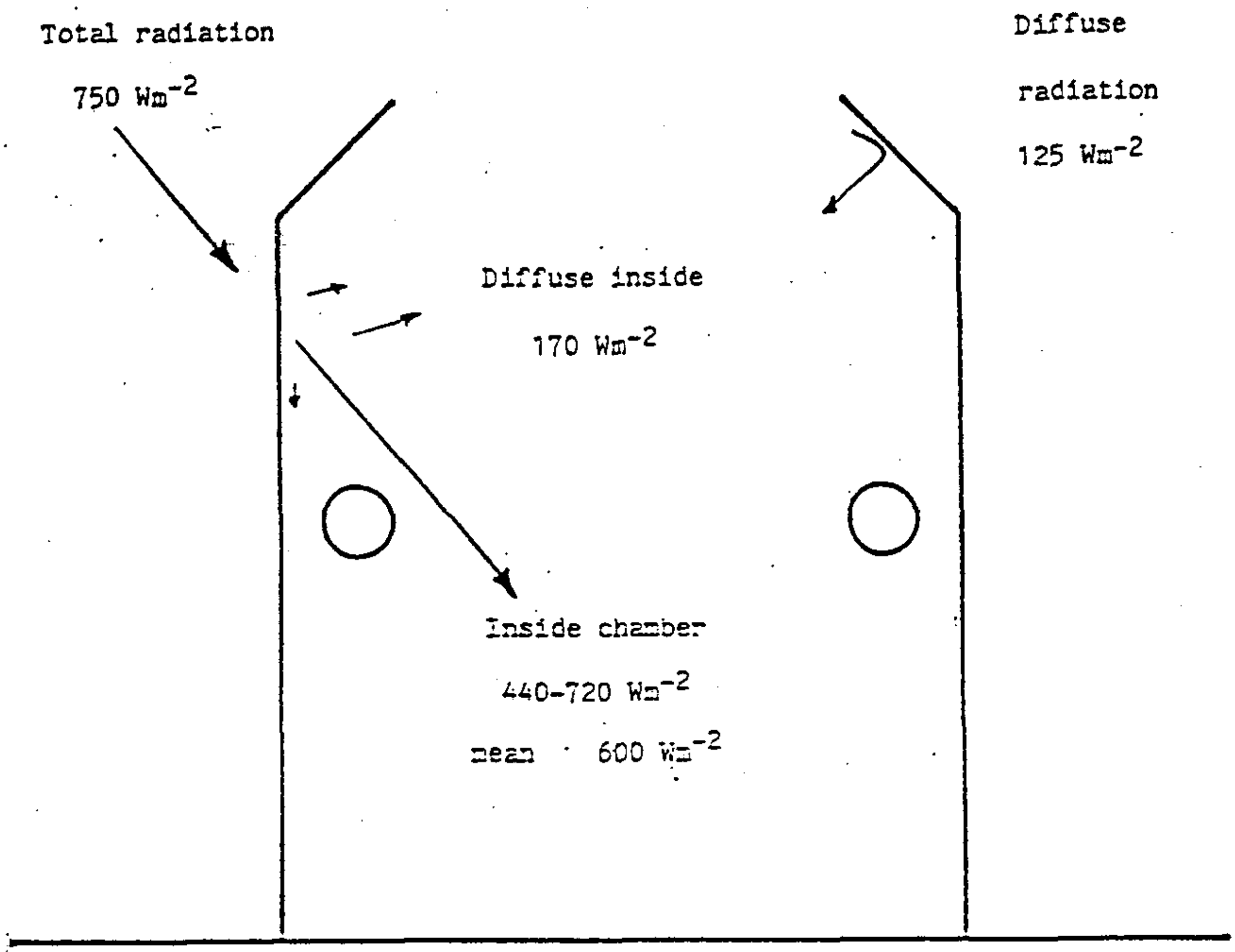


Fig. 9. Short wave energy loss by open top chambers.



On this occasion: external diffuse/total = 17%

internal diffuse/total = 28%

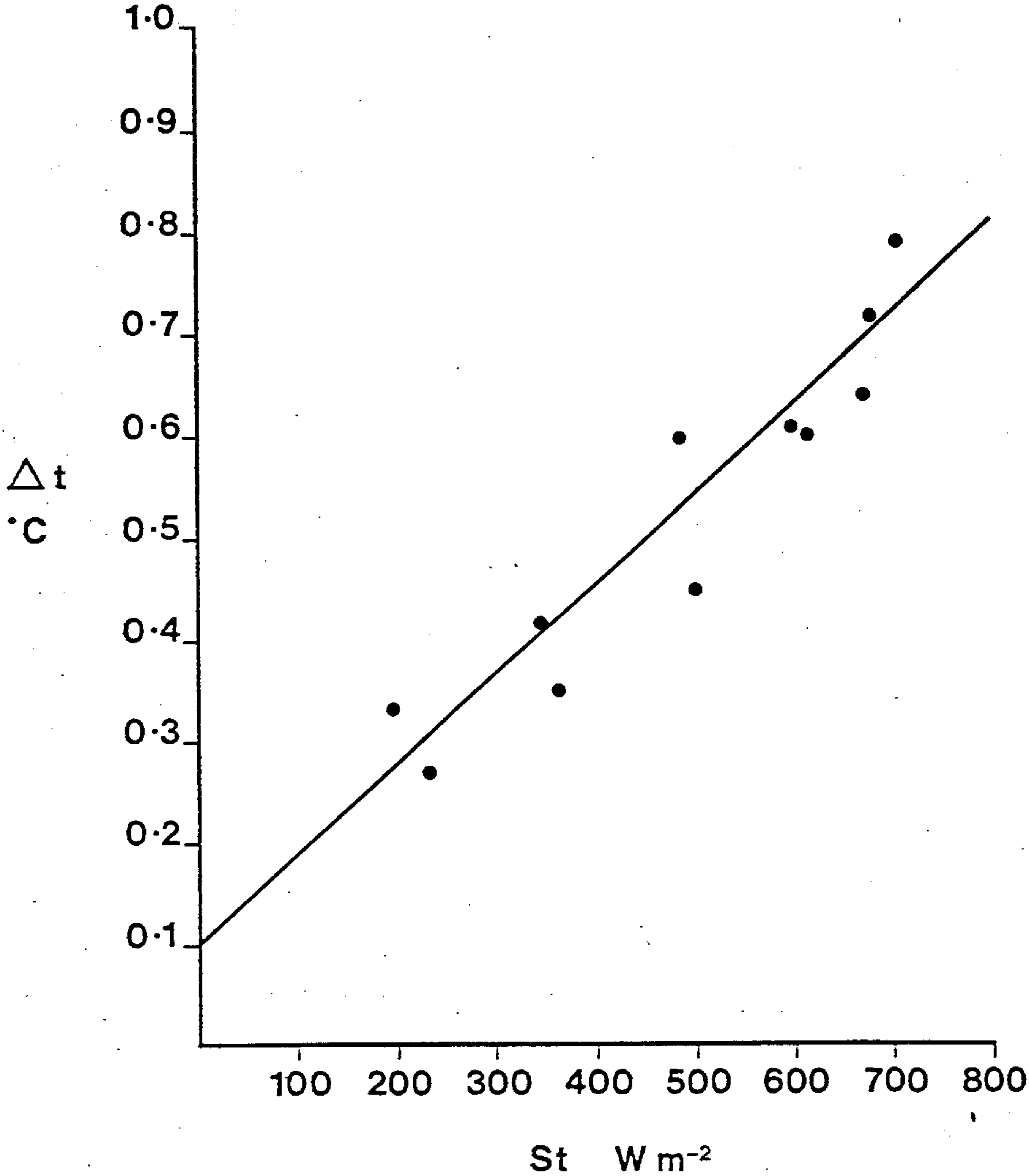


Fig. 10. The variation of air temperature difference between inside and outside an open top chamber with solar radiation.

Chamber Temp. - net radiation (Rn)

Rn < 150 Wm^{-2}

A & B>ta by < 1.0°C

Rn > 200 Wm^{-2}

A & B > ta by 1.0 to 2.0°C

(800 Wm^{-2} → + 2.0°C)

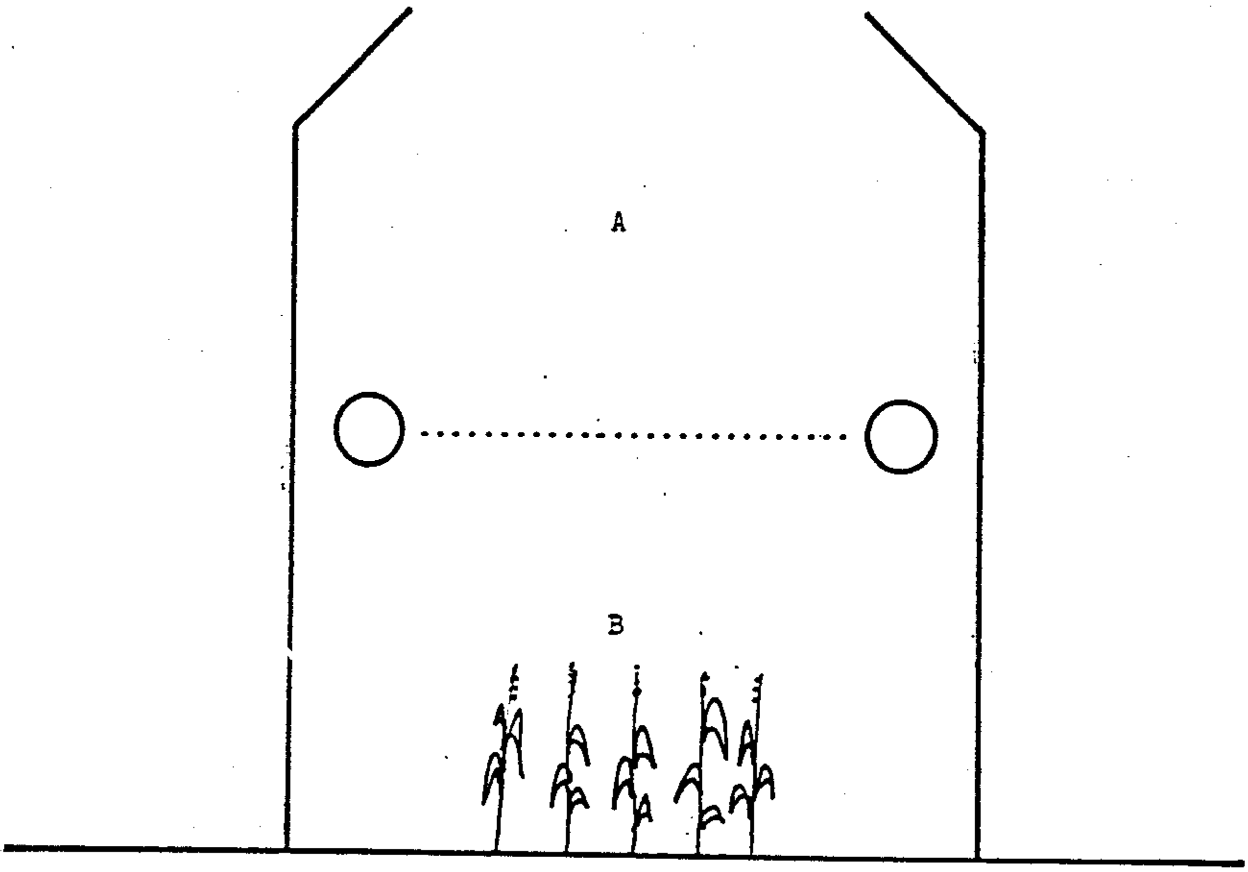
Boundary Layer Resistance

$(r_a + r_b)$ 19 s m^{-1}

for barley

≡ 3 m.s^{-1} windspeeds

over a field crop



Leaf temperature

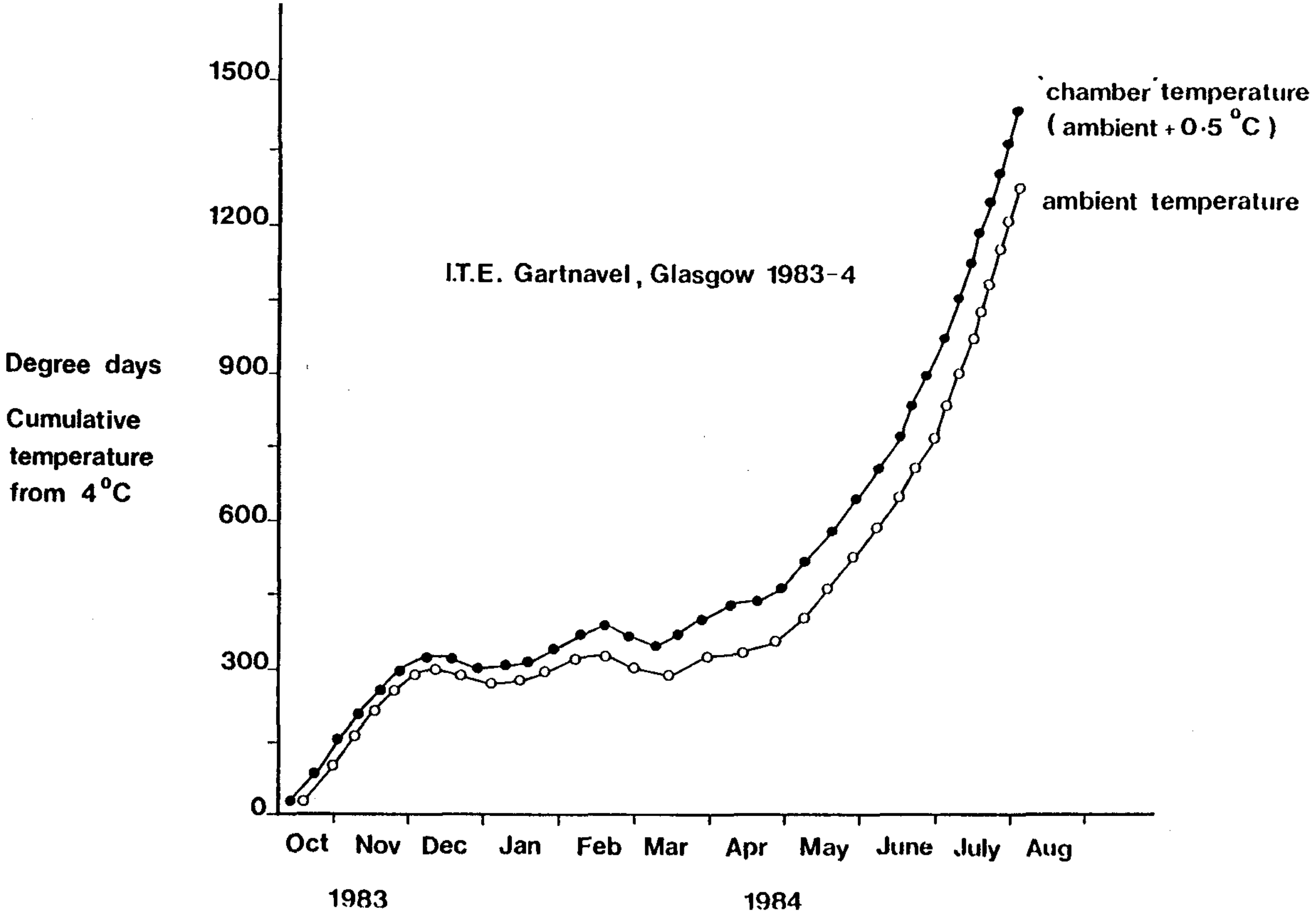
	INSIDE	OUTSIDE	
Ra	500 W m^{-2}	550 W m^{-2}	
air temp °K	293	291	
humidity	14 mb	14 mb	
ra s m^{-1}	20	40	(2 m s^{-1} at Z of 1.0 m)
Δ T°C	2	5	

Fig. 11. Barley leaf temperatures inside and outside an open top chamber.

development of the crop inside relative to outside the chamber. The difference is (from observation) generally between 10 and 14 days in the spring and may quite readily be reconciled with the small temperature difference when the heat sums inside and outside the chamber are plotted (Figure 12). This figure is a theoretical graph working from the air temperature record at the Glasgow site and an assumed temperature difference of 0.5°C. In practice the difference in temperature was more variable and generally smaller than that shown in the figure, but of the same order. Analysis of the field meteorological data from Glasgow is still in progress and will refine this treatment.

Air flow and air mixing - The air flow into each chamber is adjusted to provide identical turbulence/air flow characteristics in filtered and unfiltered chambers, the coefficient of variation of air flow into all chambers being +/- 4%. Between the crop surface and the manifold the air is turbulent, aerodynamic resistance being 20 s m^{-1} and equivalent to wind speeds over field-grown cereals of about 3 m s^{-1}. This results in very small temperature differences between plant leaves and the air in the chamber.

Fig. 12. The effect of the small temperature excess inside chambers on the heat sum during spring.



3.2 Study of the Effects of ambient ozone on growth of radish

Objective

The open top chamber facility at Glasgow allowed effects studies to be carried out on a variety of crops. During the summer of 1985, an experiment to determine the effects of ambient concentrations of O_3 on the salad crop Raphanus sativus cultivar Cherry bell took place. Work by Ashmore (1984) showed radish (Cherry bell) to be sensitive to ambient summer O_3 concentrations in the UK.

Method

On the 29th of May 1985, 154 radish seeds per plot were sown in six plots (ground area per plot 1.21 m^2). The treatments were (a) chambered and unchambered (b) filtered and unfiltered and (c) two levels of nitrogen fertiliser (30 kg ha^{-1} N and 100 kg ha^{-1}) applied to the plots over the growing season. The six plots (two per treatment) were watered regularly from the time of planting until harvest. All plots were destructively harvested on the 15th July 1985, approximately six weeks after sowing. The circular plots were divided into 4 equal quadrants and each quadrant subdivided into two equal areas, 'inner' and 'outer' sections. From each section 8 plants were selected for individual analyses. The remainder were counted and used in group analysis. Both sets of radish were separated into bulbs and shoots with the roots being removed and discarded. The bulbs and shoot were all dried at 80°C for 7 days. The results were analysed using a one-way analysis of variance and tested for differences between inner and outer sections within treatments and two way for differences between treatments in both the inner and outer sections. There was continuous monitoring of the major pollutant gases during the experimental period (NO_x, NO, SO_2 and O_3).

