AMBIENT LEVELS OF SULPHUR AND NITROGEN OXIDES IN THE UK AND THEIR EFFECTS ON CROP GROWTH

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ABSTRACT

A study was made of SO_2 and NO_x concentrations in the UK by a thorough examination of the literature and a detailed analysis of three months data on hourly mean levels in central London. Using information gained from this study, two sets of fumigation experiments were performed. In both sets of experiments outdoor chambers ventilated with charcoal filtered air were used.

In one set of four chambers, three received added SO_2 and NO_2 at three concentrations representing increasingly polluted environments. Concentrations of pollutants were fluctuated on a daily basis to give the desired means and frequency distributions. Yields of swards of *Lolium perenne* cvs S23 and S24 and *L. multiflorum* cv. RvP, grown in these chambers for nine months, were compared with yields in a clean air control. The experiment was essentially repeated over two years. In a set of six chambers SO_2, NO_2 and NO were added singly or as mixtures to simulate urban concentrations. Levels of pollutants were fluctuated on an hourly basis. Two different experiments were carried out, each lasting 6-8 months. Swards of *L. perenne* cv. S24, *Phleum pratense* cv. Odenwalder and *Dactylis glomerata* cv. S26 were grown in various polluted environments and a clean air control.

In addition, an experiment growing *L. perenne* cv. S24 and *Hordeum vulgare* cv. Maris Otter in chambers receiving filtered or unfiltered air was performed over two winters in an area of moderate pollution.

Results from all the experiments are discussed in relation to other published work and for their relevance to effects of SO_2 and NO_x on crop yield in the UK.

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CHAPTER 1

INTRODUCTION

Sulphur dioxide has long been recognised as an important phytotoxic air pollutant in the UK, particularly in and around major industrial areas. For example, Cohen & Ruston (1925), working in Leeds during the early years of this century, showed that crop yield decreased approximately in proportion to the increases in the sulphur content of the ambient air. Most SO_2 present in UK ambient air is produced during the combustion of sulphur-containing fuels, although a few percent are produced from chemical and other non fuel-burning processes (Department of Environment, 1978). Because almost all coal and oil contains a small percentage of sulphur, SO_2 forms part of most 'smoke' emitted by industry and commerce.

Unlike SO_2, nitrogen oxides (NO_x) have not been considered an important air pollutant until recently. NO_x production is again usually associated with combustion, being formed from nitrogen in the fuel and by high temperatures oxidising atmospheric nitrogen (Bruce, 1979). The predominant oxide of nitrogen produced in this manner is nitric oxide (NO), accounting for about 95% of the total, the remainder being nitrogen dioxide (NO_2). Relatively small quantities of NO_x are produced from industrial processes such as fertiliser production, but these may be locally important (Harrison & McCartney, 1979).

NO_x is produced by the same sources as SO_2 where the latter is formed by the combustion of fuels, but an additional major source of NO_x is vehicle exhausts, contributing 28% of UK NO_x emissions in 1976 (Apling, Potter & Williams, 1979) but only 1% of SO_2 (Department of Environment, 1978). Power stations emitted about 55% and 45% of total SO_2 and NO_x, respectively, in the UK in 1976. Remaining SO_2 and NO_x emissions are from various commercial and industrial sources, with domestic fuels accounting for about 3% NO_x and 5% SO_2 emissions (Apling *et al.*, 1979; Department of Environment, 1978). It should be noted that the amount of SO_2 emitted in the UK is about 5.3 million tonnes (mt) per annum compared with only 1.8 mt NO_x (Fig. 1.1).

Concentrations of SO_2 and NO_x in the atmosphere depend upon several factors including source strength, distance from source(s) and degree of dispersion. Although sources of ambient concentrations are not discussed in detail here, the measured concentrations are described fully in Chapter 2.

There is one other major and widespread phytotoxic air pollutant in the UK, viz. ozone (O_3). Ozone is a secondary pollutant, produced by photochemical reactions in the atmosphere. Some details of O_3 formation are discussed in Appendix 1, the most important feature being that O_3 concentrations are highly dependant on sunlight and are therefore seasonal, as well as showing a marked diurnal pattern. Although the effects of O_3 on plant yield are not considered in detail in this thesis they have a bearing on the interpretation of results from experimental work. For this reason O_3 concentrations in the UK are described in Chapter 2 and will be included in discussions elsewhere, as appropriate.

At the start of this work it was generally accepted that reductions in the yield of grass could be caused by fumigations with SO_2 at concentrations about double the annual mean found in urban areas (e.g. Bell & Clough, 1973; Bell, Rutter & Relton, 1979; Ashenden & Mansfield, 1977; Lockyer, Cowling & Jones, 1976). In addition, some studies had shown beneficial effects on growth when urban air was filtered to remove some of the pollutant burden (Bleasdale, 1973; Crittenden & Read, 1978b, 1979). Most importantly, Ashenden & Mansfield (1978) showed that the

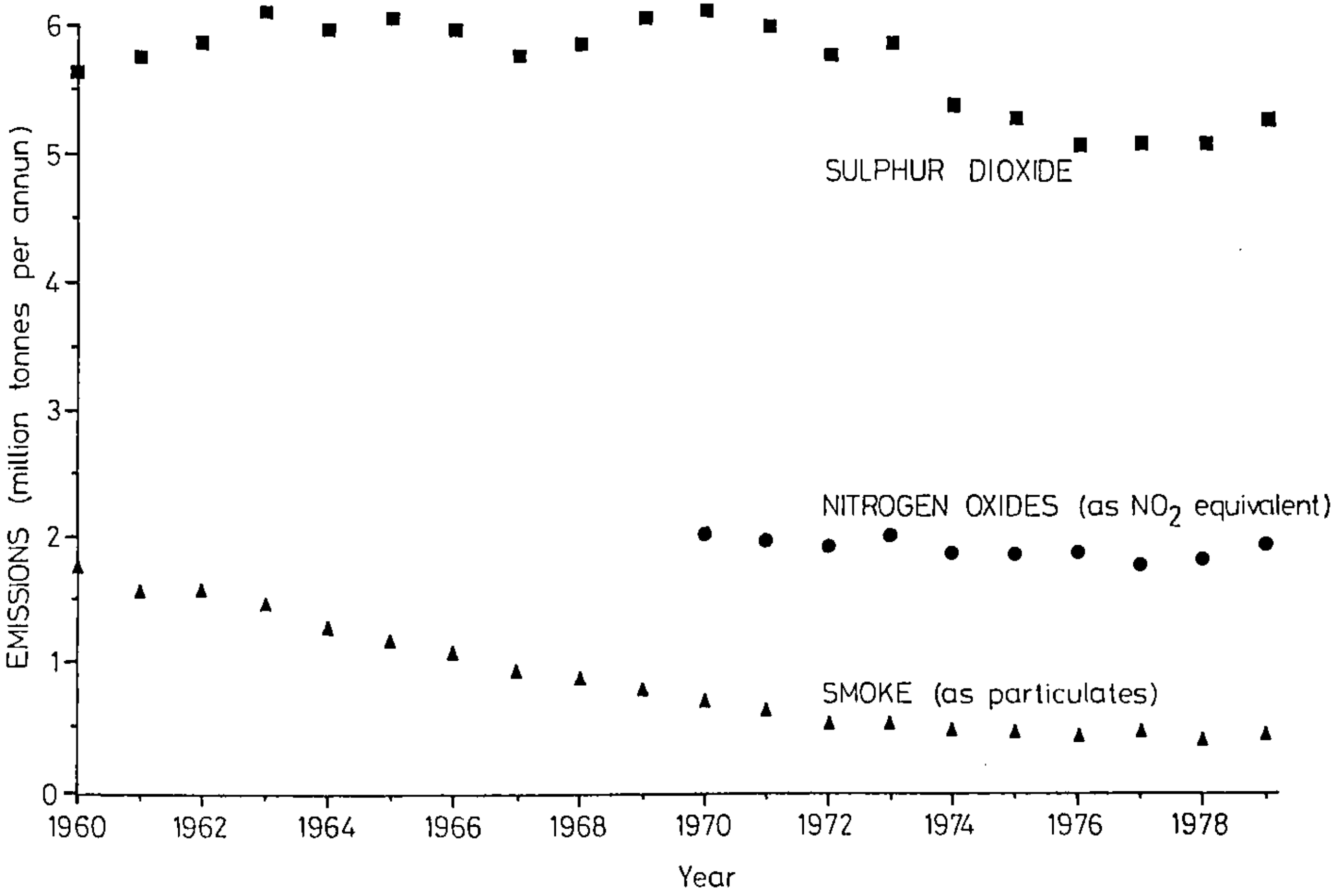


Figure 1.1 : Emissions of sulphur dioxide, nitrogen oxides and smoke in the UK from 1960 to 1979. (From Department of Environment, 1981)

growth of four grass species was severely reduced when exposed to SO_2 plus NO_2 at mean concentrations similar to those found in some urban areas. This reduction was greater than that expected from the sum of the effects of fumigations with similar concentrations of the single pollutants for three of these species. The authors suggested that interactions between individual pollutants may be particularly important in determining their effect on crop yield in the field.