Results and conclusions

The results of number of radish plants per plot (Table 9a) show no significant differences between the 3 treatments, the levels of nitrogen, type of atmosphere or chambered/unchambered for both inner and outer sections of each plot. There was a significant difference at the 5% level between the inner and outer sections of all treatments for radish number apart from the chambered/unfiltered 100 kg N ha^{-1} and the Open 100 kg ha^{-1} plot. These results show better radish growth in the inner quadrants of both the chambered and unchambered plots, (ie the chamber has an edge effect similar to that shown for barley). This edge effect was found in the total shoot dry weights significant at 5% level for all treatments, but no effect was seen in the total dry weight of the hypocotyl.

Table 9b shows a highly significant difference at the 1% level between the chambered/unchambered treatment. The open plots had a much reduced total dry weight than the corresponding chambered plots. This could result from open plots being cooler or slightly less fertile and subject to more insect pests, though the temperature effect seems most likely.

Table 9a Number of individual Radish per plot at harvest

Treatment	Quadrant	No. of Plants Inner	Outer
Filtered 30 kg ha^{-1} N	1	21	21
	2	25	16
	3	22	17
	4	25	16
	x	23.3 ± 2.1	17.5 ± 2.3
Filtered 100 kg ha^{-1} N	1	25	18
	2	22	13
	3	27	17
	4	26	20
	x	25.00 ± 2.1	17.00 ± 2.9
Unfiltered 30 kg ha^{-1} N	1	22	17
	2	20	12
	3	23	18
	4	26	19
	x	22.75 ± 2.5	16.5 ± 3.10
Unfiltered 100 kg ha^{-1} N	1	24	16
	2	24	14
	3	23	23
	4	22	23
	x	23.25 ± 0.96	19.00 ± 4.69
Open plot 30 kg ha^{-1} N	1	17	14
	2	27	17
	3	22	13
	4	28	16
	x	23.5 ± 5.06	15.00 ± 1.82
Open plot 100 kg ha^{-1} N	1	27	13
	2	25	19
	3	18	19
	4	25	24
	x	23.75	18.75 ± 4.5

Table 9_b Combined Dry weights (g) of bulb roots and shoots for grouped samples.

Chamber/Treatment	Dry weight Mean (g) Inner/Outer Sections
25 Filtered 30 kg ha^{-1} N	16.45 ± 6.03
26 Unfiltered 30 kg ha^{-1} N	16.18 ± 5.59
27 Filtered 100 kg ha^{-1} N	13.56 ± 4.92
28 Unfiltered 100 kg ha^{-1} N	16.20 ± 5.24
34 Open 30 kg ha^{-1} N	9.34 ± 5.95
40 Open 100 kg ha^{-1} N	6.38 ± 2.64

There were no differences between unfiltered and filtered at the two levels of nitrogen in the chambered plots for total plant dry weight.

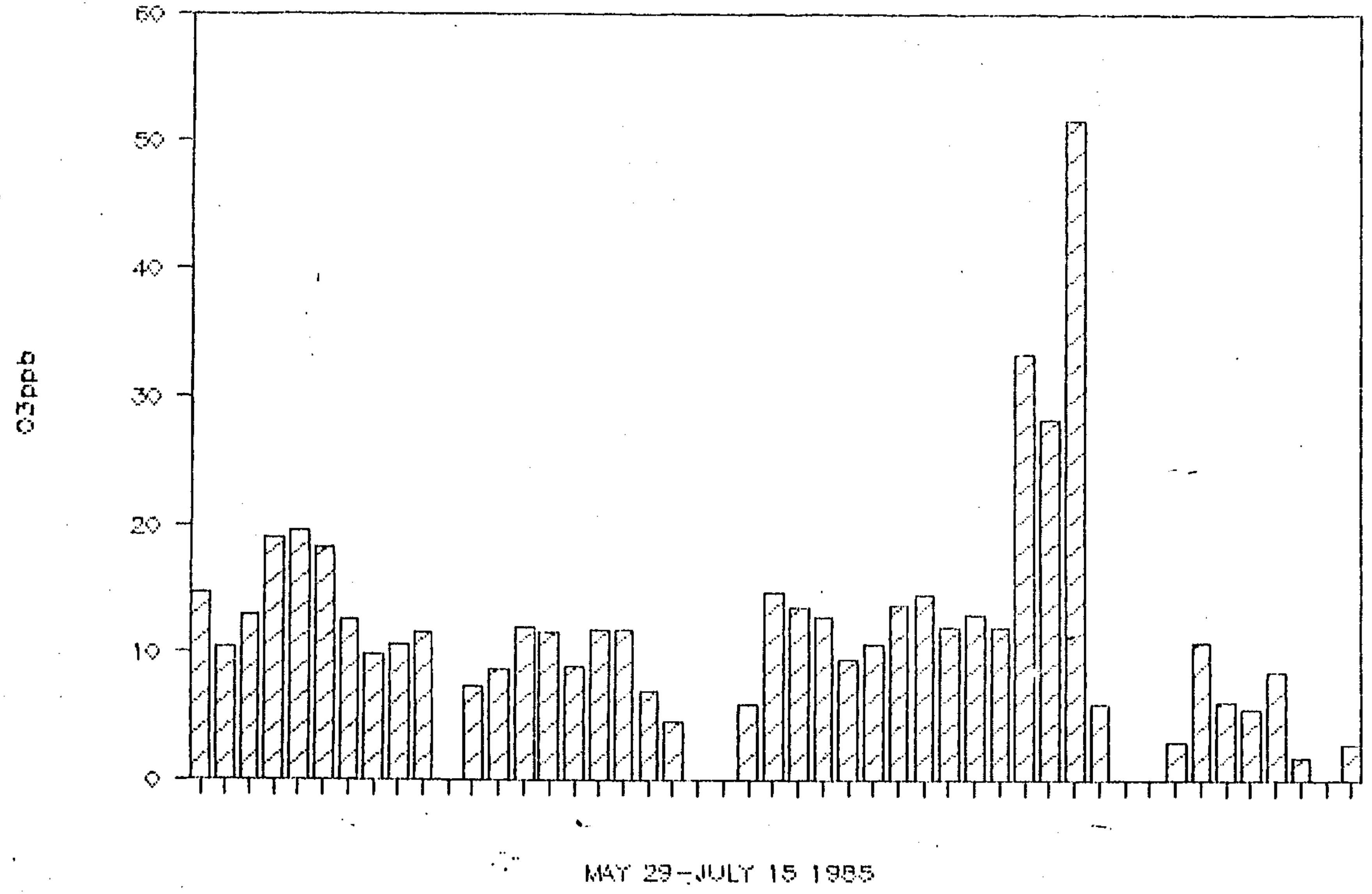
The daily mean ambient O_3 concentrations (Table 10 and Figure 13) from the 25th May - 15th July 1985, show no large photochemical episodes during the experimental period, ie concentrations 80 ppbV O_3. The lack of high O_3 concentrations is the main cause of the insignificant differences between treatments.

This result in a year with only moderate ozone concentrations underlines the difficulty in relying on the UK climate for appropriate experimental conditions.

Table 10. Daily ambient O_3 concentrations
25th May - 15th July 1985

May		June		July	
Day No.	Conc ppbV O_3	Day No.	Conc ppbV O_3	Day No.	Conc ppbV O_3
25	12.6	1	19.0	1	12.1
26	21.4	2	-	2	33.3
27	21.3	3	19.6	3	28.3
28	15.1	4	18.4	4	51.7
29	14.8	5	12.7	5	5.9
30	10.6	6	9.9	6	0.0
31	12.9	7	10.6	7	0.0
		8	11.6	8	2.9
		9	-	9	10.9
		10	7.4	10	6.2
		11	8.7	11	5.5
		12	12.1	12	8.4
		13	11.6	13	1.9
		14	8.9	14	-
		15	11.8	15	2.9
		16	11.8		
		17	6.9		
		18	4.6		
		19	-		
		20	-		
		21	6.3		
		22	14.7		
		23	13.7		
		24	12.9		
		25	9.5		
		26	10.6		
		27	13.8		
		28	14.6		
		29	12.1		
		30	12.8		
		31	-		

Fig. 13. Daily mean ambient O_3 concentrations, ITE Glasgow, 29th May - 15th July, 1985.



3.3 The photosynthetic efficiency of barley in polluted and clean air.

Objective

To determine the photosynthetic efficiency of barley plants grown in the presence of (1) filtered and (2) polluted air.

Method

The barley plants were sown in autumn 1984 in 1.2 m^2 plots. The variety of barley used in this experiment was Gerbel, as in the main experiment described earlier. There were approximately 356 barley plants on each plot which was covered by a chamber throughout the period of growth. Harvesting the plants for this experiment began on 1st May 1985, and continued at approximately ten day intervals for fifty days. Four treatments were used, clean air, polluted air and two levels of nitrogen in the soil, N1 or N2. N1 = 30 kg ha^{-1}. N2 = 100 kg ha^{-1}.

For each harvest a quadrant from each chamber of the four treatments was harvested. The quadrants were harvested in an anticlockwise order, successive harvests beginning with the northeast quadrant, and each quadrant subdivided into equal areas, one inner section and one outer section. Each section had an area of 0.146 m^2.

Solarimeters were placed one above the crop within a chamber and one below the crop in each of the quadrants next to be harvested, so that the energy intercepted by the crop could be measured. The use of an additional solarimeter outside the chamber made it possible to estimate the energy intercepted by the chamber walls. Three of the solarimeters were connected to integrators, which were read regularly and the other two were linked directly to the computer for continuous analysis.

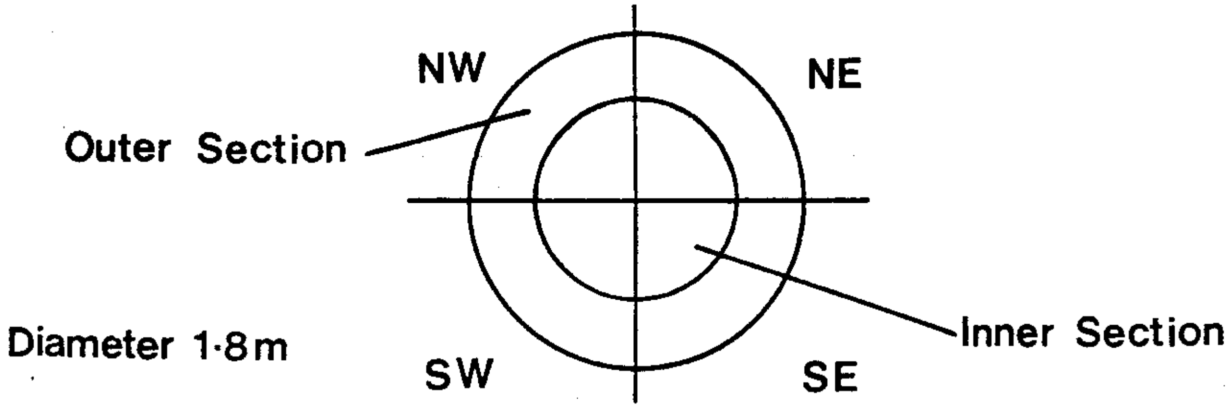
In total there were eight harvests, the first being on the first day of the experiment. Each successive harvest was 7-10 days apart. After four harvests another four plots were used each with the same conditions as those already harvested.

TREATMENTS

FILTERED/UNFILTERED	N1/N2
UF	N1
F	N1
UF	N2
F	N2

HARVEST DATES FOR THE EXPERIMENT:

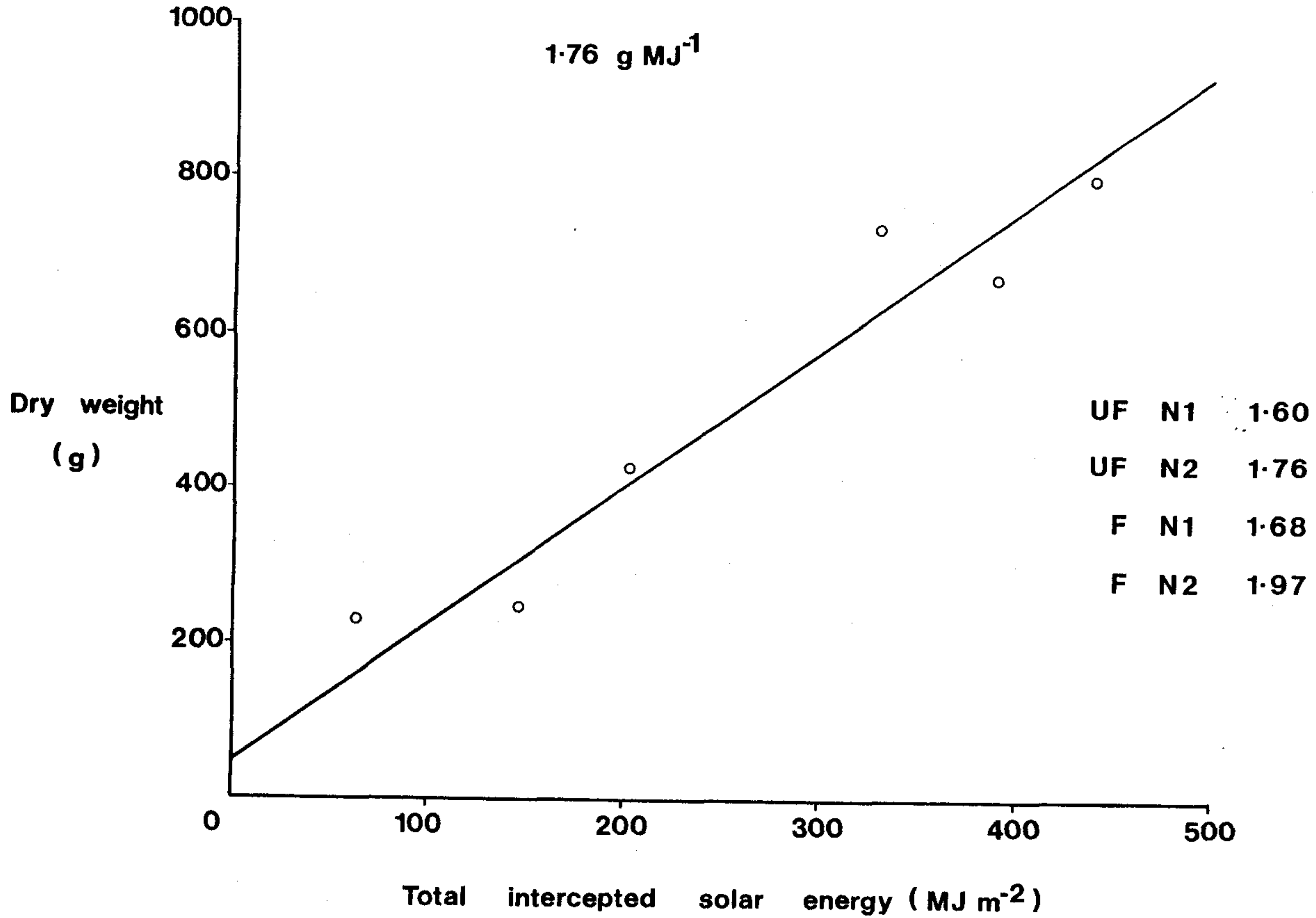
DATE	QUADRANT
1.5.85	NE
10.5.85	NW
22.5.85	SW
29.5.85	SE
5.6.85	NE
13.6.85	NW
19.6.85	SE



At the time of harvesting the number of plants in each section were counted. The number of main stems in each section were then counted and fifteen selected for analysis. Before analysis the barley was stored at 5°C in a cold room to keep the plants as fresh as possible for the green leaf area measurement. The fifteen randomly selected plants were separated into leaves, stems (and heads when emerged). These were then measured using a Delta T Area Meter. The instrument was calibrated twice daily using colour matched card of specific areas. The areas were measured in cm^2 per section and converted to m^2m^{-2} ground area. After the areas were measured, the whole sections were then dry weighted and the data converted into units of energy mJm^{-2}. (The conversion being the heat of combustion of dry matter into heat, 17.5 kJg^{-1}).

Table 11 shows the amount of dry matter expressed in energy units. The graph of dry matter produced against intercepted energy shows the close linear relationship between dry matter production and available energy, the slope of the line providing a measure of photosynthetic efficiency when converted into energy units. Figure 14 shows the data plotted for one of the treatments and table 11 shows the values for all treatments, with values between 2% and 3%. The photosynthetic efficiency is largest in the high nitrogen-clean air treatment and lowest in the low nitrogen-polluted air treatment although these are the only values that differ significantly because of the variability of the crop within chambers which is partly a consequence of aspect and is discussed earlier.

Fig. 14 Photosynthetic efficiency of barley in open-top chambers



		dry weight/ intercepted energy g MJ^{-1}	Photosynthetic efficiency %
Filtered	N1	1.68	2.85
Unfiltered	N1	1.97	2.70
Filtered	N2	1.60	3.33
Unfiltered	N2	1.76	2.90

Table 11 Photosynthetic efficiency of barley in filtered and polluted air at two different nitrogen fertilizer treatments.

3.4 Studies of the exchange of O_3, CO_2 and NO_x in open-top chambers

As part of a large-scale experiment studying the effects of gaseous air pollutants on crop growth we have used our exposure chambers as large 'cuvettes' to study the simultaneous exchange of a number of gases under field conditions of light intensity and temperature. Gas concentrations are measured on a 10-minute cycle, alternating between inlet and outlet of the chamber. The gas fluxes may be calculated from the concentration differences. Such measurements have been made continuously over a period of months, allowing us to investigate the variation of fluxes with the different stages of crop development, (fig. 15).

Turbulent transfer of gases within the chamber is constant. The aerodynamic resistance (for barley) is 20 s m^{-1}, with a viscous boundary layer resistance of 12 s m^{-1}. The maximum deposition velocity to a 'perfectly absorbing' surface is thus $1/(20 + 12) = 0.03$ m s^{-1}. Deposition velocities smaller than 30 mm s^{-1} therefore contain a surface resistance term. The largest deposition velocities observed (18.5.85) of 18 mm s^{-1} show that the surface resistance is almost as great as the combined aerodynamic and boundary-layer terms, while on average, the surface term is by far the greatest.

Ozone Uptake

Deposition of ozone to the chamber itself may be estimated by covering the ground surface with an inert material. The large initial uptake of ozone shown here is not restricted to polyethylene, as PTFE shows similar behaviour. After several hours the rate of removal by the chamber is not distinguishable from zero, (fig. 16).

Deposition of ozone to bare soil is appreciable, and appears to be related to soil moisture and organic content.

Once air enters the chamber, the short-wave photolysis of NO_2 is stopped, allowing the reaction of O_3 with NO to proceed. For the examples given here this reaction gives an apparent deposition velocity of the order 1-2 mm s^{-1}, which varies very little with time of day.

The rate of deposition to a field crop like barley depends upon the time of day, and the physiological state of the plants. The diurnal cycle (Fig. 17) shown is related to the opening of stomata for exchange of CO_2 and water vapour. The night-time values represent deposition to external plant surfaces and soil. As the crop grows, and the amount of leaf area per unit ground area (leaf area index) increases, so the deposition velocity also increases, then decreases again with grain formation and senescence (Fig. 18).

Fig. 15.

FLUX MEASUREMENTS IN O/T CHAMBERS

X_1 inlet concentration measurement, X_0 outlet concentration measurement

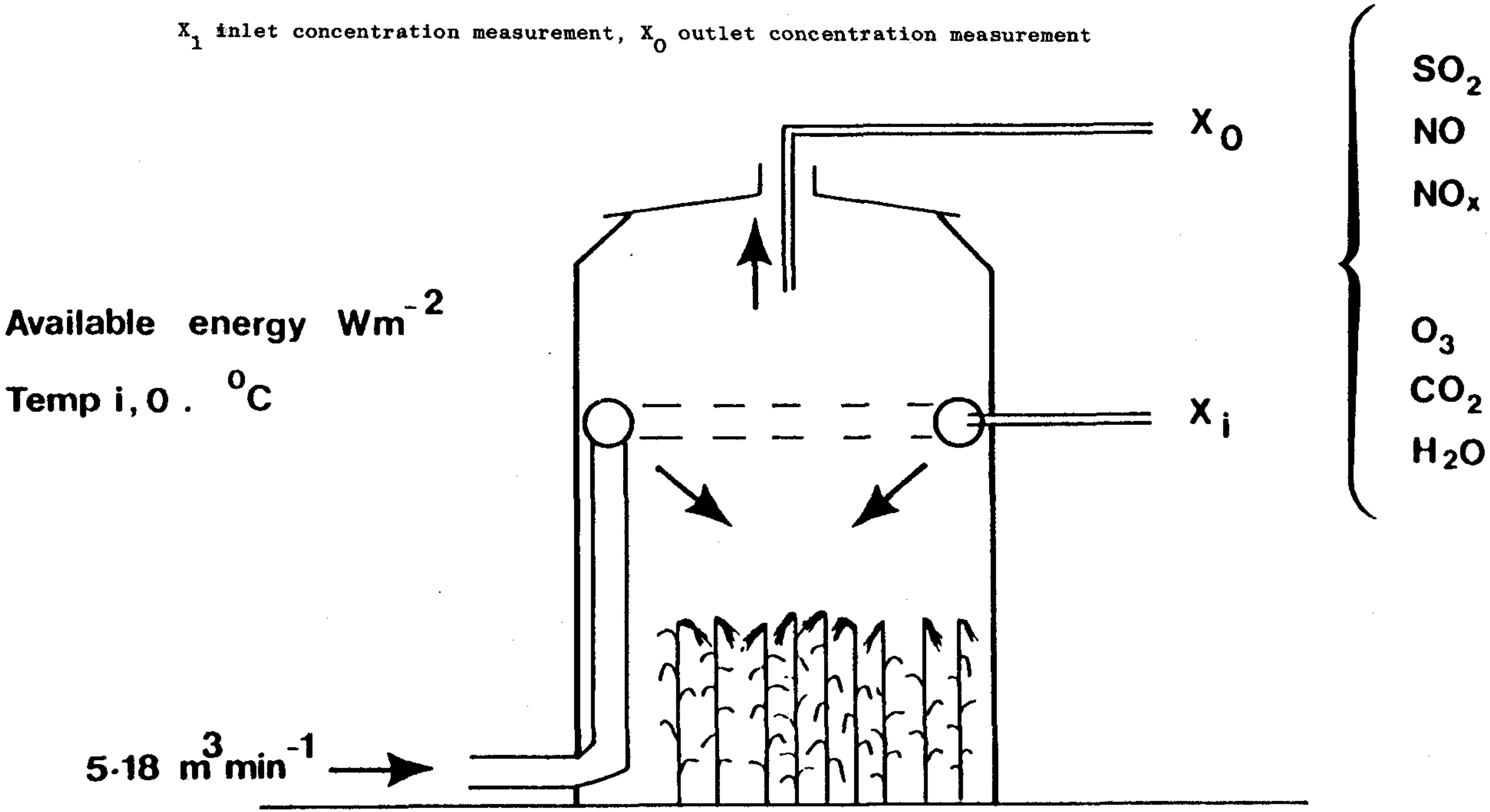


Fig. 16. Dry deposition of Ozone onto open top chamber walls.

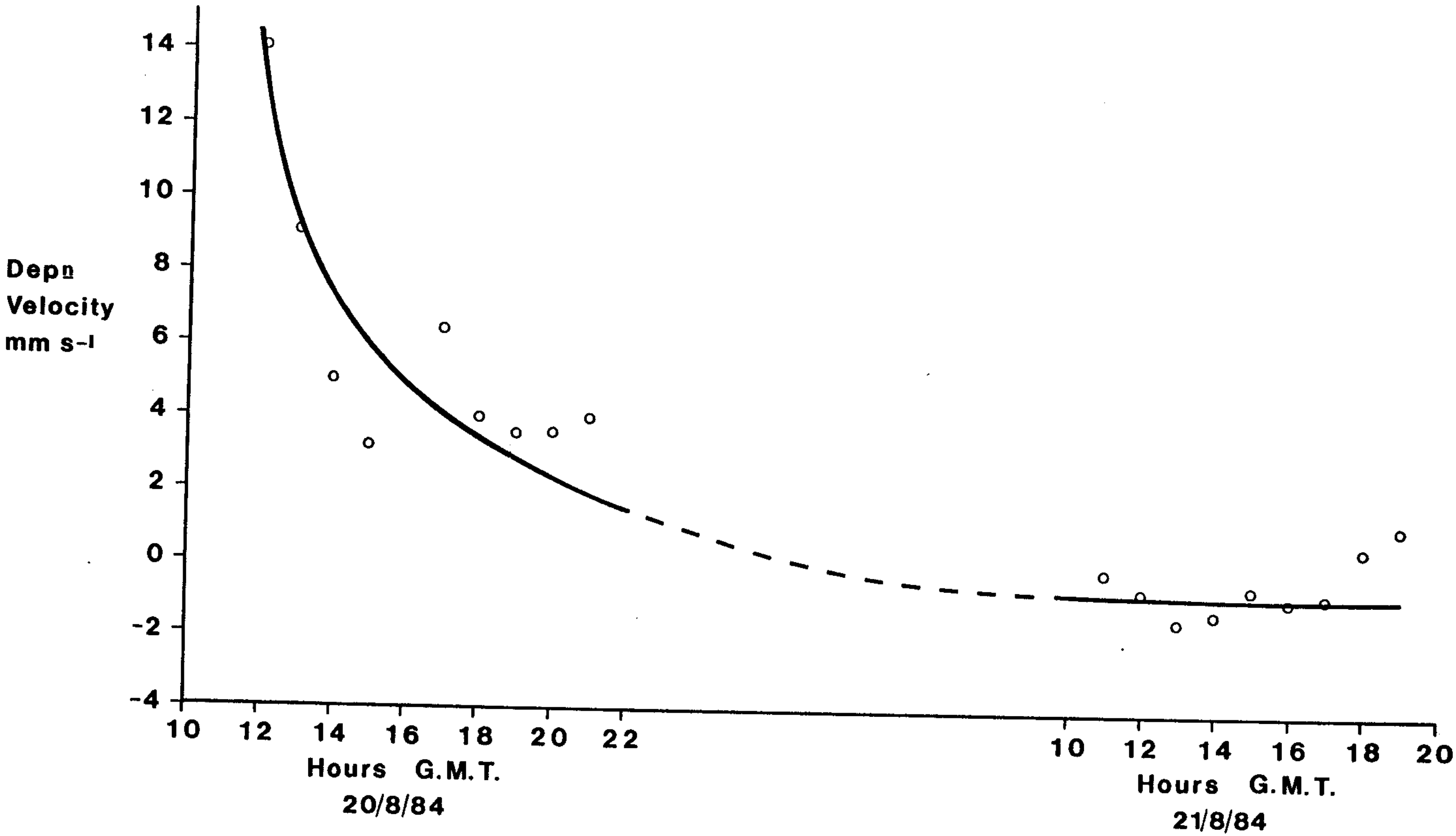


Fig. 17. Dry deposition of O_3 onto barley crop in an open top chamber showing larger peak Vg values than in early May due to a larger leaf area index of the crops. Data for 18th May 1985.

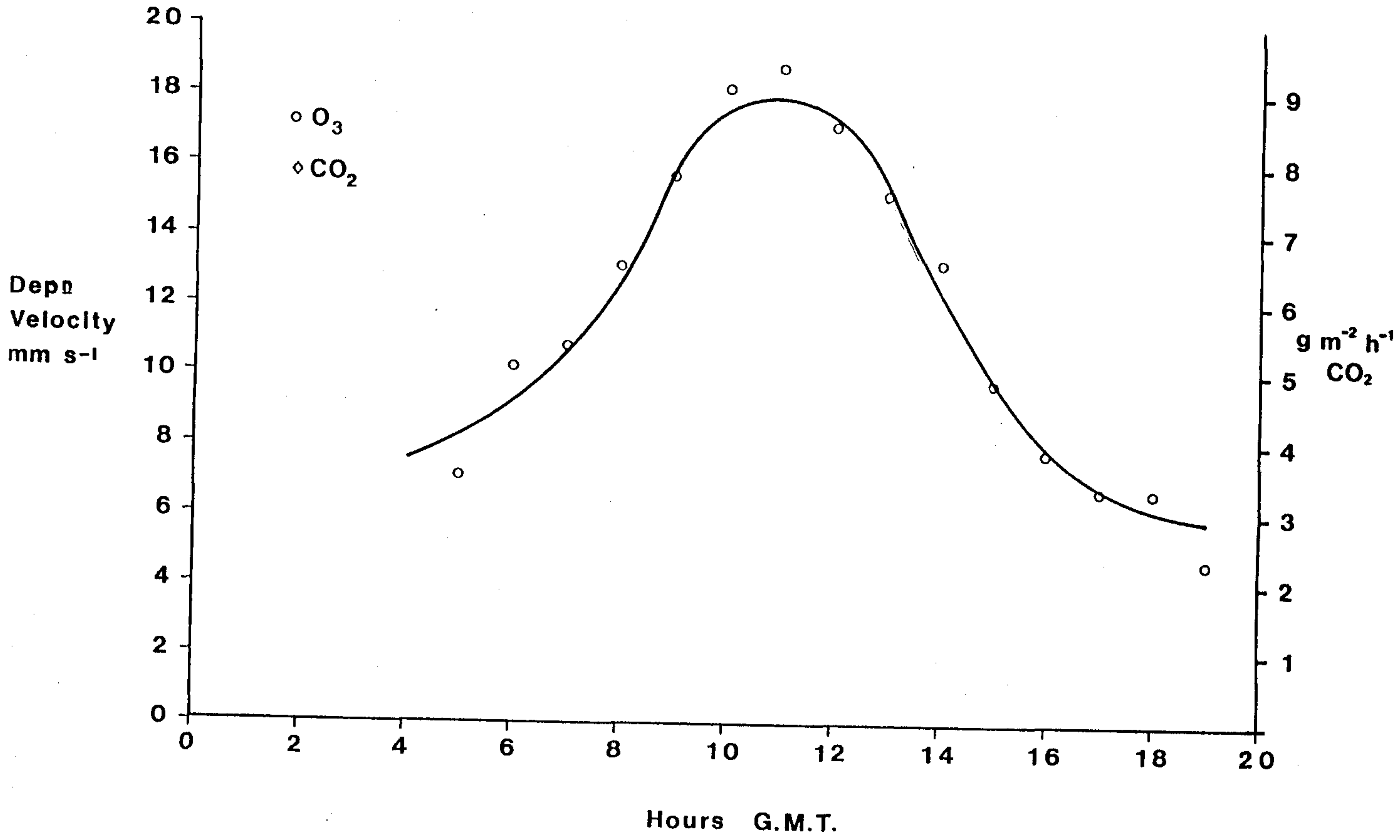
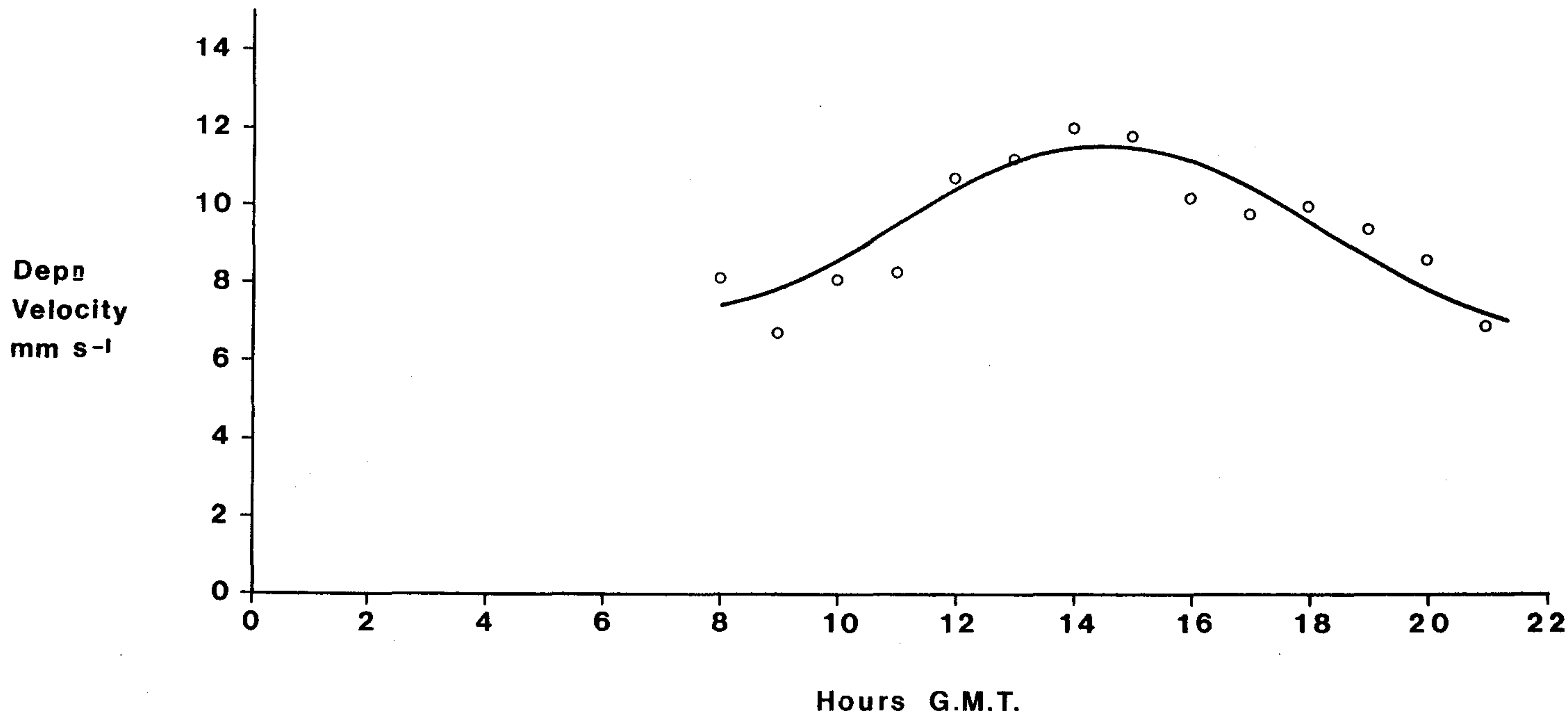


Fig. 18. Dry deposition of O_3 onto barley in an open top chamber during senescence showing smaller deposition rate.



CO_2 uptake

The same chamber technique has been used to measure CO_2 uptake by the barley crop for the majority of two field seasons. The quantity of data generated by studies of this kind is excessive but with sufficient care in instrument calibration and maintenance a data set from which days or longer periods may be selected for later study may be created.

The fluxes of CO_2 are well illustrated by the data for the 8th and 9th of May 1985, two days with contrasting weather, one bright sunny day and one cloudy wet day. The data for these days figure 19 show a large contrast in the amount of carbon fixed by the crop. One of the main objectives of this particular measurement was to study differences between CO_2 exchange on 'high' and 'low' ozone days. The data may be used to produce a net photosynthesis/light response curve as shown in figure 20 and the maximum rate of photosynthesis or the slope of the relationship at a specific photon flux density may be influenced by pollutants. In practice we have so far been unable to show effects of ozone, but the episodes during 1985 were very few and were restricted mainly to the post anthesis period (when with the ripening crop) rates of net-photosynthesis were much smaller than the peak values (in May) and no differences were seen. For experiments of this kind the O_3 injection system designed for the new site at ITE Bush is vital.

NO fluxes

This forms a part of the ITE $NO_x/NO/O_3$ suface-atmosphere exchange project and has been done at Glasgow because of the ability of the measurement system to detect the very small upward NO fluxes that are frequently present.