The pollutant concentrations used by Ashenden & Mansfield (1978) were of direct relevance only to plants growing in towns or cities (e.g. playing fields, parks and gardens). Since most crops are exposed to lower levels of pollution, it was considered important to study the effects of SO_2 and/or NO_2 at concentrations more typical of polluted rural areas. With this aim in mind, experiments were conducted using SO_2, NO_2 and NO singly and in mixtures, at concentrations designed to represent various polluted environments.

In order to understand the potential for pollutants to affect crop yield one must have a clear idea of the concentrations found in the environment: this forms the topic of Chapter 2. Following this, in Chapter 3, there is a review of some of the effects of SO_2 and/or NO_2 on crop growth, with particular reference to ambient concentrations. Subsequent chapters describe and discuss the experimental work.

1.1 A Note on Units Used to Measure Pollutant Concentration

There are two types of units used for measurement of pollutant concentrations: weight of pollutant per volume of air, usually as $\mu g\ m^{-3}$, and volume of pollutant per volume of air, usually parts per million (ppm; $\equiv \mu l\ l^{-1}$) or billion (ppb, parts 10^{-9}). Both types of measurement are commonly used for both SO_2 and NO_x. For ease of comparison, only ppm or ppb will be used throughout this thesis. Conversion from weight/volume to volume/volume is temperature and pressure dependant (for discussion see Garnett, Read & Finch, 1976) but only one conversion factor for each pollutant was used in the present work, regardless of conditions, because this was thought to be accurate enough for the purposes of determining the effects of SO_2 and NO_x on crop growth. These assumed 20°C and 1 atmosphere pressure and were:

for SO_2, 1 ppb = 2.660 $\mu g\ m^{-3}$,
for NO, 1 ppb = 1.248 $\mu g\ m^{-3}$,
for NO_2, 1 ppb = 1.913 $\mu g\ m^{-3}$,
for O_3, 1 ppb = 1.996 $\mu g\ m^{-3}$.

CHAPTER 2

AMBIENT LEVELS OF AIR POLLUTION IN THE UNITED KINGDOM

In order to put work on the effects of air pollution on crops into perspective it is necessary to have an overview of the pollutant concentrations that occur in the UK. The simplest expression of the concentration of a pollutant is the mean and this can provide much valuable information, particularly when considering regional levels and long-term trends. In general, pollutant levels fluctuate widely about the mean and are better described by cumulative frequency distributions of the measured concentrations of each pollutant. Three other parameters are useful: (a) diurnal patterns, describing mean concentrations at each hour of the day; (b) the length of time (consecutive hours) a pollutant remains above given concentrations and (c) the correlation between concentrations of pairs of pollutants. The latter is particularly important when considering the effects of pollutant mixtures. An excellent detailed discussion of the analysis of air monitoring data has been produced by the World Health Organisation (1980).

2.1 SO_2: Long-Term Trends and Area Means

Over the past three decades trends in pollutant emissions have been dominated by the effects of the Clean Air Act of 1956. This Act was implemented to reduce periods of high SO_2 and particulate concentrations which occurred during the London 'smog' episodes of 1952 and 1956. Local authorities were able to establish 'smokeless fuel zones' in urban areas, in addition there were increases in the use of smokeless and low-sulphur fuels. Prior to 1960, the large urban areas in the UK experienced winter mean smoke and SO_2 concentrations in excess of 200 $\mu g\ m^{-3}$ and 150 ppb (400 μg m^{-3}) respectively (Warren Spring Laboratory, 1972). Even in summer, smoke and SO_2 concentrations were as high as 80 μg m^{-3} and 75 ppb (200 μg m^{-3}). Commins & Waller (1967) made extensive measurements of smoke and SO_2 at a site in the city of London before the decline in concentrations occurred. The annual mean smoke and SO_2 concentrations were 150 μg m^{-3} and 124 ppb (330 μg m^{-3}) between 1954 and 1960. The concentration of smoke exceeded 1000 μg m^{-3} for an average of 2.2 days per year and SO_2 exceeded 375 ppb (1000 μg m^{-3}) for 7.7 days per year, mostly between November and February. Maximum hourly SO_2 concentrations during these episodes varied between 560 and 1700 ppb (1500-4500 μg m^{-3}). In contrast the highest recorded hourly SO_2 level at the County Hall roof-top site during the winter of 1980-81 was 250 ppb (665 μg m^{-3}) (Greater London Council, Scientific Branch, pers. comm.). Measurements of the diurnal pattern in the 1950's showed that SO_2 concentrations peaked between 8 and 10 am at 2.5 to 2 times the daily mean, whereas smoke levels peaked in the early morning and early evening.

Since the implementation of the Clean Air Act and the concurrent introduction of natural gas there has been a reduction in particulate emissions from 2.8 mt in 1960 to 0.42 mt in 1979 (Figure 1.1). Smoke concentrations in urban areas decreased from more than 150 μg m^{-3} to less than 50 μg m^{-3} over this period (Department of Environment, 1981). Emissions of SO_2 have changed less dramatically from a peak of 6.1 mt in 1970 to 5.3 mt in 1979 (Figure 1.1).

The majority of data on SO_2 concentrations in the UK have been obtained by Warren Spring Laboratory (WSL) in their 'National Survey of Smoke and Sulphur Dioxide' (WSL, 1960 et seq., 1972-76). Data from about 1000 sites throughout the UK have been summarised by WSL in two forms: one of these is a detailed analysis for the decade 1960-1970 (WSL, 1972-76), the other consists of maps of winter mean SO_2 concentrations for 1972-3 and 1975-6. These maps show that areas with winter mean SO_2 concentrations in excess of 38 ppb (100 μg m^{-3}) were centred on Glasgow, Merseyside, Leeds, Sheffield, Birmingham and London. Regions around these cities are subjected to concentrations between 19 and 38 ppb (50 and 100 μg m^{-3}). In 1972-3 areas of England and Wales receiving winter mean SO_2 concentrations of greater than 19 ppb included about 15% of the total area of all agricultural crops (including grass and rough grazings), 12% of private woodland and 5% of Forestry Commission plantations (Jeffree, 1978). However, the WSL maps for 1975-6 showed that there had been a substantial decline in areas receiving winter mean SO_2 concentrations in excess of 19 ppb. No estimate of the reduction in area of crops or woodland affected is available. With the exception of the maps, an analysis of the annually published WSL National Survey data from 1970 was not available. An analysis of trends in SO_2 during the last decade is important as the shift of some emission sources from urban to rural areas and the adoption of the tall stack policy for power stations and heavy industry (i.e. utilisation of stacks up to 200 m in height to achieve maximum dispersion of pollutants before they reach the ground) has led to the suggestion that SO_2 concentrations may have increased in some rural areas (Bell & Mudd, 1976). Indeed, WSL (1972-76) reported that mean winter concentrations at 11 'country' sites in north-west England increased from 37 ppb in 1967 to 48 ppb in 1970.