Typical early spring days show a loss of NO to the air of 10 to 40 ng NO m^{-2} s^{-1}, and fluxes of this order would not be detected using standard flux/gradient micrometeorological techniques even with the best new chemiluminescent NO analysers. In the chamber system differences between inlet and outlet concentrations of the order of 0.5 to 1.0 ppbV are detected quite easily (figure 21), and the diurnal pattern of the NO flux is rather variable (figure 22). The mechanisms which control this process have not been extracted from the data collected so far but sufficient information has been obtained to provide important clues.

The flux over a whole growing season for example shows (figure 23) that fluxes are largest during the early spring when the soil is 'wet' (and presumably contains many anaerobic 'sites') and soil NO_3^- concentrations from the applied fertilizer are largest. The decline through the season as the NO_3^- pool is depleted and the soil becomes gradually more aerobic is clear but the structure of the variability from one day to the next is of considerable interest. There appears to be a link here with rain days - with NO fluxes larger after rain (again presumably linked to the presence of anaerobic sites within the soil), but we have so far been unable to show whether the fluxes are influenced by air concentrations of NO, which would be expected, and work in this direction continues. However there is some evidence, because during the autumn NO is deposited onto the bare soil

Fig. 19. Rates of net photosynthesis in winter barley in open top chamber in a bright (9.5.85) and a cloudy dull day (8.5.85).

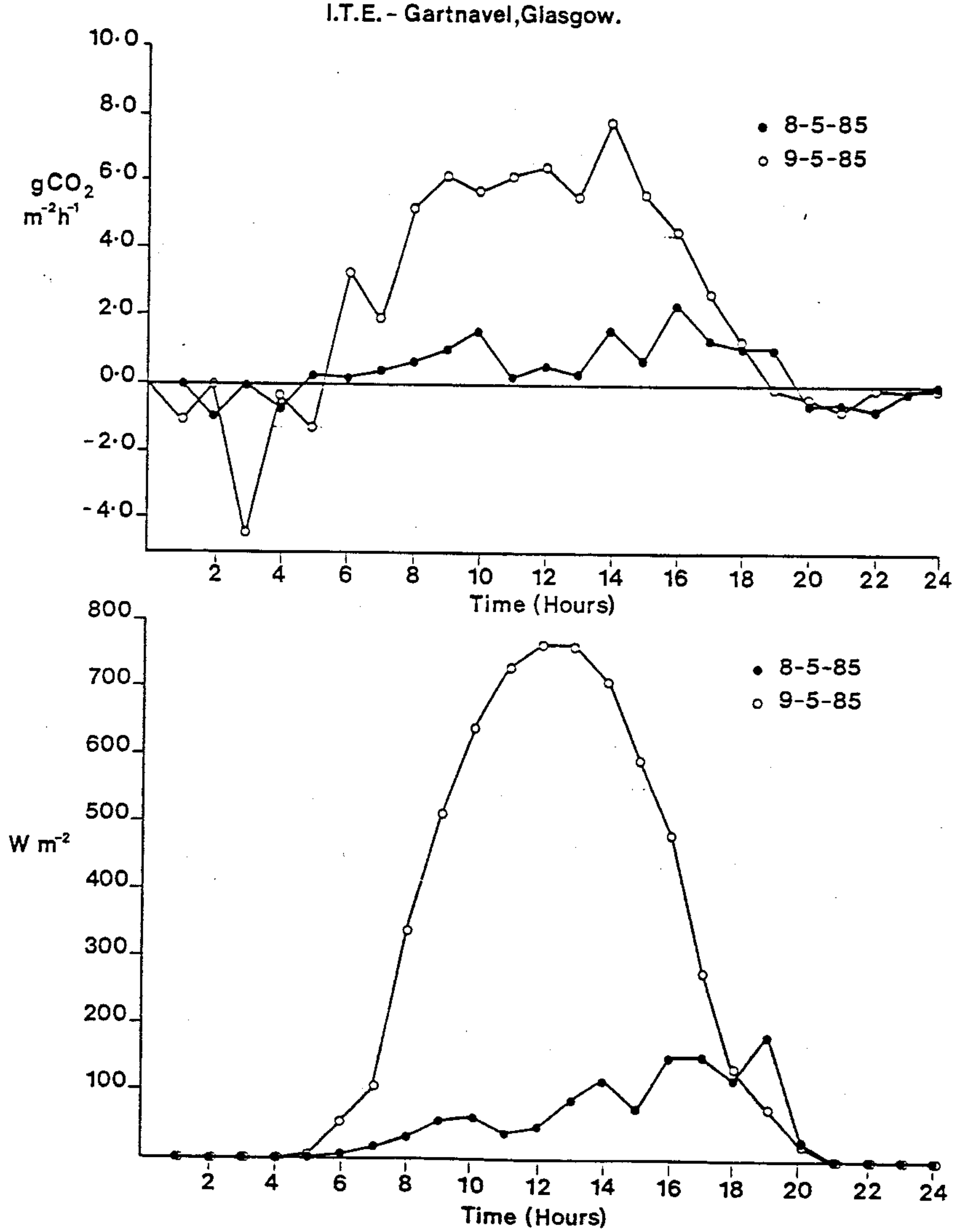


Fig. 20. Photosynthesis light response curve for barley in an open top chamber 13 May 1984.

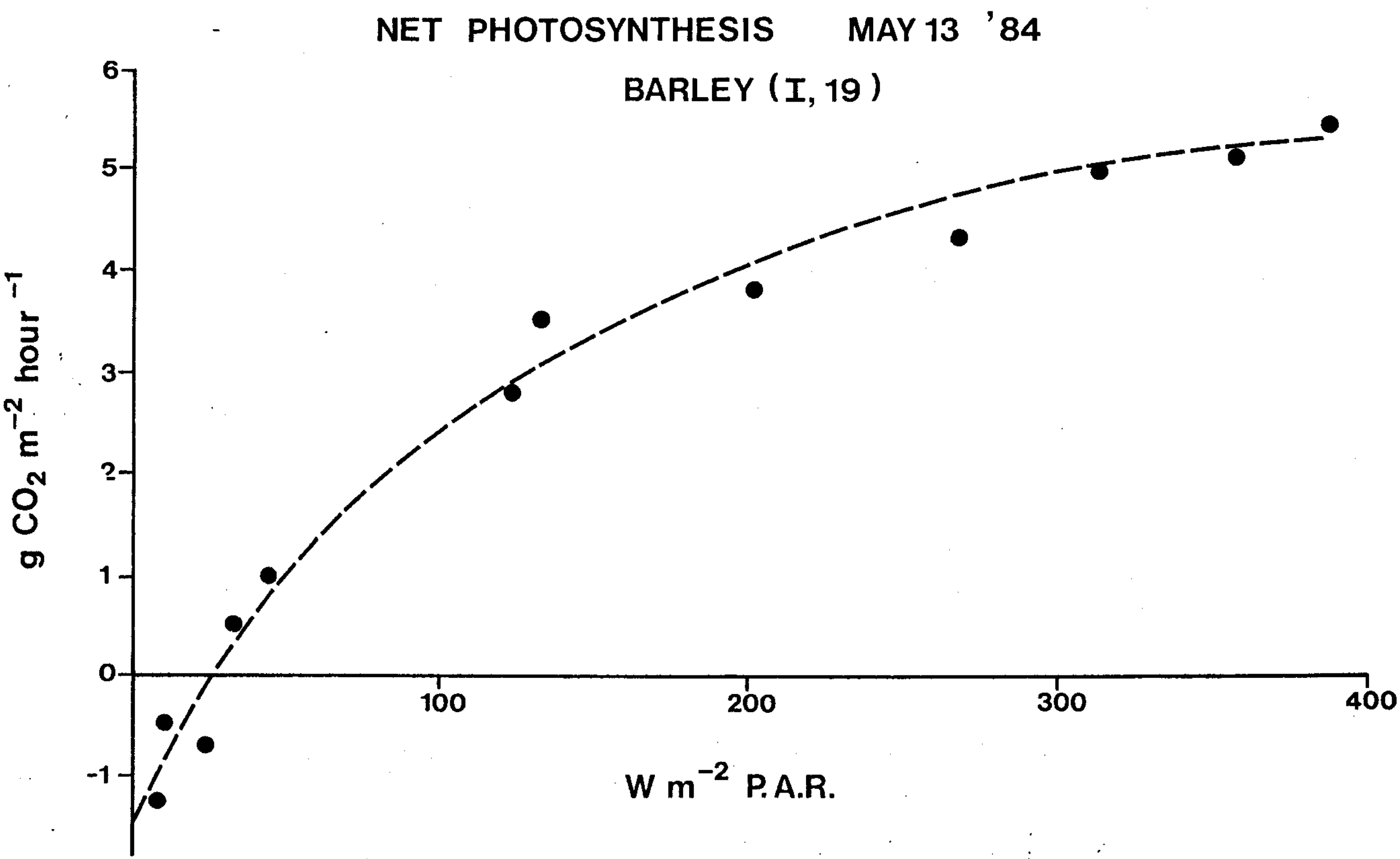


Fig. 21. Concentrations of nitric oxide (NO) in the air entering ( ) and leaving (O) the chamber system measurements for 13th May 1984.

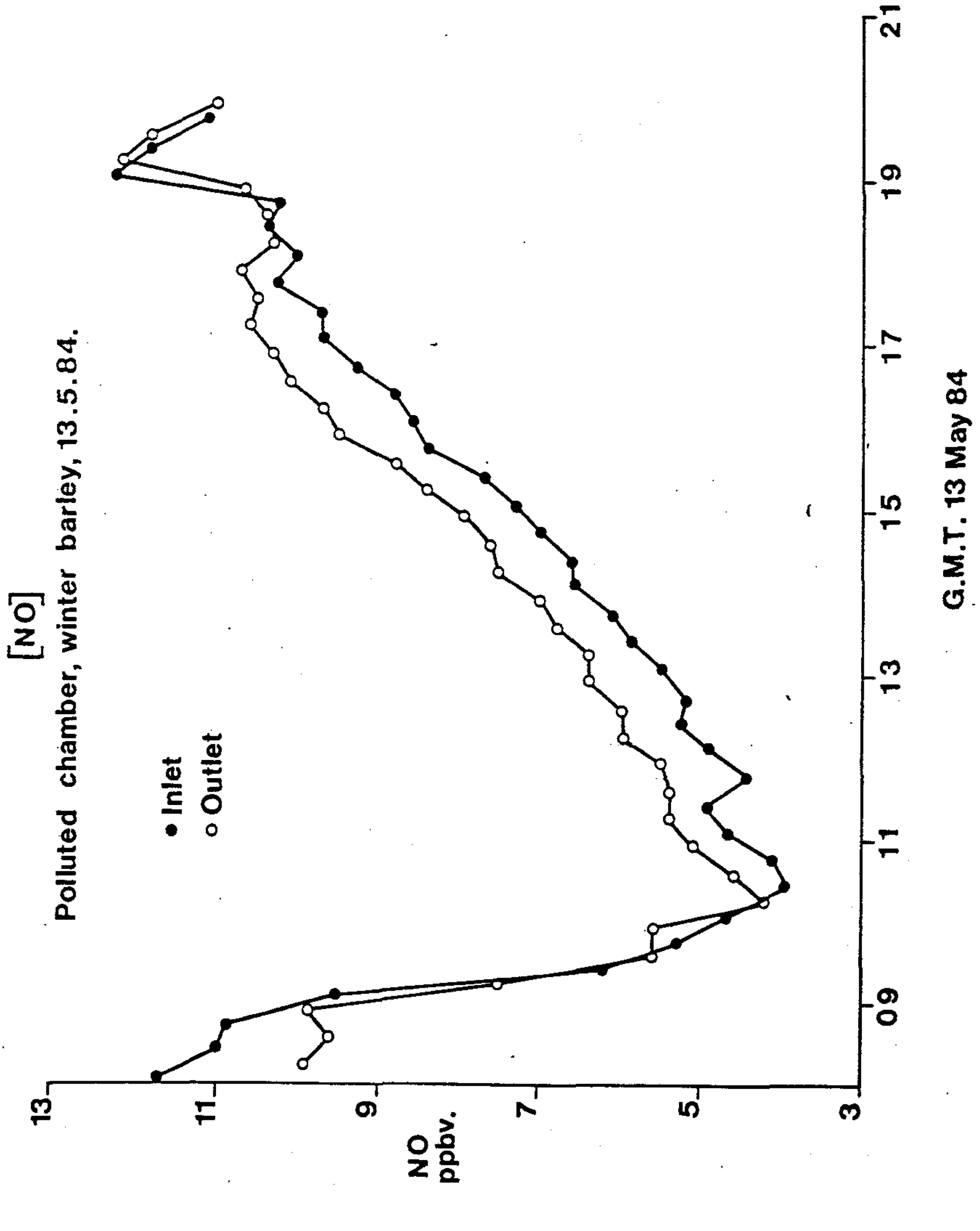


Fig. 22. Daily average nitric oxide flux leaving the barley crop and soil (your chamber measurements, 4th May 1985). Fluxes expressed on a ground area basis.

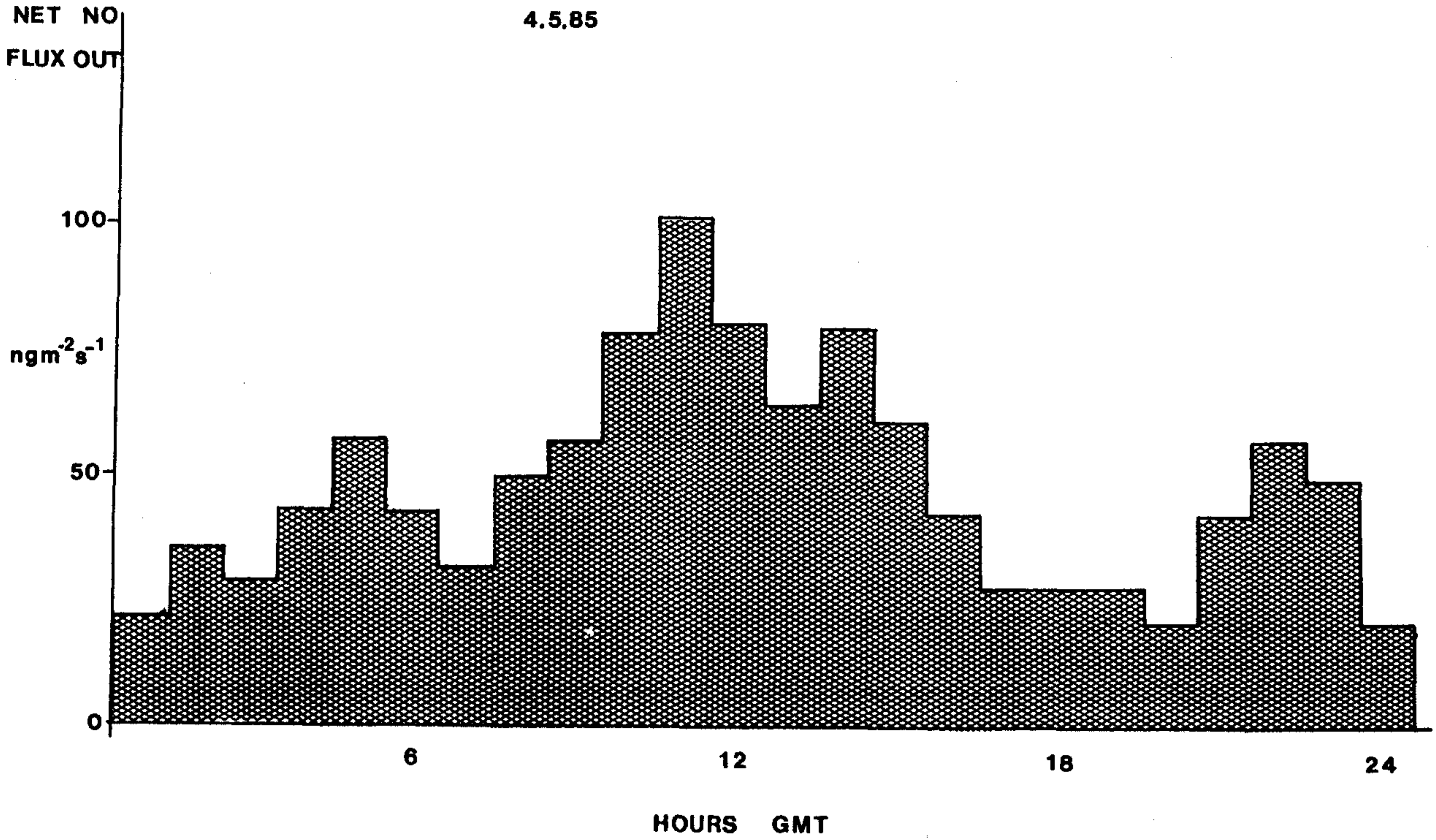
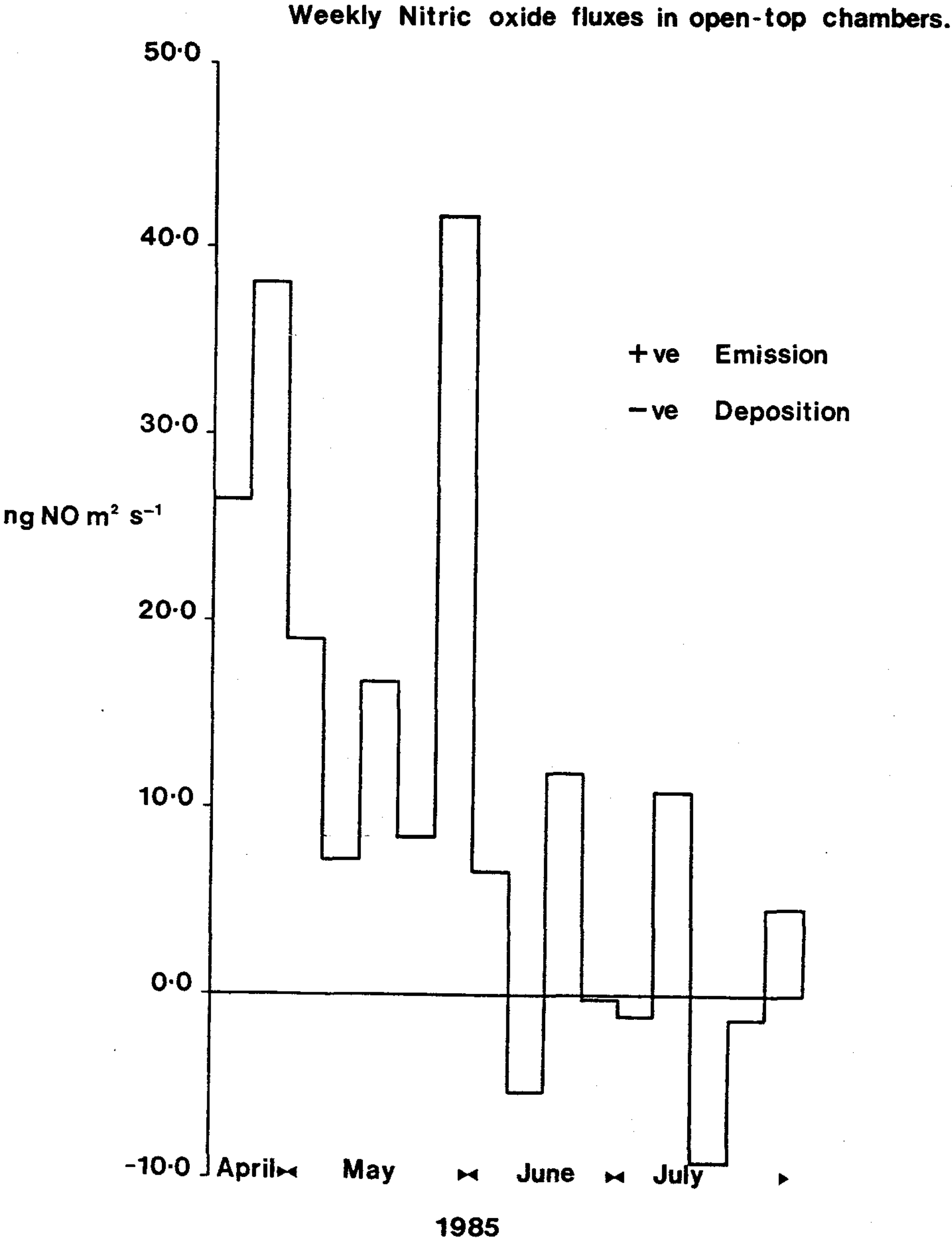


Fig. 23. Weekly average fluxes of nitric oxide measured above a canopy of barley inside an open top chamber.



(figure 23) as NO concentrations in air become larger than the denitrification NO flux out of the soil. The work necessary to analyse all of the gas exchange data collected so far is considerable, but it is obviously clear that this component of the Glasgow study has been very revealing.

3.5 Winter injury to Scots pine in a polluted environment

Objective

Little is known of the effects of a combination of low temperatures and air pollutants on coniferous trees. An experiment using open-top chambers at ITE Glasgow was established to investigate the influence of winter concentrations of the major atmospheric pollutant gases (oxides of nitrgen, sulphur dioxide, nitric oxide, and ozone) and temperature on physical injury to 3 year old Scots pine.

The experiment using filtered air (where the filters remove O_3, NO_2, SO_2) or unfiltered (ambient) air from the beginning of December 1985 till the end of March 1986. On termination of the experiment a number of measurements were made to assess the effects of the overwintering treatments.

Methods

Three year old Scots pine grown from seed were transferred from a clean air rural site 2 ppbV SO_2 per year at Banchory to the open top chamber facility at Glasgow on the 26.11.86. To minimise genetic variability the seed had been collected from a single tree at the Forestry Commission's seed orchard at Ledmore, Perthshire. The 160 trees all in 18 cm pots were numbered and placed in either filtered or unfiltered air chambers, 5 trees per chamber. As the environment of the unfiltered and filtered treatments is similar the only variable is the concentration of atmospheric pollutants received by the treatments. Throughout the experimental period pollutant gases, NO_x, NO, SO_2 and O_3 were continuously monitored along with meteorological parameters, wind direction, wind speed, atmospheric temperature and solar radiation.

There should have been no needle growth or stem elongation between December 1985 and March 1986. To ensure that early spring flushing had not occurred measurements of individual tree heights were recorded at the beginning and end of the experiment. On 27th November samples of year 0 and year 1 needle pairs were selected from the main leader tree for contact angle measurements to assess the weathering of the cuticle during the winter. The contact angle technique fully described by Cape (1983) found a decrease in contact angle indicated changes in the epicuticular wax structure or composition. This decrease correlated well with several needle surface properties. It was shown that needle retention was much reduced in Scots pine at polluted air sites 40 $\mu g\ m^3$ SO_2 compared to clean air sites 10 $\mu g\ \mu g\ m^3$ SO_2. To show whether the filtered/unfiltered air treatment influenced needle retention, counts of numbers of empty needle bases and needle pairs still attached to the mainstem were made from 78 trees in March 1986.

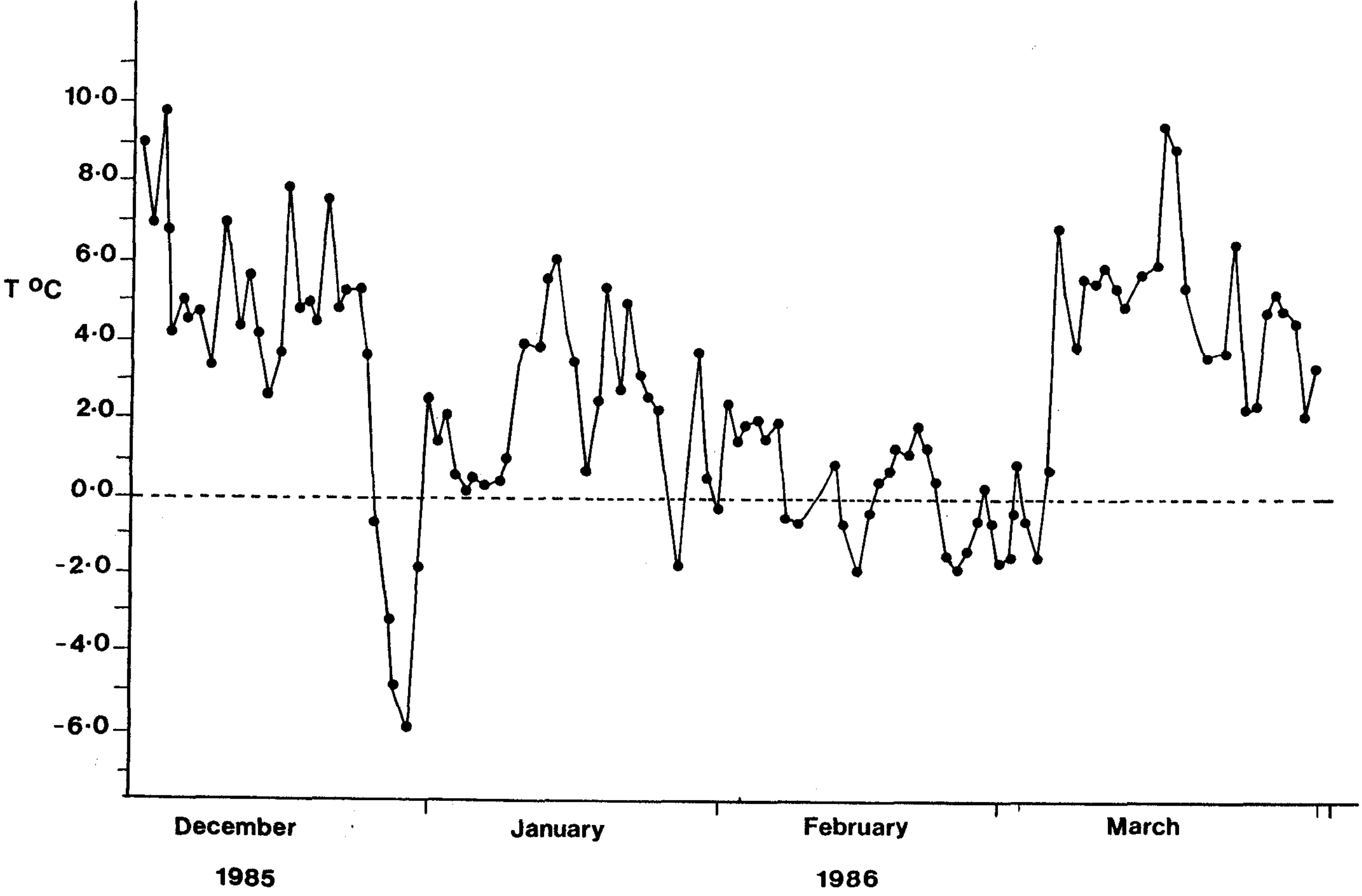
Results and conclusions

Table 12 and figure 25 shows the average daily air temperatures for 1st December to 31st March 1986 at I.T.E. Glasgow. In general the temperatures recorded were above those which Scots pine experience in typical field conditions, i.e. normally grown at higher altitudes and in more exposed

Table 12 Mean Daily Temperature °C Dec 1985 - March 1986
I.T.E. Gartnavel, Glasgow.

Day No.	December	January	February	March
1	9.00	1.25	1.60	-0.90
2	7.00	2.10	1.80	-1.90
3	10.00	0.60	1.30	0.60
4	4.20	0.10	1.90	6.70
5	5.10	0.30	-0.70	5.20
6	5.00	0.00	-0.90	3.50
7	4.60	0.20	-0.60	5.50
8	4.70	0.80	0.00	5.30
9	3.20	3.40	0.30	5.80
10	6.20	3.80	0.90	5.10
11	7.10	3.80	-0.90	4.80
12	4.30	5.40	-2.10	6.50
13	5.80	6.10	-0.60	6.70
14	4.10	4.00	0.20	6.90
15	2.10	3.30	0.50	9.60
16	3.60	0.50	1.10	6.90
17	8.00	2.30	0.90	5.30
18	4.60	5.30	1.80	4.30
19	5.00	2.50	1.10	3.40
20	4.20	5.10	0.20	3.50
21	7.60	3.10	-1.90	3.60
22	4.90	2.50	-2.30	6.60
23	5.20	2.20	-1.60	2.00
24	5.30	0.20	-0.80	4.60
25	3.60	-2.00	0.20	4.60
26	-0.50	0.60	-2.00	4.60
27	-3.50	3.60	-1.70	5.20
28	-5.20	1.10	0.90	4.60
29	-6.20	-0.50		4.40
30	-2.60	2.30		1.90
31	2.50	1.30		3.20

Fig. 25. Average daily air temperature. ITE Glasgow. 1st December 1985 - 31st March 1986.



locations. However temperatures were below 0°C for a 5 day period 26th - 31st December 1985 and for about 14 days during February 1986.

The ambient concentrations of pollutant gases NO_x, NO, SO_2 (tables 13-16 and Figures 26-29) were found to be lower than expected for winter concentrations in an urban area. Tables 13-16shows ambient daily mean concentrations of the gases.

The monitored chamber (unfiltered) during most of the experimental period measured gas fluxes. The gas fluxes measured were generally very small. O_3 concentrations were also small during the winter generally less than 10 ppbV (table 15 and figure 15).

There were days with a combination of high NO_x, NO or SO_2 100 ppbV with low temperatures. The 29th December with an average temperature of -6.2°C had a NO concentration of 138 ppbV, but SO_2 concentrations of only about 11 ppbV. This suggests that during such inversion periods the main pollutant gases are the oxides of Nitrogen, NO_2 and NO. The SO_2 concentrations monitored were small compared to 1970's concentrations (Warren Spring Smoke and SO_2 Survey).

The results from the comparison of the winter and spring contact angles (Table 17) show no significant difference between treatments for year 0 needles.

Table 18 shows no significant differences between the treatments for paired needle samples, indicating little change in the structure/composition of the epicuticular wax over the winter period.

Measurements of tree heights found no stem elongation or signs of early spring flushing.

The comparison of % needle loss between filtered/unfiltered treatments also shows no significant difference in needle retention (Table 19). The plants in polluted and clean air lost about 43% of the year 1 needles. This, quite a large needle loss from both treatments, could be caused by the trees being slightly pot bound and water stressed during the experimental period with low temperature and the turbulent climate within the chambers.

Results from both the needle retention and contact angle study show that exposure winter temperature and ambient Glasgow gas pollutants concentrations did not cause any detectable physical injury to the Scots pine, no physiological or post treatment growth studies were possible.

NOX Data 1985/86 ppbV

Day	Dec 85	Dec 85	Jan 86	Jan 86	Feb 86	Feb 86	Mar 86	Mar 86
	UNFIL	FIL	UNFIL	FIL	UNFIL	FIL	UNFIL	FIL
1	20.98	16.67	46.27	49.66	6.93	6.76	5.92	6.47
2	29.22	27.38	14.31	12.37	6.24	6.27	52.16	50.99
3	13.14	11.15	57.41	70.74	14.47	13.81	22.97	22.25
4	30.26	32.25	61.17	69.12	16.75	16.33	11.21	11.29
5	21.28	24.69	21.44	25.57	20.61	21.11	7.52	7.43
6	68.01	77.74	191.3	196.45	17.22	16.45	8.97	8.98
7	20.34	20.69	21.09	20.9	21.43	20.07	17.32	16.3
8	31.33	33.35	36.41	41.25	21.65	21.83	8.8	8.73
9	92.17	104.1	44.04	44.21	23.03	21.43	10.9	11.15
10	70.51	73.23	15.73	14.56	14.25	13.78	22.38	22.63
11	59.89	60.66	6.45	6.64	33.44	32.63	26.87	26.93
12	27.03	25.92	4.2	3.82	21.95	21.65	28.38	28.4
13			4.58	3.98	6.69	6.52	24.94	23.56
14			1.83	1.63	6.2	5.99	10.09	9.55
15			9.73	8.85	6.35	6.42	3.6	3.65
16	15.09	13.59	86.34	82.38	5.46	5.55	2.78	2.66
17	32.98	33.62	77.29	77.23	12.2	13.27	3.89	3.95
18	20.42	22.15	16.31	16.15	17.64	17.76	16.58	16.85
19	16.94	18.59	13.69	13.62	58.7	55.24	44.33	43.45
20	13.44	13.01	10.82	10.48	49.77	50.08	4.62	4.82
21	15.11	15.1	18.32	17.27	55.2	56.43	6.36	5.92
22	14.95	16.32	10.94	10.72	68.58	65.91	2.57	2.54
23	18.02	19.27	7.59	7.59	24.33	24.11	1.83	1.83
24	43.05	48.44	16.85	18.12	182.9	182.2	2.67	2.63
25	16.47	14.26	86.81	87.55	56.58	55.66	3.03	2.92
26	20.8	29.44	30.78	29.97	15.41	14.8	3.4	3.57
27	81.74	106.9	15.66	15.36	51.33	51.59	8.24	7.96
28	103.9	117.0	18.95	18.77	5.05	4.65	13.05	12.7
29	142.0	165.4	67.84	63.84			6.8	6.79
30	59.82	56.31	10.52	20.41			11.82	12.22
31	55.14	61.84	10.82	8.53			19.26	19.03
MEAN	42/21	44.97	33.4	34.12	30.01	29.58	13.32	13.17

UNFIL = Inlet)measuring fluxes in unfil chamber
FIL = Outlet)

TABLE 13 Daily Mean ambient NO_x/concentrations in ppbV ITE Gartnavel.