The following section describes the methods used to analyse some of the WSL data and the results obtained.

2.1.1 Analysis of daily mean SO_2 levels in the UK

(WSL National Survey data)

Methods

Data from the WSL National Survey of Air Pollution provide information on daily mean SO_2 levels at about 1000 sites in the UK. To determine trends over the past decade, sites from four broadly-defined areas were chosen for analysis on the basis of descriptions (WSL, 1960 et seq.) and/or class types as defined by WSL (1970-1980; also see Appendix 2). The sites and their class types used in the analysis are given in Appendix 2. In order to minimise the effect of differences between individual sites, data were used only from those sites producing information from 1968-9 until at least 1976-7 (not necessarily continuously). The site categories were:

1. Urban: Sites in or near city centre (London, Birmingham, Manchester and Sheffield), corresponding to areas on WSL maps (1975-6) with winter mean levels of greater than 38 ppb (100 $\mu g\ m^{-3}$). Data were analysed from 10 sites.
2. Urban fringe: Sites around the edge of cities in low density residential areas, with or without minor industry or commerce (20 sites).
3. Rural fringe: Sites around the edge of cities in rural (small community) areas (8 sites).

Sites in the fringe categories (2 and 3) are intended to differ only in their immediate surroundings. Their distances from cities are similar and represent areas with 19-38 ppb SO_2 as a winter mean. Fringe sites, particularly rural fringe, in effect represent areas with the highest concentrations of SO_2 to which agricultural land is likely to be subjected.

4. Country: Sites in areas varying from completely open country to rural communities, corresponding to areas with winter mean SO_2 levels of less than 19 ppb (26 sites).

It was decided to investigate five parameters describing SO_2 levels. These were:

1. The mean winter SO_2 concentration, i.e. the arithmetic mean of all daily concentrations obtained during the months October to March.
2. The mean summer SO_2 concentration, defined similarly to 1 but for April to September.
3. The mean annual SO_2 concentration, again defined similarly to 1 but for April to March.
4. The highest daily mean level of SO_2 (HD mean) recorded during the year April to March. This represents a minimum value because not all days during the year were sampled. However it is used in the analysis, no matter how few samples were taken.
5. The number of days in each year when the SO_2 concentration was greater than 94 ppb (ND 94). Again this is a minimum value (see 4 above), also it is only available from April 1971 onwards. (N.B. 94 ppb = 250 $\mu g\ m^{-3}$ SO_2.)

The arithmetic mean of each parameter for each of the four site types was determined for each year from 1968-9 to 1978-9. This provided the 'urban winter arithmetic mean', 'urban summer arithmetic mean' etc., for each year. In addition one other method of calculation was used (described by WSL, 1972-76, and included in Appendix 2). This method is designed to eliminate the variation caused by missing data resulting in the use of slightly different sets of sites from one year to the next. These 'derived means' were also used to produce trends. When all the data are present then the derived mean is the same as the arithmetic mean, and generally they are similar. However, due to the large proportion of missing data in some cases, the derived and arithmetic mean trends occasionally differ significantly. Both the arithmetic and derived mean trends for each parameter at each of the site types are shown in Figures 2.1 to 2.6. (The ND 94 was near zero at country sites in all years and was ignored.) A linear regression line (calculated using the mean values for each year) has been plotted for each curve and the probability of its slope differing from zero is given.

Results and discussion

In general the derived mean and arithmetic mean trends are similar (Figures 2.1 to 2.6). The few exceptions are due to a small number of sites with available data. With these very small samples, neither the derived nor the arithmetic means are likely to be accurate. This is due to the large variation in SO_2 levels between sites, even within a single category.

However, it is clear that the urban, urban fringe and country sites show a decrease in mean SO_2 levels from 1968-9 to 1978-9. The absolute change is most pronounced in urban areas (Fig. 2.1), least in country (Fig. 2.4) and with urban fringe areas intermediate (Fig. 2.2). The decrease in mean concentrations was slightly more marked in winter than in summer at urban and urban fringe sites resulting in a winter:summer SO_2 concentration ratio of 1:0.60 in 1979, compared with 1:0.55 in 1969. At country sites the ratio remained around 1:0.85 throughout the decade. Only at rural fringe sites (Fig. 2.3) are some of the mean trends not significant (annual derived mean, summer arithmetic mean) but this may be an artefact of the small number of sites utilised. Nevertheless, even here there is good evidence for a decline in winter SO_2 levels.

Trends in HD mean concentrations and ND 94 are shown in Figures 2.5 and 2.6. All except rural fringe ND 94 show significant decreases over the periods concerned (10 years for HD means, 7 for ND 94).

The percentage decreases in all parameters for all site types were estimated from the regression lines and are shown in Table 2.1. Evidently the greatest change occurred in urban and urban fringe ND 94 (approximately

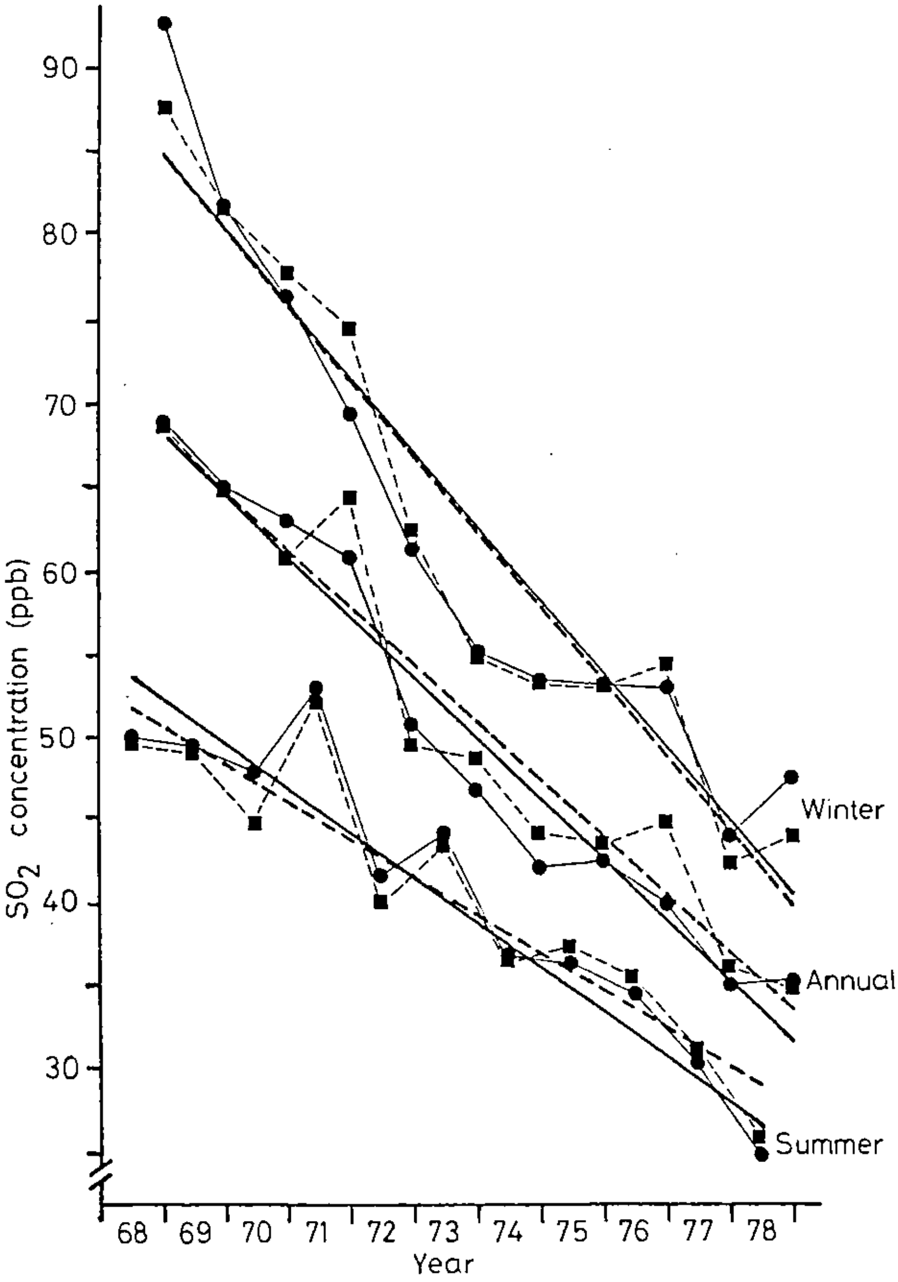


Figure 2.1 : Trends in daily mean SO_2 levels at urban sites. Winter, annual and summer derived and arithmetic mean concentrations with fitted regression lines.

●——● derived mean

■– –■ arithmetic mean

——— regression

– – – regression

Probability of the slope of each regression line differing from zero: winter d.m., $p < 0.001$; winter a.m., $p < 0.001$; annual d.m., $p < 0.001$; annual a.m., $p < 0.001$; summer d.m., $p < 0.001$; summer a.m., $p < 0.001$.

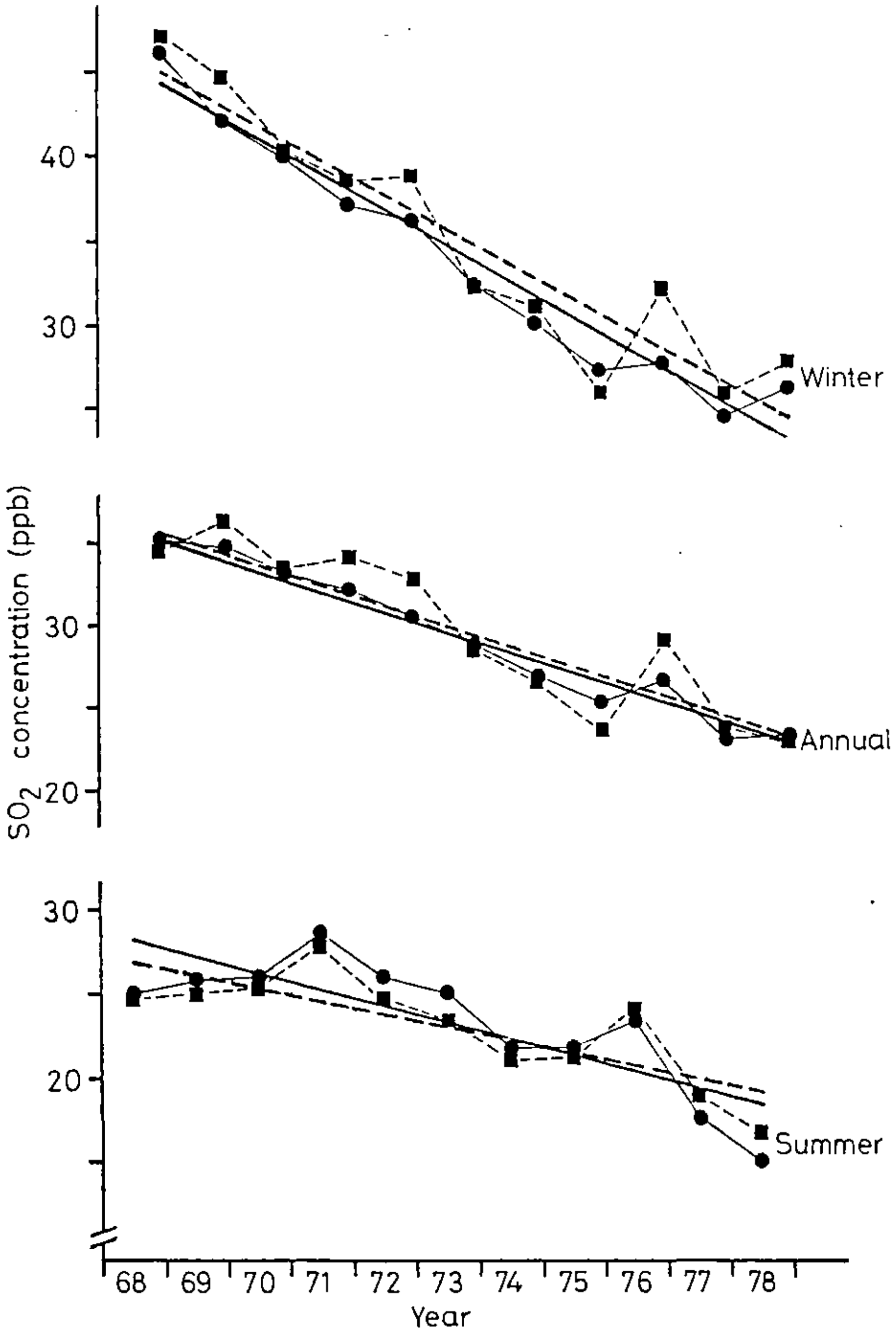


Figure 2.2 : Trends in daily mean SO_2 levels at urban fringe sites. Winter, annual and summer derived and arithmetic mean concentrations with fitted regression lines.

●——● derived mean

■— —■ arithmetic mean

——— regression

— — — regression

Probability of the slope of each regression line differing from zero: winter d.m., $p < 0.001$; winter a.m., $p < 0.001$; annual d.m., $p < 0.001$; annual a.m., $p < 0.001$; summer d.m., $p < 0.01$; summer a.m., $p < 0.01$.