SO_2 DATA 1985/86

MEAN DAILY CONCENTRATIONS ppb

DAY	DEC85	DEC85	JAN86	JAN86	FEB86	FEB86	MAR86	MAR86
	UNFIL	FIL	UNFIL	FIL	UNFIL	FIL	UNFIL	FIL
1	0.02	0	3.81	2.42	2.19	1.39	3.99	1.95
2	0.49	0.98	3.75	2.73	2.23	1.56	12.65	8.22
3	0.58	0	6.68	5.64	4.71	3.3	4.41	2.25
4	2.16	0.68	7.15	7.36	47.25	4.88	0	0
5	1.32	0.5	5.48	5.5	3.96	2.2	0	0
6	3.21	1.23	16.56	37.9	8.07	5.02	0	0
7	1.6	0.36	8.74	12.08	8.87	5.63	1.79	0.9
8	2.08	0.8	8.94	13.16	4.42	2.71	1.71	0.76
9	3.97	3.11	8.97	13.85	9.1	6.18	1.73	0.63
10	5.23	5.82	2.24	1.22	11.56	8.12	4.05	2.44
11	4.48	4.88	2.75	1.43	35.25	26.54	4.25	2.71
12	2.8	1.35	2.89	2.28	29.95	22.41	10.75	7.59
13			2.13	1.38	10.96	7.84	19.44	14.44
14			1.66	0.51	3.8	1.73	2.29	1.04
15			5.91	4.2	7.3	3.87	2.17	0.98
16	3.53	2.14	13.61	9.4	6.49	3.4	2.17	0.88
17	3.59	2.63	10.52	6.99	4.87	2.65	3.2	1.89
18	3.06	2.1	0.97	0.08	1.45	0.47	2.94	1.6
19	2.81	1.82	1.38	0.1	7.96	5.33	4.16	2.27
20	1.25	0.24	0.09	0	10.95	7.88	1.27	1.5
21	0.4	0.07	0.32	0.03	17.78	14.96	1.55	0.7
22	1.13	0.19	0		15.36	11.29	0	0
23	2.03	0.97	0		6.14	4.37	0.12	0.37
24	3.82	3.14	2.56	1.81	34.3	27.01	0	0
25	3.97	2.87	8.71	5.95	15.23	11.49	0	0
26	5.64	4.41	9.45	6.86	8.03	5.54	0.06	0
27	7.1	6.57	3.45	1.7	13.13	9.64	0.04	0.02
28	7.39	9.02	1.13	0.18	5.05	2.86	0	0
29	8.46	11.52	7.64	3.94			2.85	3.55
30	7.59	10.01	7.4	5.22			1.03	1.34
31	3.67	2.49	3.07	2.18			7.52	6.22
MEAN	3.32	2.85	5.09	5.37	10.58	7.51	3.1	2.07

Unfil = inlet) measuring fluxes in unfil chamber.
Fil = outlet)

TABLE 14 Daily mean ambient SO_2 in ppbV ITE Gartnavel

OZONE DATA 1985/86

DAY	DEC85 UNFIL	DEC85 FIL	JAN86 UNFIL	JAN86 FIL	FEB86 UNFIL	FEB86 FIL	MAR86 UNFIL	MAR86 FIL
1	0	0	1.34	0.75	11.48	11.65	9.68	7.72
2	0	0	5.27	8.57	12.09	12.08	2.02	1.39
3	0	0	3.65	4.17	7.38	7.22	4.73	3.98
4	0	0	1.09	0.76	7.74	6.95	8.4	7.03
5	0	0	3.45	3.57	7.33	6.45	11.42	8.85
6	0	0	0.65	0.61	8.76	7.76	10.73	9.19
7	0	0	0.78	0.64	9.51	8.2	7.37	6.28
8	0	0	0.61	0.64	8.37	7.38	12.9	11.44
9	0	0	0.71	0.67	3.26	2.8	8.37	7.18
10	0	0	0.47	0.55	5.25	4.39	5.35	4.13
11	0	0	0.08	0.07	1.35	1.22	2.38	1.94
12	0	0	0.07	0.07	2.16	1.79	0.62	0.57
13			0.06	0.08	7.28	6.16	3.08	2.68
14			0.07	0.07	8.3	7.37	8.33	7.14
15			0.06	0.07	8.85	7.07	10.45	9.17
16	0	0	0.07	0.06	10.55	8.62	8.83	7.62
17	0	0	1.8	1.47	9.43	8.01	7.82	6.29
18	0	0	8.16	7.02	9.27	8.04	5.59	4.45
19	0	0	9.25	7.91	3.62	3.02	4.41	3.62
20	0	0	11.25	10	1.73	1.42	11.18	10.71
21	0	0	8.19	7.29	4.48	3.75	9.85	9.37
22	0	0	11.02	9.77	5.33	4.83	13.53	13
23	2.09	3.51	11.56	1.09	6.89	5.86	13.7	13.66
24	3.52	4.37	6.48	6.08	0.93	0.9	10.76	9.83
25	6.29	10.75	1.71	1.41	3.79	3.04	10.74	9.12
26	6.87	10.83	1.71	1.55	6.36	5.1	11.08	9.18
27	2.58	1.17	5.72	4.96	4.42	3.8	10.93	9.88
28	1.54	1.17	4.65	4.01	9.18	7.66	7.65	7.38
29	1.21	1	1.91	1.83			11.36	10.95
30	1.28	1.06	7.78	7.04			10.97	10.7
31	1.61	1.89	10.56	10.18			6.31	6.02
MEAN	0.96	1.28	3.87	3.63	6.62	5.81	8.4	7.47

Unfil = inlet) measuring fluxes in unfil chamber
Fil = outlet)

TABLE 15 Daily mean ambient O_3 in ppbV ITE Gartnavel

NO DATA 1985/86

DAILY MEAN CONCENTRATIONS ppb

DAY	DEC85	DEC85	JAN86	JAN86	FEB86	FEB86	MAR86	MAR86
	UNFIL	FIL	UNFIL	FIL	UNFIL	FIL	UNFIL	FIL
1	5.4	5.34	19.59	31.42	1.92	1.85	2.75	2.86
2	14.62	13.54	4.94	4.96	1.78	1.74	35.51	34.89
3	6.27	6.36	38.45	55.5	1.86	1.61	15.99	15.58
4	18.96	22.59	40.56	52.56	1.49	1.41	6.08	6.1
5	12.5	16.82	7.45	12.31	6.48	7.05	1.63	1.45
6	44.98	54.75	151.91	155.63	2.56	2.22	1.85	1.81
7	6.49	7.03	9.56	10.52	7.61	6.32	6.35	5.93
8	12.58	16.34	26.48	32.27	12.11	12.54	4.13	4.03
9	67.36	83.86	33.73	35.17	14.17	13.01	7.07	7.1
10	44.32	48.74	5.14	5.38	9.17	8.73	11.81	11.87
11	36.31	40.59	2.74	2.82	29.17	28.42	11.38	10.86
12	12.08	13.76	1.51	1.11	17.88	17.54	10.65	10.5
13			2.12	1.68	5.39	5.16	8.19	7.93
14			0.9	0.94	5.42	5.11	3.09	2.9
15			7.24	6.44	4.77	4.58	2.5	2.35
16	5.2	5.51	79.98	75.55	4.06	4.06	2.6	2.43
17	15.7	18.19	65.4	65.58	5.03	5.15	3.55	3.71
18	5.91	7.64	2.87	2.9	3.72	3.8	11.65	12.1
19	5.1	6.95	2.72	2.55	35.29	32.78	36.25	35.73
20	4.27	4.92	2.33	2.22	23.55	24.67	1.99	1.96
21	5.67	6.04	4.59	3.74	38.6	40.22	3.35	3.12
22	4.94	5.81	2.28	2.11	55.15	53.39	2.55	2.5
23	5.31	6.58	1.72	1.71	18.65	18.45	1.89	1.92
24	21.14	28.25	5.96	6.94	147.79	147.74	2.72	2.67
25	7.19	6.98	18.76	67.78	37.1	36.85	3.07	2.88
26	13.19	23.12	14.42	14.16	9.02	8.6	3.44	3.51
27	58.31	84.5	14.11	13.26	45.44	45.29	3.51	3.32
28	63.5	89.87	8.64	8.33	3.35	3.01	4.55	4.55
29	101.15	138.96	48.09	44.85			2.86	2.83
30	31.54	29.82	3.06	3.08			7.96	8.26
31	32.51	45.35	5.17	2.68			10.09	10.09
mean	23.66	29.94	22.01	23.49	19.59	19.33	7.45	7.35

Unfil = inlet) measuring fluxes in unfil chamber
Fil = outlet)

TABLE 16 Daily mean ambient NO in ppbV ITE Gartnavel.

Fig. 26.

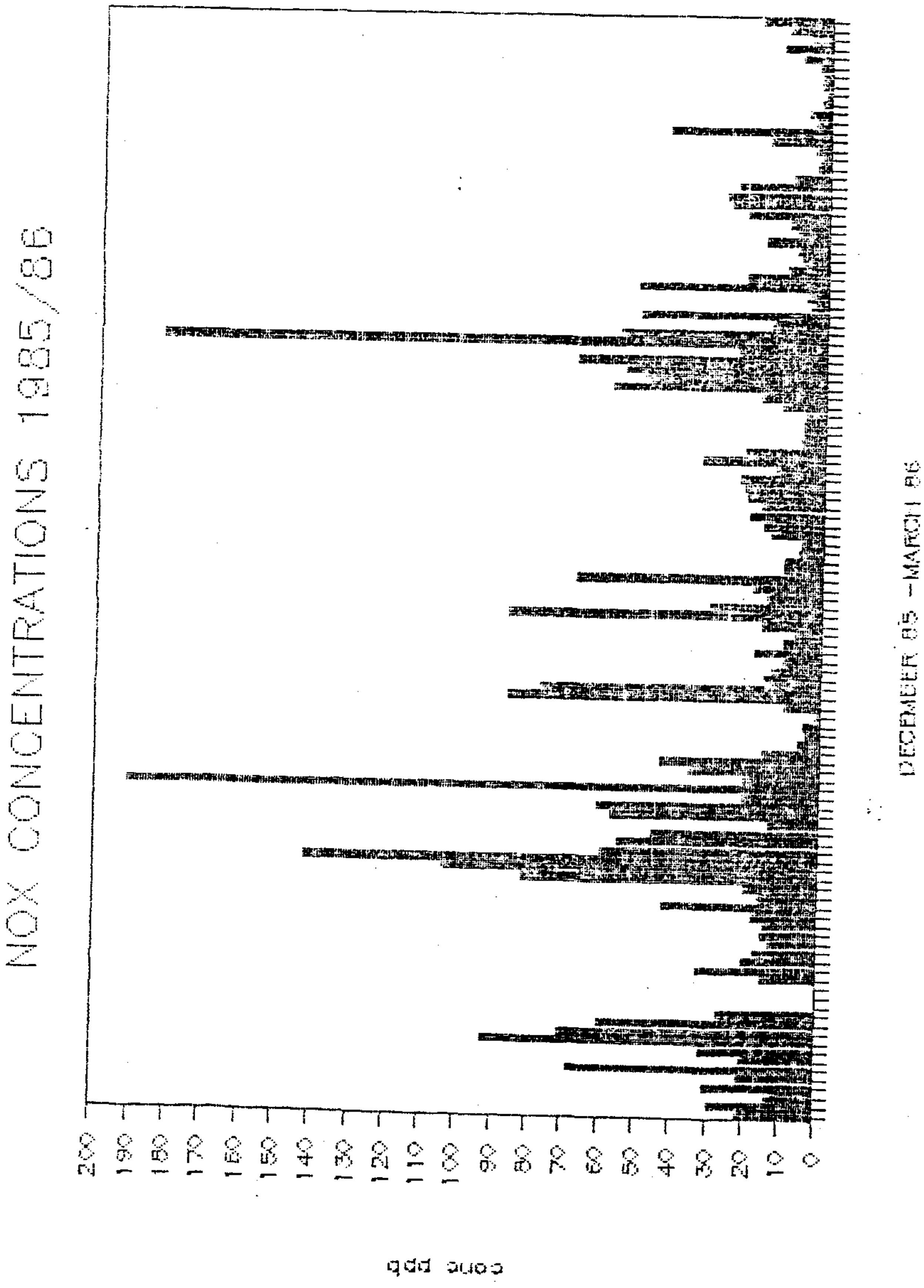

NOX CONCENTRATIONS 1985/86
DECEMBER 85 - MARCH 86
conc ppb
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180
190
200

Fig. 27.

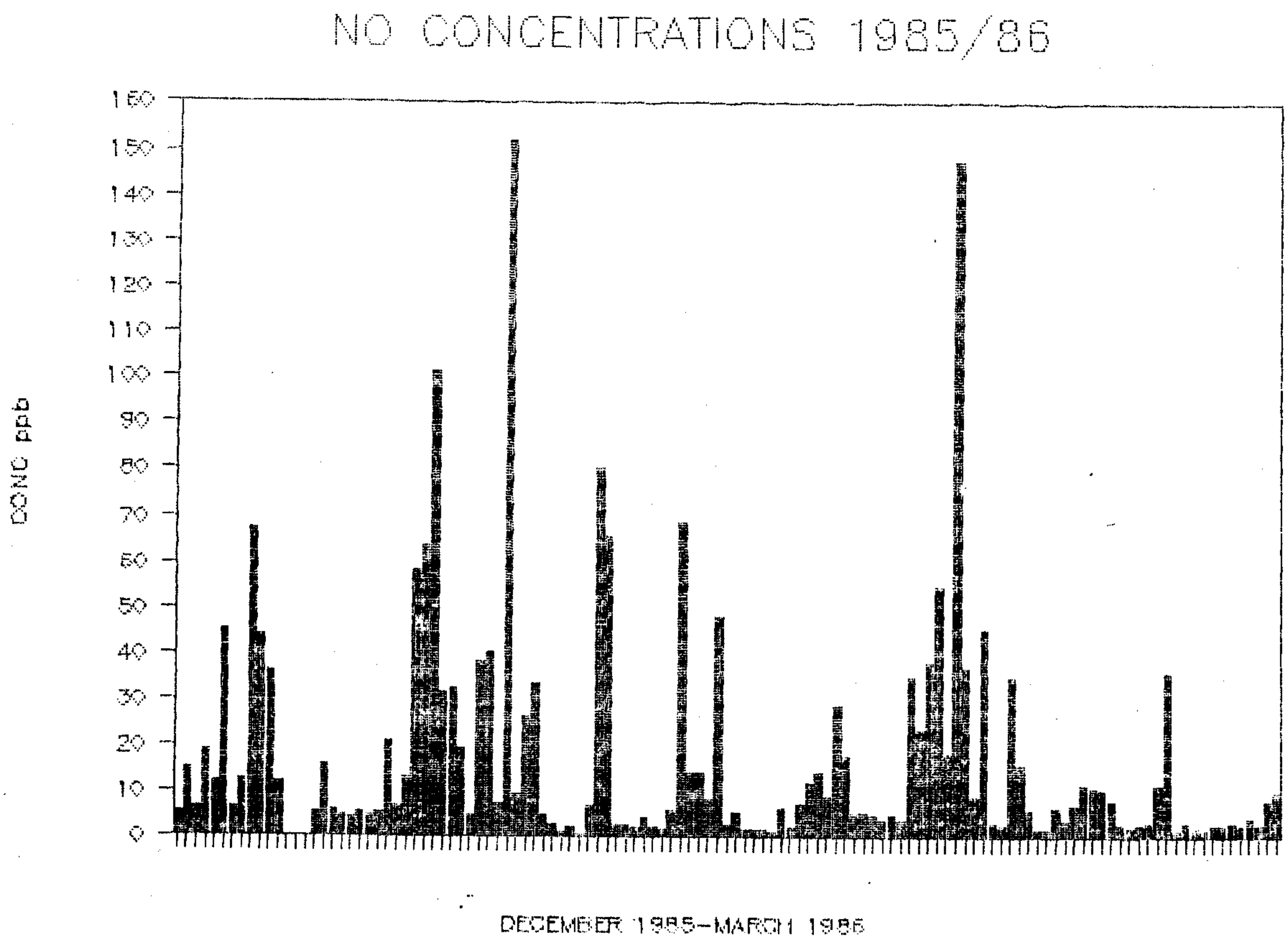

NO CONCENTRATIONS 1985/86
CONC ppb
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
DECEMBER 1985–MARCH 1986

Fig. 28.

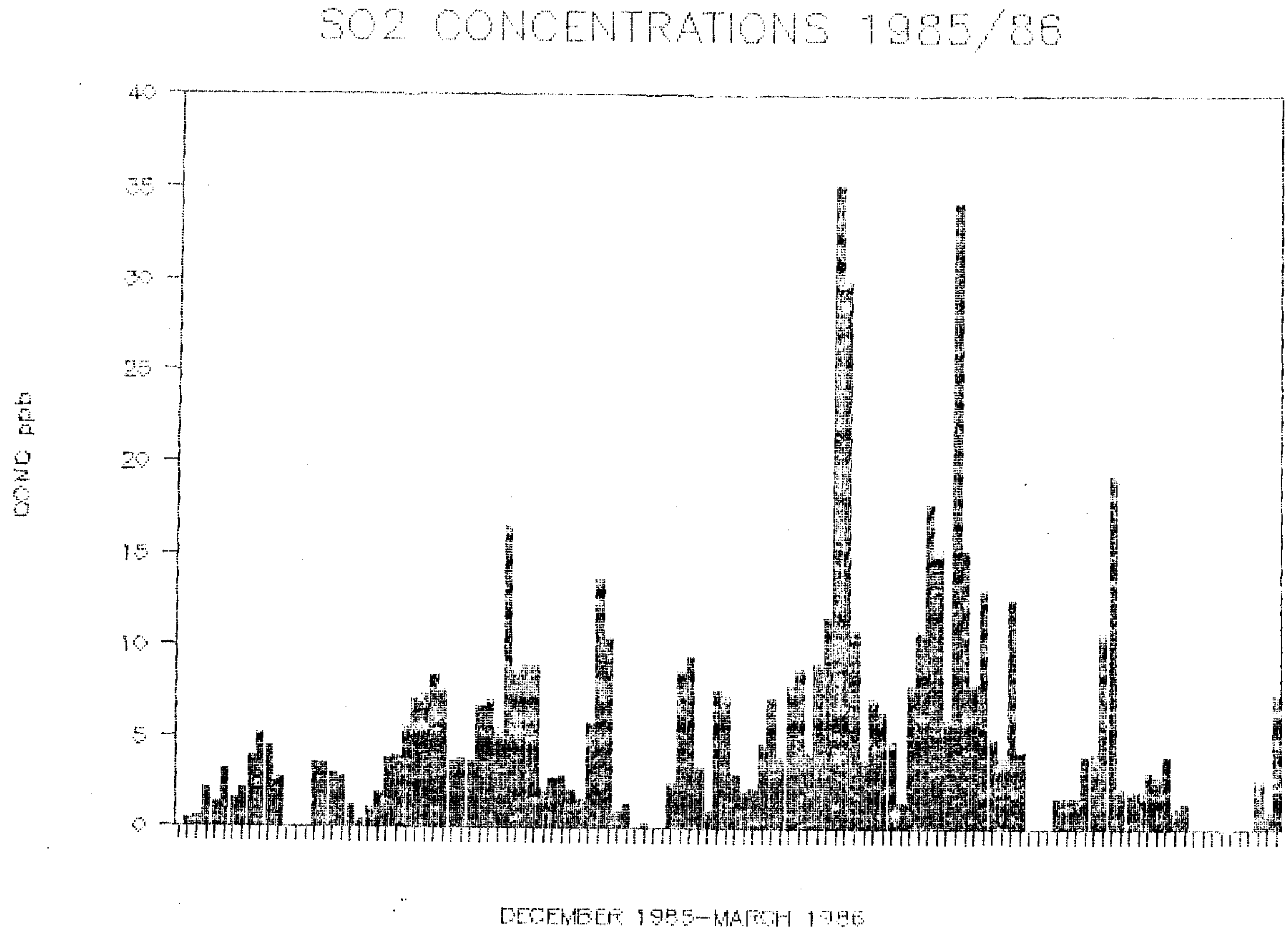

SO2 CONCENTRATIONS 1985/86
CONC ppb
0
5
10
15
20
25
30
35
40
DECEMBER 1985–MARCH 1986

Fig. 29.