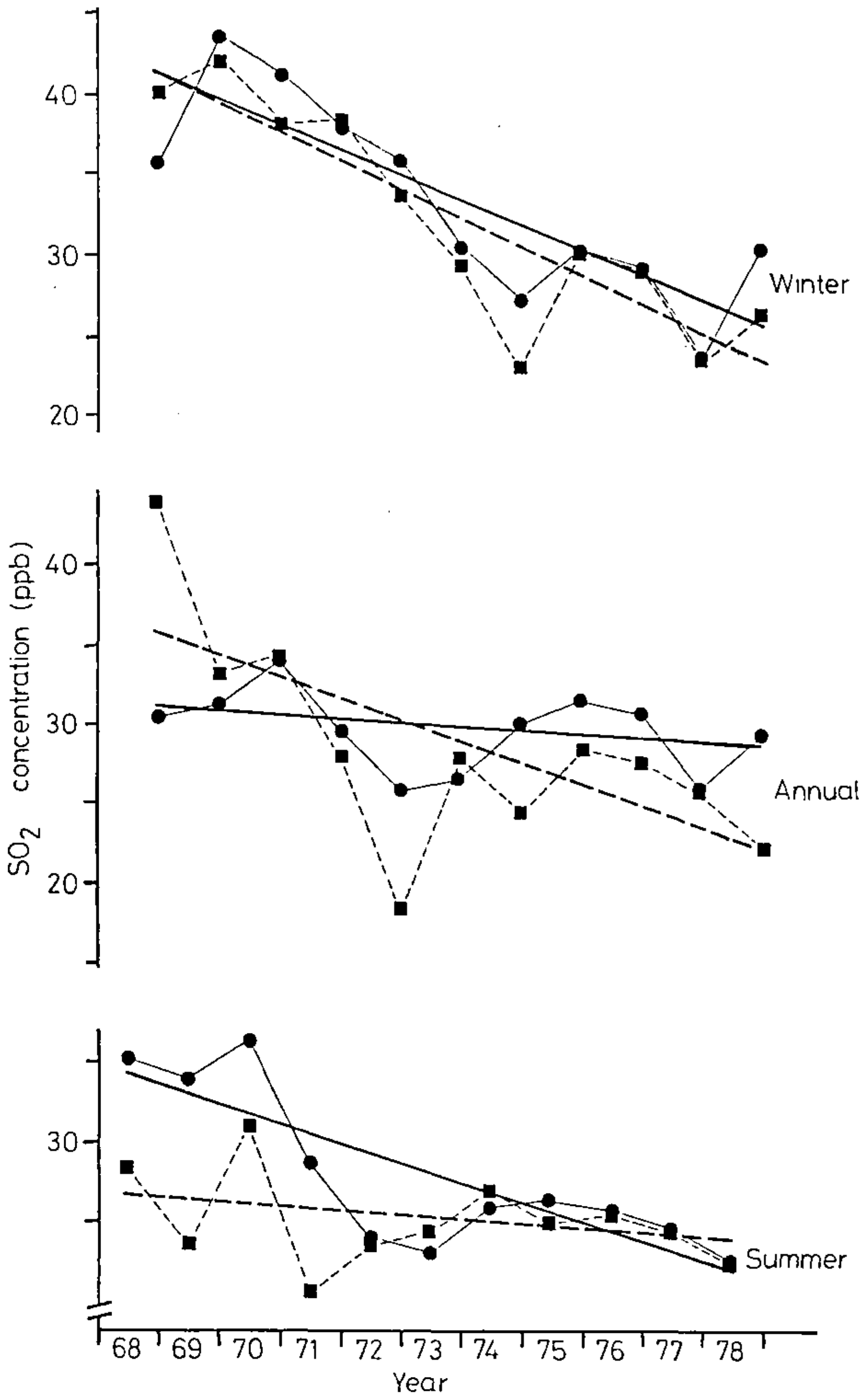


Figure 2.3 : Trends in daily mean SO_2 levels at rural fringe sites. Winter, annual and summer derived and arithmetic mean concentrations with fitted regression lines.

●——● derived mean, ——— regression

■– –■ arithmetic mean, – – – regression

Probability of the slope of each regression line differing from zero: winter d.m., $p < 0.01$; winter a.m., $p < 0.001$; annual d.m., p=n.s.; annual a.m., $p < 0.05$; summer d.m., $p < 0.01$; summer a.m., p=n.s.

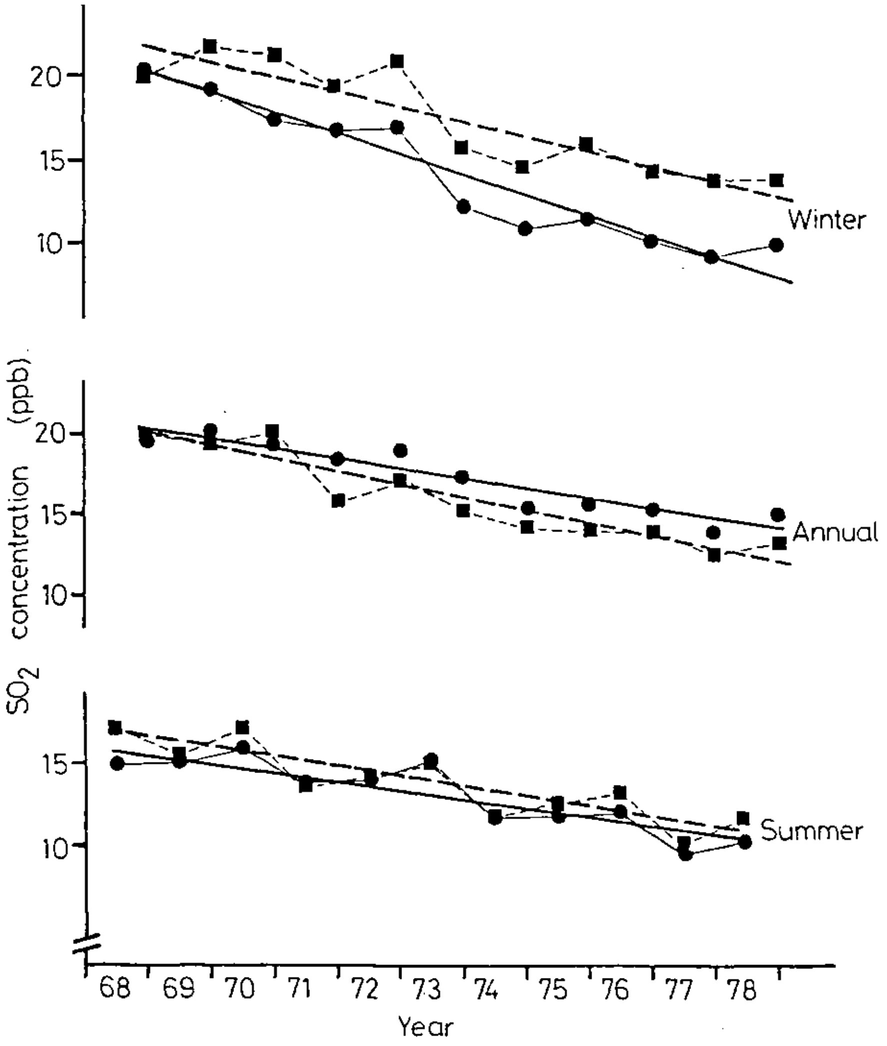


Figure 2.4 : Trends in daily mean SO_2 levels at country sites. Winter, annual and summer derived and arithmetic mean concentrations with fitted regression lines

●——● derived mean,

■– –■ arithmetic mean,

——— regression

– – – regression

Probability of the slope of each regression line differing from zero: winter d.m., $p < 0.001$; winter a.m., $p < 0.05$; annual d.m., $p < 0.001$; annual a.m., $p < 0.05$; summer d.m., $p < 0.001$; summer a.m., $p < 0.05$.

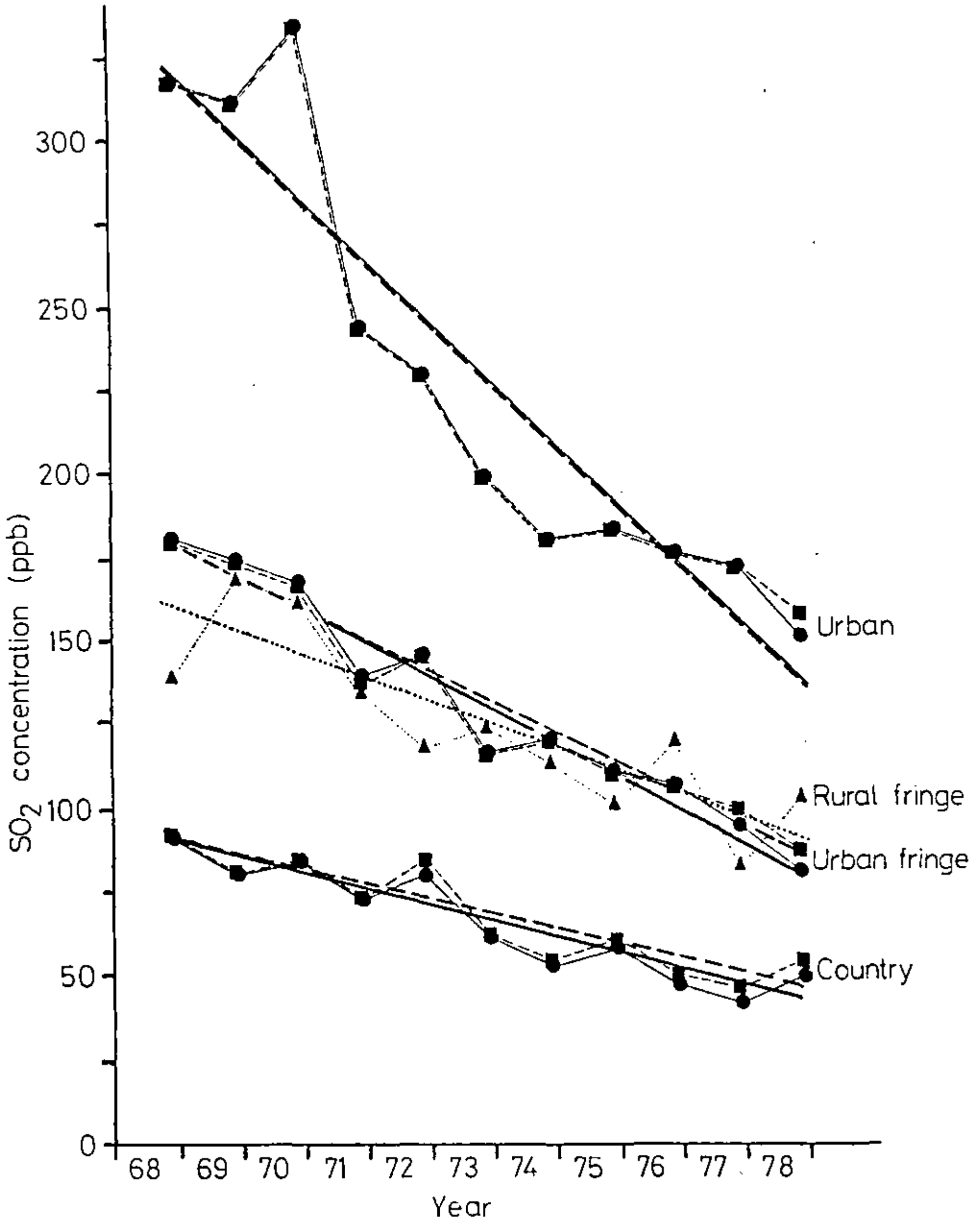


Figure 2.5 : Trends in daily mean SO_2 levels: HD mean at urban, urban fringe, rural fringe and country sites, with fitted regression lines.

●——● derived mean, ——— regression } urban, urban fringe and country

■— —■ arithmetic mean, — — — regression

▲·······▲ derived mean = arithmetic mean } rural fringe

·········· regression

Probability of the slope of each regression line differing from zero: for all lines $p < 0.001$.

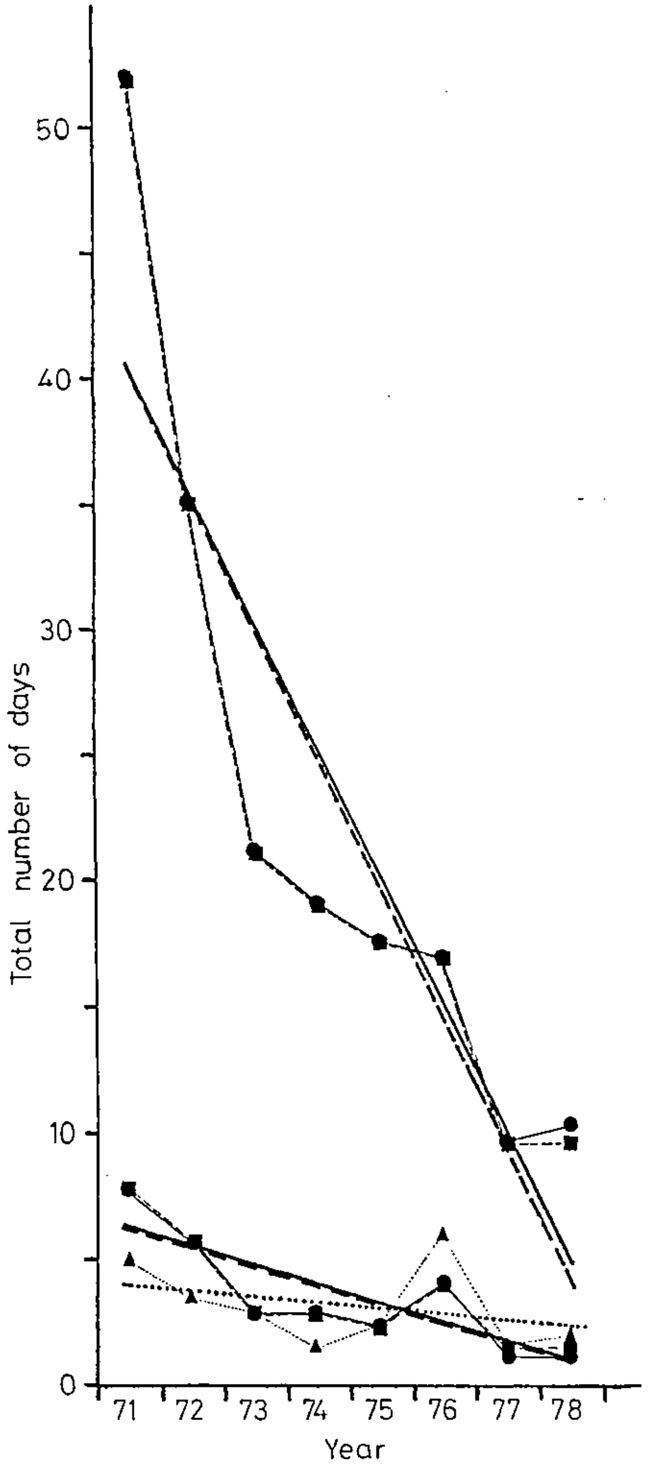


Figure 2.6 : Trends in daily mean SO_2 levels: ND 94 at urban, urban fringe and rural fringe sites.

●——● derived mean, ——— regression } urban and urban fringe
■– –■ arithmetic mean, – – – regression
▲······▲ derived mean = arithmetic mean } rural fringe
········ regression

Probability of slope of regression lines differing from zero: urban d.m., $p < 0.001$; urban a.m., $p < 0.001$; urban fringe d.m., $p < 0.01$; urban fringe a.m., $p < 0.01$; rural fringe d.m. = a.m., p=n.s.

Table 2.1 : Percent decrease in summer, winter and annual mean SO_2 levels, HD mean and ND 94 from 1968-9 to 1978-9 estimated from the regression lines of both the derived and arithmetic means.

	Derived mean				Arithmetic mean			
	Country	Rural fringe	Urban fringe	Urban	Country	Rural fringe	Urban fringe	Urban
summer mean	33	36	34	50	35	11(N.S.)(2)	28	43
winter mean	59	37	47	52	40	43	46	53
annual mean	30	8(N.S.)	37	53	40	39	37	50
HD mean(1)	52	43	48	57	49	43	53	57
ND 94(1)	N.C.(3)	43(N.S.)	85	88	N.C.	43(N.S.)	83	89

(1) HD mean and ND 94 only from 1971-2 onwards.

(2) N.S. = slope of regression line not significantly different from zero (all others significant at $p < 0.05$ or greater).

(3) N.C. = not calculated.

85% decrease over a seven year period). The remaining significant decreases vary from 28 to 59%, with urban sites showing, in general, only slightly greater percentage decreases than the other three types.

Inspection of Figures 2.1 to 2.6 suggests that in some cases there has been a slower rate of decline since about 1974 than during preceding years. This is particularly true for winter (urban, urban fringe and rural fringe) and urban (winter, HD mean, ND 94) trends. The use of linear regresssion analysis in these cases may not be justified.

Figure 1.1 shows that there was an approximately 15% decrease in SO_2 emissions from 1970 to 1979. The discrepancy between the 15% reduction in emissions and the observed 30 to 53% decrease in annual mean levels (Table 2.1) may be due to increased dispersion, either explained by meteorological factors (Schmidt & Velds, 1969) or to the tall stack policy.

Van Dop & Kruizinga (1976) studied SO_2 levels around Rotterdam for the winters of 1961-2 to 1973-4 (similarly to Schmidt & Velds, 1969, but for a longer period). They concluded that meteorological factors could only partly explain the 50% decline in SO_2 levels over the 13 year period and that a decline in emissions must have been involved. In the UK however, a decrease in emissions is known to have occurred but the work of these authors suggests that meteorological factors may also be important in the measured decrease in ambient levels.

If better dispersion occurs then it may seem reasonable to suggest that the SO_2 generated in or near urban areas would be transported to more rural areas, resulting in an increase in SO_2 levels in the latter, although this idea is not supported by the preceding analysis (e.g. Fig. 2.4). However, it was supported by a graph produced by WSL illustrating a slight increase in SO_2 levels at country sites in the north-west region of England from 1966-7 to 1969-70 (WSL, 1972-76, Vol. 2, p. 94, Fig. 7.3).