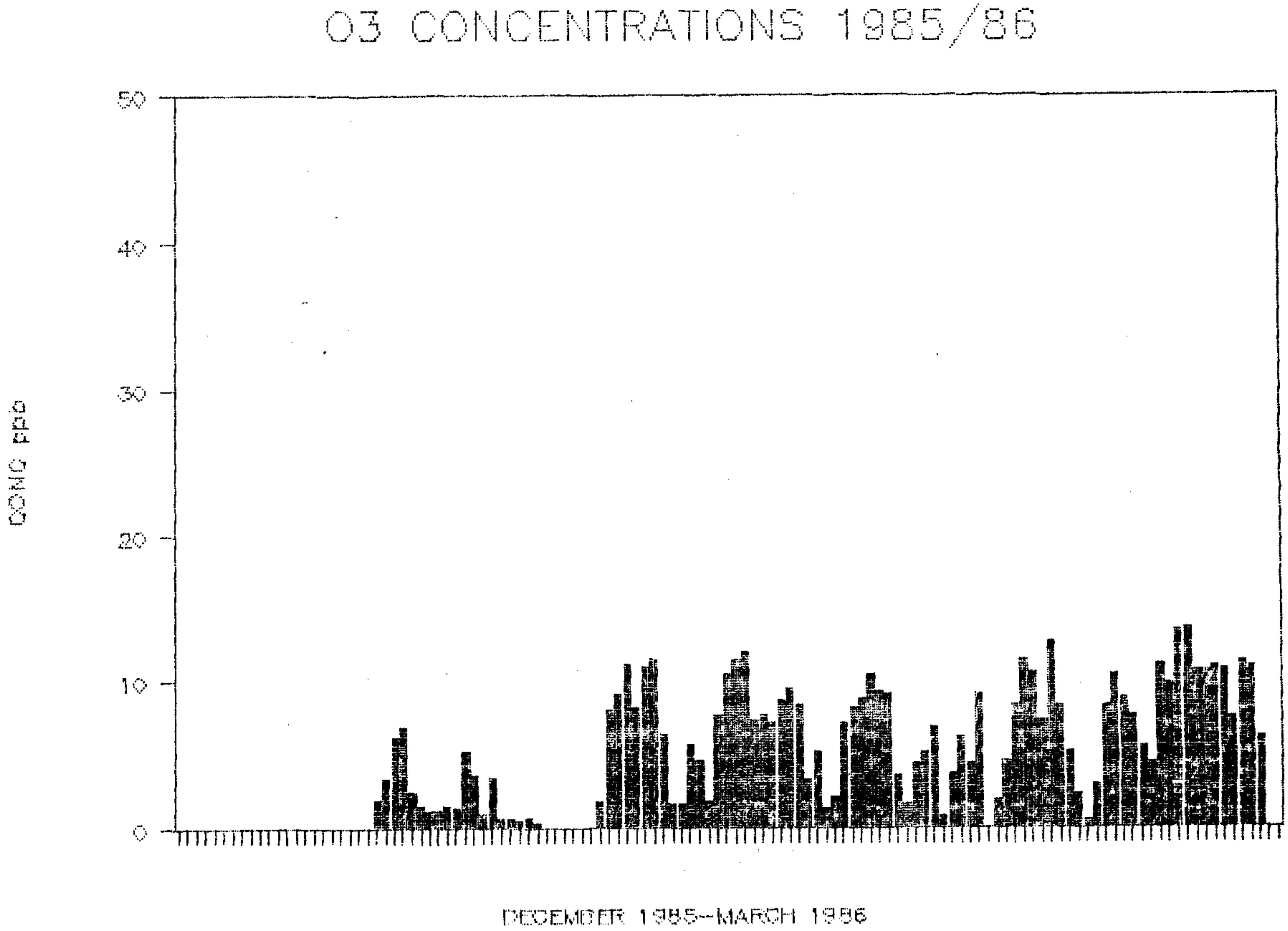

O3 CONCENTRATIONS 1985/86
CONC ppb
50
40
30
20
10
0
DECEMBER 1985–MARCH 1986

Table 17. Mean contact angles for year 0 and 1 needles

	27th November 1985 Contact Angle	20th March 1986 Contact Angle	
		Unfiltered	Filtered
Year 0	$88.670^{\circ} \pm 7.39^{\circ}$	$86.2^{\circ} \pm 5.4^{\circ}$	$85.0^{\circ} \pm 5.3^{\circ}$
Year 1	$72.293^{\circ} \pm 6.39^{\circ}$	-	-

Table 18. Mean change in contact angle of year 0 individual paired samples 20th March 1986

Filtered	-2.1 ± 10.9	n=17
Unfiltered	-4.9 ± 7.5	n=9

Table 19.

Comparison of unfiltered and filtered treatments for average % loss of 1st year needle pairs

Chamber No.	Unfiltered % loss	Chamber No.	Filtered % loss.
1	73	2	39
3	44	4	43
6	48	8	40
7	40	9	54
12	49	11	34
13	49	14	41
17	53	16	51
21	48	22	36
23	25	24	44
26	62	25	50
28	45	27	63
32	30	29	32
36	25	30	26
38	39	33	35
39	35	35	30
	x 45.00 ± 12.84		x 42.75 ± 11.46

3.6 Effects of simulated episodes of O_3 on the growth and development of field bean (Vicia faba)

Vicia faba (the field bean) an agricultural crop grown for animal feed has been shown to be sensitive to high concentrations of ozone. When sown in spring, it grows rapidly, reaching about 1.5 m before harvest in the autumn.

In order to demonstrate whether or not a limited number of ozone episodes influenced the growth and development of Vicia faba this study was set up at the Gartnavel research site in August 1986. Young plants of Vicia faba were exposed to 4 concentrations of O_3 (zero, ambient, and episodes of 100 ppbV, 200 ppbV, O_3) in open top chambers.

An O_3 generator was used to produce the desired concentrations in air which was dried before entering the ozonizer. Flow rates into the chambers were standardised to 5 m^3/min at the beginning of the experiment, the generated O_3 concentrations being introduced into the main air flow before it entered the chamber.

Figure 30 shows the experimental design for these exposures. Daily average ambient O_3 concentrations were in the range 10-23 ppbV*. Ozone was released in 2 chambers (each containing 80 plants in trays) for 10 days, for 6 hours per day, between 1000 and 1600 hrs. During the remaining 18 hours, the field beans were all exposed to ambient concentrations of O_3.

Results

There was a significant reduction in leaf area between the plants receiving filtered or ambient air and the 200 ppb treatment (Table 20) and a smaller difference between those receiving either filtered or ambient air and 100 ppb of ozone. There were no differences in leaf area between plants grown in the filtered and ambient treatments. Mean O_3 concentrations of 10-23 ppb were insufficient to cause detectable effects.

There were also marked reductions in the dry weights of harvested plants in the ozone episode treatments. The episodes to 200 ppbV and 100 pppV (for only 10 days) reduced dry matter yields relative to the charcoal filtered treatment by 31% and 21% respectively. In the ambient O_3 treatment with average values of about 14.1 ppbV dry matter yields were almost identical to those in the filtered treatment (within 0.5%!) (Table 22). The use of these treatments is of course arbitrary but at 100 ppbV and 200 ppbV the episodes increase the average concentration over the 10-day exposure period to only 35.5 and 60.6 ppbV and expressed as a proportion of the growing period of a field crop this sequence of episodes would raise the average concentrations only a very small amount. There is nothing very new in this idea, but ozone is an episodic pollutant and continuous exposure treatments fail to reproduce the nature occurrence of this pollutant.

* 1 ppbV O_3 = 2.00 $\mu g\ m^{-3}$ at 25°C and 1-1.3 KPa.

Physical leaf damage was observed in plants exposed to the 200 ppb treatment after 10 hours of exposure, in the form of a grey blotching on the axadial surface of the leaf. This grey blotching was also found on the leaves of plants receiving the 100 ppb treatment, but only towards the end of the 60-hour treatment. Thirty hours of exposure caused severe leaf damage in the 200 ppb treatment (yellow/browning of the leaves).

The bottom leaves in all treatments turned yellow, a feature of natural senescence as the season progresses. In estimation of leaf damage the remaining lowermost 2 leaves and unemerged leaves were not counted. An estimation of physical leaf damage was made by scoring every leaf from a sample of plants from each treatment for different types of damage (Table 21). The plants receiving 200 ppb treatment had 92% total leaf damage compared with 17% on those growing in the filtered chamber.

Grey blotching in leaves is assumed to be the result of exposure to high O_3 concentrations; 37% of leaves on plants in the high O_3 treatments were damaged, compared with 0.4% on those in filtered air.

The concentrations used for these experiments were designed to simulate episodes of photochemical ozone that occur in the field. Thus the 100 ppb O_3 treatment for 6 hours per day is similar to the peak O_3 concentration during photochemical episodes at many rural locations in England and in continental Europe. Such episodes also occur in Scotland, but the peak concentrations are typically 80 ppbV. The meteorological conditions that are associated with these episodes are generally sunny and anticyclonic; when these persist for several days the photochemical ozone peaks occur each day, reaching a maximum in the early afternoon. The 10-day exposure is longer than the average photochemical episode in Britain but such episodes have been observed at Shauinsland (FRG). The 200 ppbV O_3 treatment is considerably larger than the maximum for typical photochemical episode days. However, concentrations of O_3 at rural locations in England exceeded 250 ppbV during the summer of 1976; the concentration used for this treatment is therefore within the observed range. The duration of the treatment (10 days) is longer than the observed duration of such extreme treatments, but anticyclonic conditions which cause photochemical ozone episodes may persist for 2 or 3 weeks, so that even in this respect the treatment is not unreasonable.

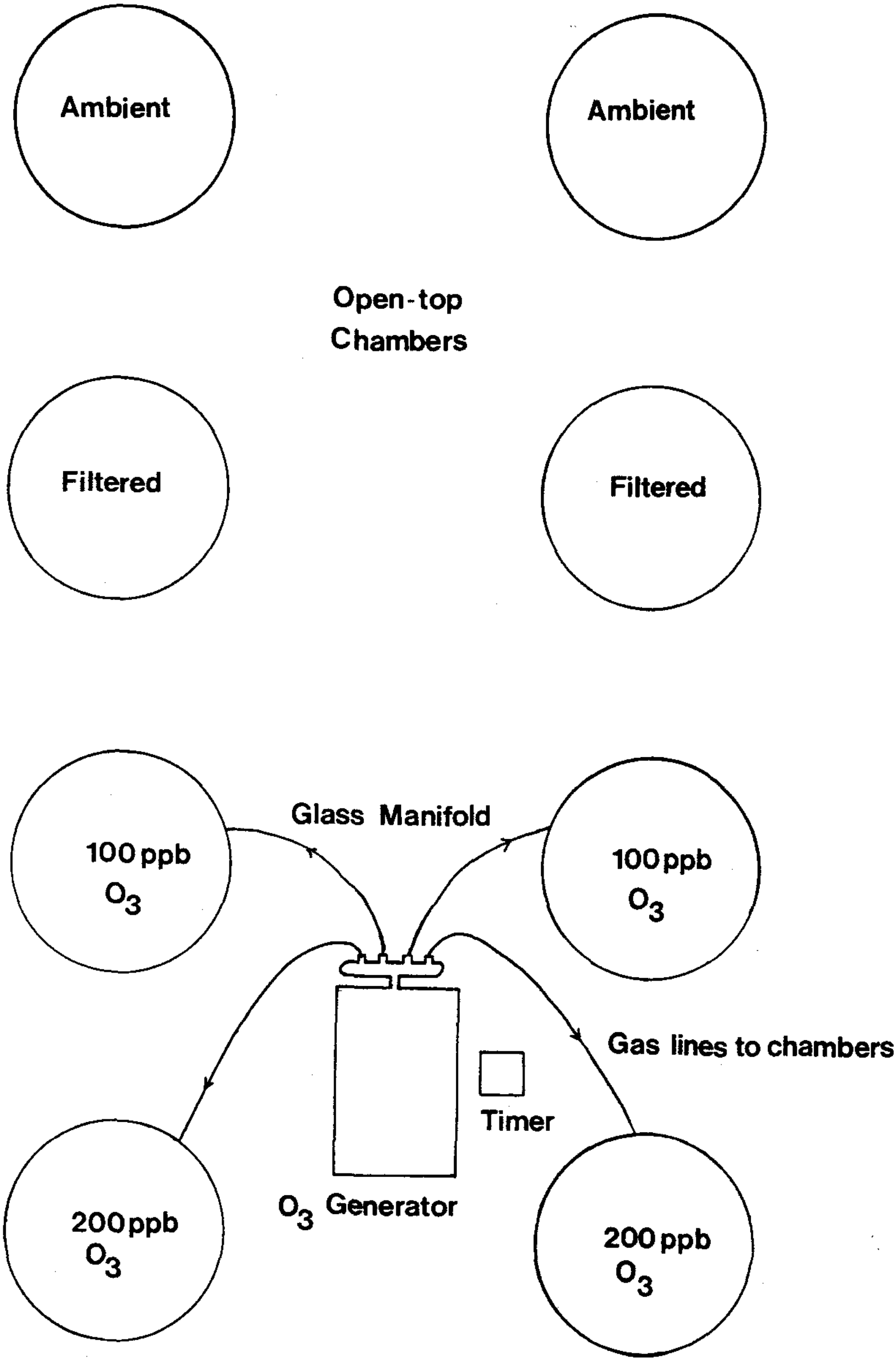


Fig. 30. Experimental layout for O_3 exposure treatment.

TABLE 20

The influence of O_3 on the average leaf area of <u>Vicia faba</u> plants.

LEAF AREA cm^2

Treatment	Leaf/cm^2	SD
Filtered air	200.85	49.5
Ambient air	194.62	45.05
100 ppb O_3	163.47	49.3
200 ppb O_3	131.44	41.27

Exposure to elevated O_3 concentrations was for 6 hours a day (1000-1600) for a period of 10 days.

TABLE 21

Leaf damage observed in plants of *Vicia faba* exposed to different concentrations of ozone

TYPES OF LEAF DAMAGE

Expressed as % of the total number of leaves/treatments

	Grey	Brown	Yellow/Brown	Yellow	Damaged	Undamaged
Filtered	0.4	1.2	8.2	7.8	17.6	82.4
Ambient	3.0	0	11.0	11.0	25.0	75.0
100 ppb	25.3	4.3	19.2	11.0	59.8	40.3
200 ppb	37.2	31.9	23.3	0.0	92.4	7.6

Brown — severely damaged leaf, nearly 100% brown/dead

Yellow/brown — less damaged than brown, with areas of yellow on leaves

Yellow — leaf losing its green colour and turning yellow. Plant will also have leaves yellowing naturally from bottom of plant as season progresses.

Grey — greyness/loss of chlorophyll, first signs of damage by O_3.

TABLE 22

Total dry weights of *Vicia faba* in each of 4 treatments varying in O_3 exposure

Treatment	Weight (g)	n
Ambient	1.392	187
Filtered	1.384	161
100 ppb O_3	1.094	162
200 ppb O_3	0.953	174

APPENDIX

Air pollution experiments at Glasgow
Crop Management Record 1982-83, 1983-84, 1984-85

The research enclosure lies at an elevation of 25 m on a gentle south facing slope in the grounds of Gartnavel Royal Hospital, 4 km WNW of Glasgow city centre. Residential development surrounds the hospital grounds. Records show a decline in winter mean SO_2 concentrations in Glasgow from 73 ppbV in 1961-62 to 93 in 1978-79. The two monitoring sites closest to Gartnavel indicate winter mean SO_2 concentrations of 33 ppbV and summer means of 20 ppbV. Recent measurements show much smaller SO_2 concentrations in the range 5 to 15 ppbV.

Soils

50 tons of soil were brought from near Auchterarder, S. Perthshire, from deposits overlying Old Red Sandstone formations. The soil had previously carried barley crops.

Analysis by the Macaulay Institute gave a moderate lime, phosphate and potassium status with a pH of 6.2, and an organic matter content of 8%. A magnesium deficiency was corrected with calcined magnesite at 150 kg Mg ha^{-1}. Ground limestone was spread at 2½ tonnes per ha.

Fertilizer (see p. for dates of application).

Compound	Winter barley	Spring barley
5: 24: 24	400 kg ha^{-1}	400 kg ha^{-1}
NH_4 NO_3	125 kg N ha^{-1}	80 kg N ha^{-1}

Total application of:-

	Winter barley	Spring barley
a) Water sol. P_2O_5	91 kg ha^{-1}	91 kg ha^{-1}
b) " " K_2O	96 kg ha^{-1}	96 kg ha^{-1}
c) N	145 kg ha^{-1}	100 kg ha^{-1}

Barley varieties

1. Winter (a) Igri A two row, feed barley, with short stiff straw. Average all round disease-resistance. Later maturing than 6 row types (Ackerman, Germany).

   (b) Gerbel A six row, feed barley. Straw shorter and stronger than average. Limited resistance to mildew and yellow rust. Matures earlier than average. (Desprez, France).

2. Spring (a) Golden Promise Malting barley. Very short straw, moderately stiff. Extremely susceptible to mildew and susceptible to *Rhyncosporium*. Good resistance to ear loss. Mature early.

(b) Golf New variety not generally available, but highly regarded in trials. Limited resistance to mildew, otherwise resistance good.