However, trends for the same region have been reanalysed using nine country sites (listed in Appendix 2). This analysis shows that there was an approximate 40% decrease in summer and winter SO_2 levels from 1969-70 to 1974-5, with little change thereafter (Fig. 2.7). This is essentially similar to the trends illustrated in Figures 2.1 to 2.4 for England and Wales as a whole.

If improved dispersion is a cause of lower SO_2 concentrations it appears that the SO_2 must be transported away from the UK landmass, rather than only from cities to more rural areas.

One other point that should be made is that the rural fringe and urban fringe sites used in the calculation of trends were, by chance, almost all in the north-west of England or around London; none were in the Midlands (an area in which many power stations are situated). However analysis of nine (mostly urban) fringe sites (listed in Appendix 2) in the Midlands showed very little difference from fringe sites elsewhere (Table 2.2).

As SO_2 levels in rural areas are of particular interest a more detailed analysis of the trends in SO_2 concentrations at country sites was carried out. Each of the sites used to produce the country trends (Figures 2.4 and 2.5) was classified by WSL into one of three categories:

02, completely open country; no sources within at least ¼ mile,
01, open country but not entirely without source(s) of pollution,
R, rural community.

Separate analysis of the three types of site shows that SO_2 trends and levels at the 01 and R sites are similar, but differ from those at 02 sites (Table 2.3). Generally, 02 sites show a lower SO_2 level than 01 or R sites, and show no or only slightly significant downward trends compared to highly significant decreases at 01 and R sites. Similarly, Bailey,

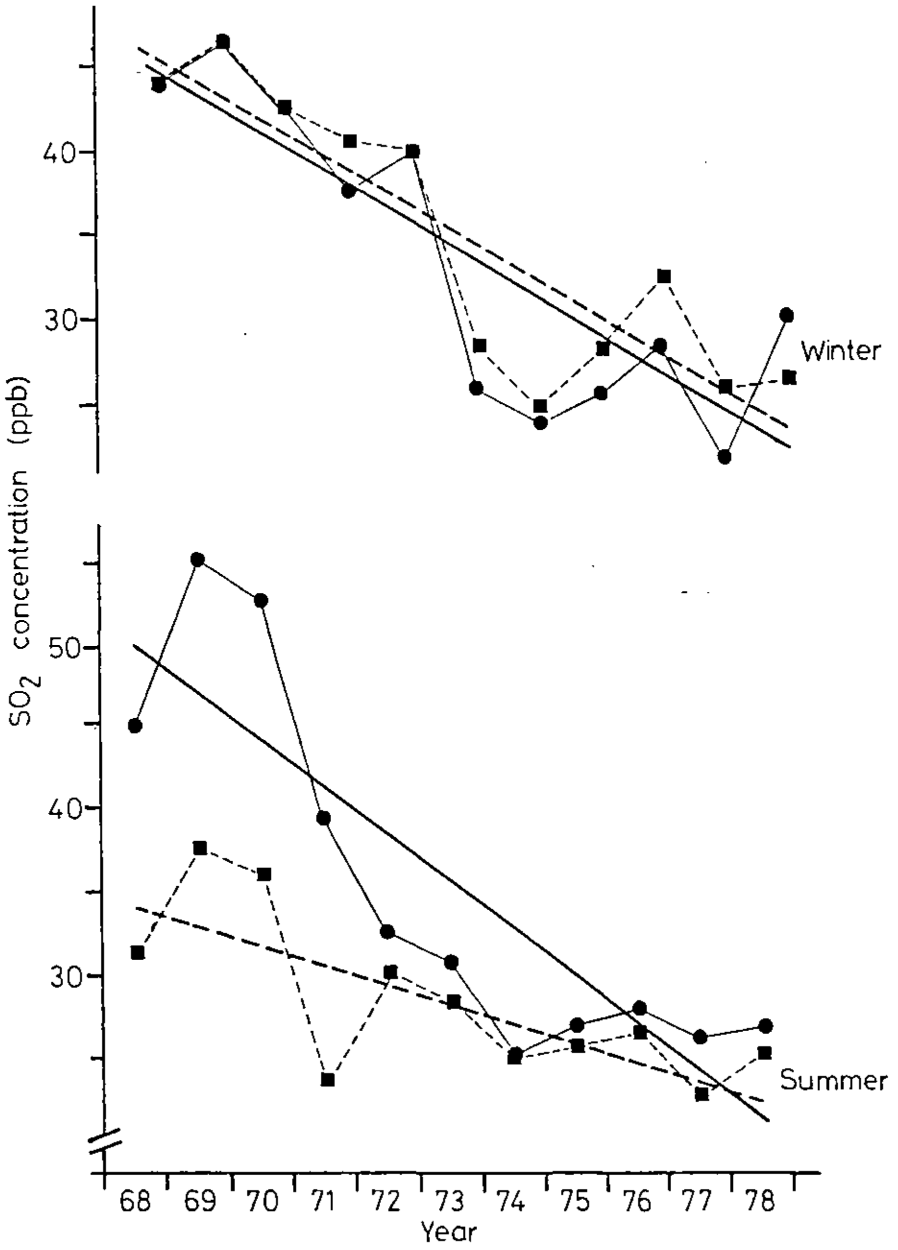


Figure 2.7 : Trends in daily mean SO_2 levels of north-west region country sites. Winter and summer derived and arithmetic mean concentrations with fitted regression lines.

●——● derived mean

■– –■ arithmetic mean

——— regression

– – – regression

Probability of the slope of each regression line differing from zero, winter d.m., $p < 0.001$; winter a.m., $p < 0.001$; summer d.m., $p < 0.001$; summer a.m., $p < 0.01$.

Table 2.2 : Comparison of the results from regression analyses on the arithmetic and derived mean trends for rural, urban and Midlands fringe sites.

	Derived means			Arithmetic means		
	Slope(1)	p(2)	Average(3) SO_2 (ppb)	Slope	p	Average SO_2 (ppb)
WINTER						
Rural fringe	-1.52	0.005	33	-1.79	0.001	32
Urban fringe	-2.11	0.001	34	-2.07	0.001	35
Midlands fringe	-1.75	0.001	33	-2.11	0.001	32
ANNUAL						
Rural fringe	-0.25	N.S.	29	-1.38	0.05	28
Urban fringe	-1.29	0.001	29	-1.30	0.001	29
Midlands fringe	-1.00	0.001	28	-1.52	0.001	27
SUMMER						
Rural fringe	-1.23	0.005	28	-0.29	N.S.	25
Urban fringe	-0.97	0.005	23	-0.75	0.005	23
Midlands fringe	-0.54	0.001	23	-0.72	0.001	22

(1) 'Slope' refers to the slope of the regression line and is equivalent to the change in SO_2 levels (ppb) from one year to the following year.

(2) 'p' is the probability that the slope differs from zero; N.S. = not significant at p = 0.05.

(3) The average SO_2 concentration (ppb) over the period 1968-9 to 1978-9.

Table 2.3 : Results of regression analyses on the arithmetic and derived mean trends for 02, 01 and R sites (see text for definitions).

	Derived means			Arithmetic means		
	Slope(1)	p(2)	Average(3) SO_2 (ppb)	Slope	p	Average SO_2 (ppb)
WINTER						
02	-0.47	0.05	14	-0.47	N.S.	13
01	-1.25	0.001	20	-1.24	0.001	19
R	-1.79	0.001	11	-0.63	0.001	17
ANNUAL						
02	-0.05	N.S.	14	-0.40	N.S.	12
01	-0.68	0.001	16	-1.25	0.001	18
R	-0.83	0.001	17	-0.44	0.05	15
SUMMER						
02	0.00	N.S.	12	-0.10	N.S.	11
01	-0.42	0.005	14	-0.92	0.001	16
R	-0.92	0.001	16	-0.39	0.05	12
HD mean						
02	-2.17	0.05	49	-2.28	0.05	52
01	-5.53	0.001	77	-5.38	0.001	77
R	-3.75	0.005	64	-3.98	0.005	66

(1) to (3) See Table 2.2

Barrett & Cooper (1978), found no trend in SO_2 levels at 02 sites from 1964-5 to 1974-5. It is clear that the observed trends in country SO_2 levels are not found at remote sites and therefore perhaps the 02 sites should not have been included in the country trend determinations.