Fungicides

1) Seed dressing	Active Ingredient	
Panagen M Milstem	Ethirimol	Mildew specific
2) Spray		
Winter Barley Bayleton BM	Triadimezon + Carbendazim	Brown & Yellow rust, Rhyncosporium, Mildew & Eyespot
Spring barley Fenpropomorph		Mildew specific

Operation

1) Winter Barley

Date	
14.9.82	Ground limestone and magnesite spread
28.9.82	Fisons 5:24:24 fertilizer spread at 400 kg ha_{-}^{1}
29.9.82	Plots sown with seed at spacing of 5½ x 5½ cm using a grid square. Sowing depth ca. 35 mm.
17.3.83	NH_4NO_3 spread at 50 kg N ha^{-1}
7.4.83	NH_4NO_3 spread at 75 kg N ha^{-1}
8.4.83	Sprayed with Bayleton BM fungicide to control mildew

2) Spring Barley

23.2.83	Ground limestone and magnesite spread
16.3.83	Fisons 5:24:24 fertilizer spread at 400 kg ha^{-1}
16/17.3.83	Plots sown at 5½ x 5½ cm spacing at 35 mm depth
20.4.83	NH_4NO_3 spread at 80 kg N ha_{-}^{1}

Fertilisers used

Fisons compouns 5:24:24
Fisons Potassium Super 0:20:20
NH_4NO_3
Calcined magnesite
Manganese sulphate

Herbicides Mecoprop

Fungicides seed dressing Milstem & Panogen M
Mildew & Rust Spray - Bayleton BM
Mildew Spray - Fenpropomorph

Insecticides Dursban contains Chloropyrifos

Winter Barley 82/83

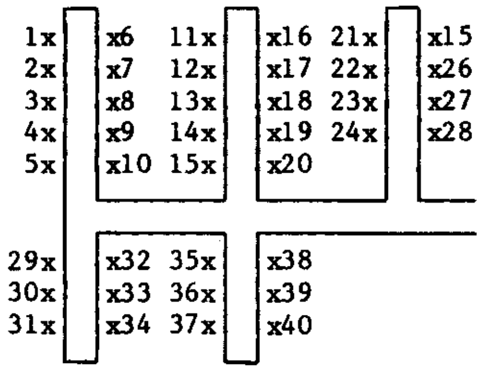
22.9.82	Soil consolidated in boxes
24.9.82	Ground limestone and calcine magnesite applied (2.5 tonnes ha^{-1} & 150 kg ha^{-1} respectively)
28.9.82	Fisons 5-24.24 fertiliser spread at 400 kg ha^{-1}
29.9.82	18 Plots sown with Igri (9) and Gerbil (9)
6.10.82	Seed brairding but soil surface caked so plots raked over very lightly.
13.10.82	Sub plots laid out (3 per plot). 10 random seedlings measured and % germination noted.
15,18,&19.10.82	Resowed where barley seed had failed.
7 & 8.12.82	Sub plot measurements recorded (no. of plants tillers and random height (5)).
Late Feb/early March	Chickweed sprayed with Mecaprop
17.3.83	NH_4NO_3 spread at 50 kg N ha^{-1} Sub plot measurements
26.3.83	Sub plot measurements
7.4.83	NH_4NO_3 applied (top dressing) at 75 Kg N ha^{-1} Westerwolths Ryegrass sown around edges of all plots.
8.4.83	Sprayed with Bayleton BM fungicide for Mildew (16g to 5 1).
15.4.83	Treatments started and chambers put on.
28.4.83	Sub plot measurements Single plant measurements.
3.5.83	Shade nets put round chambers and unchambered plots.
6.5.83	Sub plot measurements.
18 & 19.5.83	An emergence in chambered plots noted and assessed. Noticed some loose smut on gerbil.
24.5.83	Assessment of head development.
26.5.83	Single plant measurements.
27.5.83) 30.5.83)	Assessment of anthesis

1.6.83) 10.6.83) 23.6.83) 30.6.83)	Senescence estimates made
1.7.83	Grain at milky stage. Aphids on barley (infestation assessed).
18&19.7.83	Harvest of crop.

Spring Barley 1983

23.2.83	Ground limestone and calcined magnesite applied (2.5 tonnes ha^{-1} & 150 kg ha^{-1} respectively).
16.3.83	Fisons 5.24.24 fertiliser applied at 400 kg ha^{-1}.
17.3.83	Plants sown with Golden Promise (9) and Golf (9).
7.4.83	Spring barley brairded.
13.4.83	Pollution treatments started on Spring barley plots. Westerwolths sown round all chambers.
20.4.83	Top dressing of NH_4NO_3 applied at 80 kg N ha^{-1}.
26.4.83	Permanent quadrats measured (No plants, tillers & 5 random heights)
28-29.4.83	Single plants measured.
3.5.83	Shading nets put round chambers.
11&12.5.83	Primordia sampling.
18.5.83	Sub plot measurements.
24.5.83	Sub plot measurements.
26.5.83	Single plant measurements.
31.5.83	Sub plot measurements.
1.6.83) 9.6.83) 23.6.83) 30.6.83)	Single plant measurements.
1.7.83	Flag leaf measurements.
7&8.7.83	Single plant measurements & Flag leaf measurements.
14.7.83	" " "
7&8.8.83	Harvest of spring barley.

Gartnavel Plot Layout 1983-84



Experiment 3 - Winter Barley (Gerbel [G]) and Igri[I])

Block 1		Block 2		Block 3		Block 4	
Ch.		Ch.		Ch.		Ch.	
11	I/P	16	G/P	21	G/UP	25	I/P
12	I/UP	17	G/UP	22	G/P	26	I/UP
13	G/P	18	I/UP	23	I/P	27	G/UP
14	G/UP	19	I/P	24	I/UP	28	G/UP

Non-chambered Plots 15 Gerbel; 20 Igri

Experiment 4 - Spring Barley (GP = Golden Promise) (G = Golf)

Block 1		Block 2		Block 3		Block 4	
Ch.		Ch.		Ch.		Ch.	
1	G/UP	6	GP/P	29	GP/UP	30	G/P
2	G/P	7	GP/UP	32	GP/P	33	G/UP
3	GP/UP	8	G/UP	35	G/P	36	GP/P
4	GP/P	9	G/P	38	G/UP	39	GP/UP

Non-chambered Plots 5 Golf; 10 Golden Promise

Winter Barley 1983-84

23&24.8.83	Prepared soil on all winter plots.
30.8.83	Plots raked over.
26.9.83	Fertiliser applied (Fisons 5.24.24) 400 Kg ha^{-1}.
27.9.83	Winter barley sown depth 25-35 mm 50 mm apart Igris (9) Gerbil (9).
28.9.83	Chambers put on and treatments started.
7.10.83	Seed brairded.
19.10.83	Missing rows resown with germinated seed (see note by JWK).
1&2.11.83	Sub plots set up No's of plants, tillers and 5 random heights recorded.
16.11.83	Tip burn noticed.
23.11.83	Leaf yellowing asessed Mildew infection noticed (not yet serious) Slug bait put round plots.
29.11.83	Leaf yellowing assessed.
30.11.83	" " "
1.12.83	" " "
5.12.83	Mildew attack quite severe.
14.12.83	Mildew attack very severe Leaf yellowing assessed.
15.12.83	Sprayed mildew with Fenpropomorph, during mild spell in weather.
21.12.83	Measured single plants.
22.12.83	Leaf yellowing assessed.
2.1.84	Insect damage on plot 22 noticed.
13.1.84	Heavy snow fall. Leaf yellowing assessed prior to snow fall.
1.2.84	Snow still lying on unchambered plots but chambers clear Leaf yellowing assessed.
3.2.84	

Winter Barley 83-84 continued

3.2.84	Mildew still present in all chambers. Plant samples taken from outer ring of plots 13, 17, 20, 22, 25 and 26 for mildew assessment by college. Area is now clear of snow.
8.2.84	Leaf yellowing assessed. Mildew damage assessed.
15.2.84) 22.2.84) 29.2.84)	Leaf yellowing assessed.
	also cover estimates.
6.3.84	Sprayed mildew with Fenpropimorph No's of plants, tillers and 5 random heights taken.
7.3.84	Primordia samples taken for examination Leaf yellowing assessed Single plants measured.
13.3.84	Leaf yellowing assessed Cover estimates made.
21.3.84	Nitrogen top dressing applied 50 kg N ha^{-1} as NH_4NO_3
23.3.84) 26.3.84) 28.3.84)	Assessment of greenness of plots made.
4.4.84	Single plants measured.
17.4.84	Nitrogen top dressing applied 75 kg N ha^{-1} as NH_4NO_3 Samples taken for primordia examination.
30.4.84	6 gallons water applied to each plot.
1&2.5.84	Shading nets put round chambers and unchambered plots. Applied 4½ gallons water to each plot. Plant NO's, tillers and 5 random heights taken. Single plants measured. Raised annuli in winter chambers.
8&9s.5.84	Applied 6 gallons water to each plot Recorded Flag leaf measurements Awns emerging - between 75 & 98% of plants showing awns
15.5.84	Applied 6 gallons water to each plot.

Winter barley 83-84 continued

16.5.84	Applied 3 gallons water to plots Flag leaf measurements recorded Leaf senescence noted Almost all ears have emerged and ahtnesis is taking place in chamberded plots. Unchambered plots at least 1 week behind.
20.5.84	Applied 1½ gallons water to plots Senescence of leaves assessed.
22.5.84	Applied 1½ gallons water to plots Recorded flag leaves Assessed mildew infestation.
23.5.84	Sprayed mildew with Fenpropimorph Recorded ear emergence and anthesis.
24.5.84	Applied 1½ gallons water to plots Put nets on top of chambers to keep out birds.
30.5.84	Put bird nets round unchambered plots Took random height measurements of barley (10).
5.6.84	Awns starting to show signs of senescence.
8.6.84	Applied 3 gallons water to each plot Sprayed plots with Fenpropimorph for mildew Recorded flag leaf lengths and width at widest part of leaf " height of inflorescence " senescence of leaves on marked plants.
13.6.84	Sprayed barley with 'Dursban' to kill greenfly Senescence of crop assessed.
19.6.84	Applied 3½ gallons water per plot.
20.6.84	Applied 1½ gallons water per plot Recorded marked plant senescence of leaves also senescence of whole plot.
27.6.84	Senescence of barley almost complete Recorded senescence of single plants and of whole plot.
4.7.84	Senescence complete on all plots.
10&11.7.84	Harvested chambered plots.
18.7.84	Harvested unchambered winter barley plots.

Spring Barley Season 1984

Varieties - Golden Promise and Golf

Sown - 27 March 1984

Treatments started - Blocks 3 & 4 28.3.84
Blocks 1 & 2 4 & 5.4.84

Brairding - 16 April 1984

Fertiliser	Date	Rate	Amount per plot
Limestone - ground		Nil	
Calcined Magnesite		Nil	
Fisons 5.24.24	21.3.84	400 kg ha^{-1}	90 gm
NH_4NO_3	8.5.84	80 kg ha^{-1}	54 gm

Fungicides	Type	Date	Rate	Amount
Seed dressing	Panagen & Milstem			
Mildew	Fenpropomoprh	23.5.84	1 l ha^{-1}	16.7 ml per 5 l H_2O

Harvested 7 & 8.8.84

Spring Barley 1984

31.8.84	Plots dug over
7.3.84	Plots forked over and raked.
21.3.84	Plots raked and Compound fertiliser (Fisons 5.24.24) worked into surface (400 kg ha^{-1}).
27.3.84	Golf (9 plots) and Gerbil (9 plots) seed sown in ideal conditions.
28.3.84	Started treatments on blocks 3 & 4.
4&5.4.84	Treatments started on blocks 1 & 2.
11.4.84	Barley not showing yet. Soil surface drying out.
16.4.84	Seed brairded Golf is good, Golden Promise not so good. patchy.
18.4.84	Grass (Western wold) sown round plots.
25.4.84	Barley at 2 leaf stage and about 3-4 cm high Temperatures in 70s this week. Plots beginning to dry out.
30.4.84	Set out permanent quadrats and marked plants 3 quadrats each containing a marked plant in each plot Recorded no. of plants, tillers and 5 random heights Recorded marked plants, leaf length and tiller height
1.5.84	Applied 4½ gallons water to plots
8.5.84	Recorded permanent quadrats (plant nos, tillers and 5 heights Recorded single plants Applied N top dressing 80 kg N ha^{-1} at NH_4NO_3
15.5.84	Recorded permanent quadrats (plants nos, tillers and 5 heights) recorded marked plants Applied 6 gallons water to reach plot.
16.5.84	" 1½ " " " " "
20.5.84	" 1½ " " " " "
22.5.84	" 3 " " " " "
22&23.5.84	Recorded permanent quadrats " marked plants Sprayed mildew with Fenpropomorph, all plots Took samples for primordia examination.

24.5.84	Applied 1½ gallons water to each plot
30.5.84	Recorded permanent quadrats (plants nos, tillers and 5 heights Recorded marked plants.
4.6.84	Raised annuli in chambers
5.6.84	Awns starting to appear Recorded permanent quadrats (plant nos, tillers and 5 heights). Recorded marked plants and flag leaf lengths.
8.6.84	Applied 1½ gallons water to each plot.
12.6.84	Ears partially emerged on var. Golf but less obvious on Golden Promise. Anthesis just starting. Recorded flag leaf lengths on marked plants. Sprayed plots with Fenpropomorph as preventative measure No sign of mildew.
13.6.84	Put shading nets round chambers and unchambered plots.
19.6.84	Anthesis is finished no apparent signs Measured senescence of marked plants " height to base of inflorescence and to flag leaf (base) Applied 3½ gallons water to each plot.
20.6.84	" 1½ " " " " " Put bird nets over spring barley plots.
26.6.84	Applied 3 gallons water to each plot.
27.6.84	All ears have now emerged fully Senescence obvious on lower leaves (drought effect) particularly in centre of plots. Recorded senescence of marked plants and heights to base of inflorescence and to base of flag leaf. Also took 5 heights.
4.7.84	Applied 16 gallons water to each plot. Plots were very dry.
7.7.84	Senescence has now progressed to outer edge of plots.
11.7.84	Applied 12 gallons water to each plot. Recorded senescence of marked plants and took 5 random heights.
13.7.84	Assessed aphid attack and sprayed plots with Dursban.
18.7.84	Applied 12 gallons water to each plot.

25.7.84	Applied 12 gallons water to each plot.
1.8.84	Applied 6 gallons water to each plot.
7.8.84	Harvested blocks 1 & 2
8.8.84	Harvested blocks 3 & 4
15.8.84	Harvested unchambered plots
11.9.84	Took soil samples for analysis.

Gartnavel Plot Layout 1984-85

Two N Treatments   1 variety Gerbel   Filtered (F) Unfiltered (UF)

Block 1		Block 2		Block 7		Block 8	
Ch		Ch		Ch		Ch	
1	UFN1	6	UFN2	29	FN2	30	FN1
2	FN1	7	UFN1	32	UFN2	33	FN2
3	UFN2	8	FN1	35	FN1	36	UFN2
4	FN2	9	FN2	38	UFN1	39	UFN1

Unchambered plots

5	N1	10	N2	15	N1	20	N2

Winter Barley 1984-85

Four experiments started

Experiment 5 - Main experiment using 1 barley variety Gerbil (6 row), 2 treatments (filtered and unfiltered) and 2 nitrogen levels:- N_1 110 kg N ha^{-1} & 180 kg N ha^{-1}.

Experiment 6 - Frost damage assessment
2 treatments and 2 Nitrogen levels as above.

Experiment 7 - Radiation

Experiment 8 - Flux and Monitoring.

Winter Barley 1984-85

12-19.9.84	All plots prepared for sowing.
22.9.84	Applied fertiliser 100 kg ha^{-1} of P & K in compound N_1 treatment 10 kg N ha^{-1} as NH_4NO_3 N_2 " 30 kg N ha^{-1} " "
25&26.9.84	Plots sown with Gerbil seed
2.10.84	No sign of brairding.
9.10.84	Plots starting to braird.
16.10.84	Brairding very variable Rows 1, 2, 7, 8 and 9 are good Rows 3, 4, 5 and 6 become progressively worse from W to E. Plot 19 is very good.
18.10.84	Resowed blanks in rows 3, 4, 5 and 6 and filled in gaps in rows 1, 2, 7 and 8 with germinated plants in pots.
23.10.84	Sprayed plots with Dursban - coarse spray - to kill bean seed fly in soil (1½ l Dursban in 200 l water ha^{-1}). Started treatments on main experiment.
30.10.84	Started treatments on experiments 6, 7 and 8 Sowed grass seed (Westerwolths) round chambers.
5.11.84	Marked out permanent quadrats recorded plant nos and 1 height. Selected marked plants measured cotyledon.
13.11.84	Resown seed on rows 3, 4, 5 and 6 have brairded.
28.11.84	Sprayed plots with Fenpropomorph as a precautionary measure against mildew attack (some mildew present).
6.12.84	Recorded permanent quadrats (nos plants, tillers and 5 heights). Recorded marked plants.
8.1.85) 29.1.85) 5.2.85)	Plots scored for yellowing of leaves.
26.2.85	Recorded permanent quadrats (nos plants, tillers and 5 heights). Recorded marked plants on chambered plots only.
4.3.85	Recorded permanent quadrats and marked plants on unchambered plots.

7&8.3.85	Frost experiment harvested. Sprayed all other plots with Fenpropomorph as precautionary measure against mildew (profilactic).
15.3.85	Top dressing of Nitrogen applied to all plots at NH_4NO_3/ N_1 40 kg N ha^{-1} and N_2 60 kg N ha^{-1}.
25.3.85	Assessed uniformity of cover growth and greenness for all plots in Experiment 6.
8.4.85	Assessment as for 25.3
16&17.4.85	Applied N to all plots 60 kg ha^{-1} to N_1, and 90 kg ha^{-1} to N_2. Recorded plant nos, nos tillers and 5 heights in firm quadrats. Put lids on plots 13, 14, 18 and 19 Flux expt.
24.4.85	Applied Manganese sulphate to all plots. 5 kg ha^{-1} in 300 l H_2O.
2.5.85	Installed irrigation system. Harvested NE Quartile of Radiation expt 7 (Row 5)
8.5.85	Shading nets put on all chambers. Unchambered plots left at moment. Started to water plots see separate sheet for amounts and dates.
15.5.85	Sprayed plots for mildew (preventative measure - no sign of the disease) with Fenpropomorph. Raised shading nets. Put shading nets round UC plots. Assessed own emergence.
28.5.85	Recorded crop heights. Noted presence or absence of anthesis. (Height to base of inflorescence).
4.6.85	Recorded crop heights 10 measurements (random).
10.6.85	Pumps fialed from approx midnight until 10.30am BST.
26.6.85	Barley starting to senesce but flag leaves still mostly green.
2.7.85	Sprayed plots with Dursban to kill aphids (plots 38 most affected also some on plot 6). All plots sprayed.
25.7.85	Blocks 1 and 2 harvested.
26.7.85	Blocks 7 and 8 harvested.
7.8.85	Unchambered plots harvested.