At country sites there appears to be very little annual variation in SO_2 concentration (Fig. 2.4, Table 2.3): this is possibly an artefact of measurement by the method used in the WSL National Survey. Bailey *et al.* (1978), comparing the hydrogen peroxide bubblers used by WSL with more sophisticated bubblers (modified from an European Air Chemistry Network sampler), showed that the WSL type of bubblers at remote (02) sites overestimated SO_2 by about 6 ppb in summer and by 3 ppb in winter. This would have the effect of bringing measured summer SO_2 levels nearer to those in winter. However, these potential errors in measurement were not taken into account during the calculation of any of the trends as they were not available for all site types. Therefore it should be noted that the SO_2 levels in Figure 2.4 and Table 2.3 for country sites are probably overestimated, particularly in summer. (This may represent a 50% overestimate for 02 summer mean values in the late 1970's.) At sites with higher levels of SO_2 a similar absolute error would be less important.

Conclusions

Over the decade from 1969 to 1979 annual mean concentrations of SO_2 in urban areas have declined by about 50% (from 70 to 35 ppb) but this has not resulted in an increase in concentrations in surrounding areas. Indeed there has been a decline of 30-40% in annual mean SO_2 levels at fringe and country sites (other than at remote country (02) sites, which show no significant trends). The mean highest daily concentrations were approximately halved to 150, 90 and 50 ppb at urban, fringe and country sites, respectively. The number of days with a mean SO_2 concentration in excess of 94 ppb has fallen dramatically at urban and urban fringe sites, but no change was found at rural fringe sites. Country sites experienced effectively no days with a mean greater than 94 ppb SO_2 over the period concerned.

2.1.2 SO_2 concentrations in rural areas

The WSL National Survey has most of its sites situated in urban areas. Sites in country areas are relatively few and suffer from the limitation/ inaccuracy of the hydrogen peroxide method mentioned above. WSL make no attempts on their maps of winter SO_2 concentrations to subdivide areas with means less than 19 ppb. As an alternative, knowledge of concentrations away from urban areas can be based on predictions made by dispersion models. Martin (1980) used a dispersion model based on a source inventory to calculate SO_2 levels at rural sites in the UK. The resulting map is shown in Figure 2.8 (on which are included areas with a winter mean of greater than 38 ppb for comparison). Checking this model against recent specific measurements of SO_2 at 20 open-country sites produced good agreement (Martin, 1980).

2.2 Cumulative Frequency Distributions of SO_2

2.2.1 WSL daily means

The most recent WSL National Survey reports (1980 et seq.) include cumulative frequency distributions (cfd's) of the daily mean SO_2 concentrations at each site. Some examples from urban, fringe and country sites are shown in Figures 2.9 to 2.11 respectively.

A straight line on log x probability axes indicates a log-normal distribution. At both urban and fringe sites (Figs. 2.9 and 2.10) the cfd's fit this distribution well over most of their ranges. At country

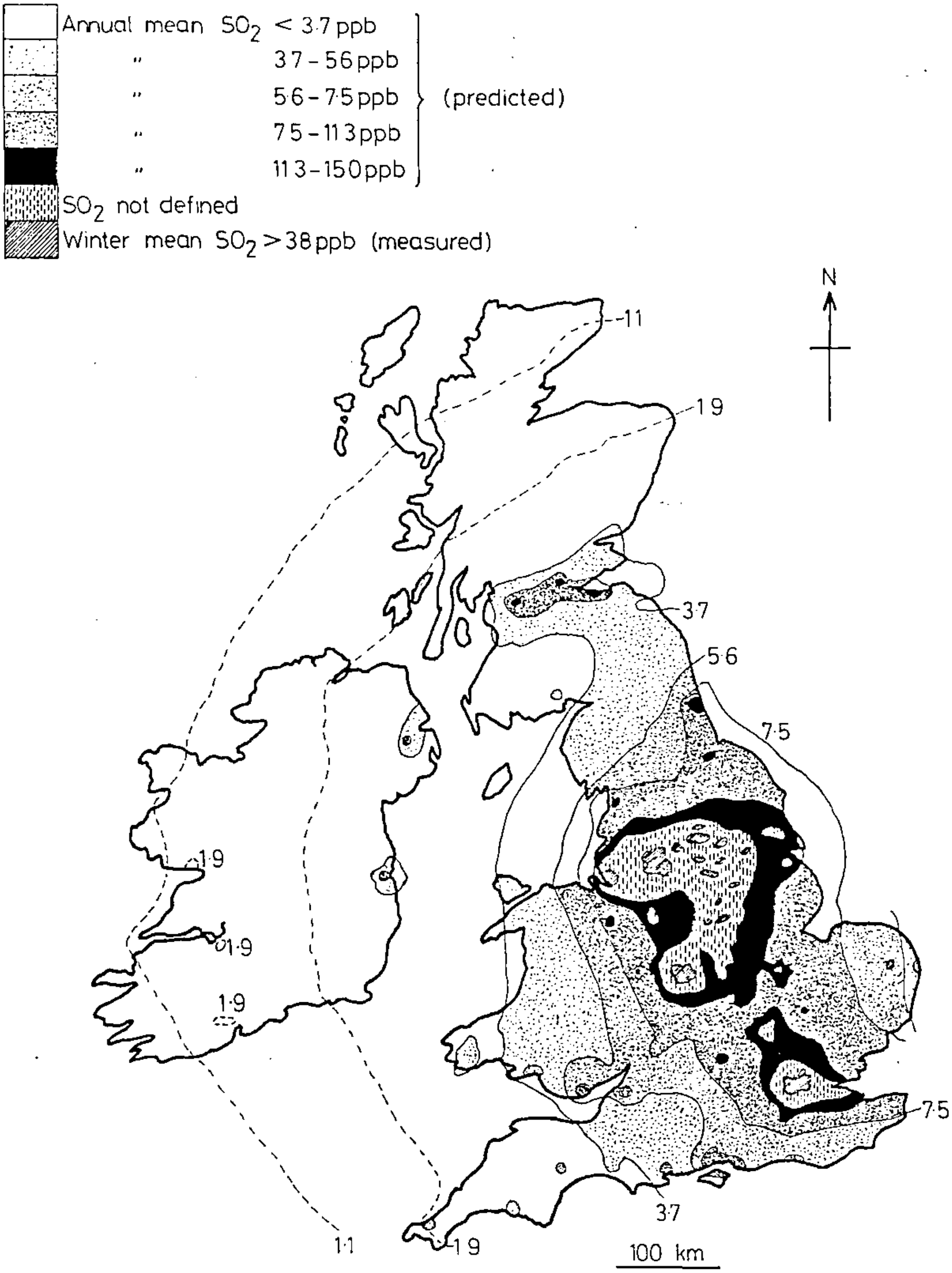


Figure 2.8 : Contours of annual SO_2 concentrations (ppb) predicted by model for rural sites at least 100 m from single house, 1 km from village, 10 km from town. (Redrawn from Martin, 1980) Also included are areas with winter mean SO_2 > 38 ppb from WSL map for 1975-76.

Figure 2.9 : Cumulative frequency distributions of daily mean SO_2 concentrations at some urban sites for April 1978-March 1979. Data from WSL National Survey (1980).

——— West Bromwich 12

— — — Manchester 11

·········· Manchester 19

—·—·— Camberwell 5

—··—··— Kensington 8

+++++ Kew 1

Figure 2.10 : Cumulative frequency distributions of daily mean SO_2 concentrations at some fringe sites for April 1978-March 1979. Data from WSL National Survey (1980).

——— Bolton 18

— — — Halton, Runcorn 1

·········· Kingsnorth 12

—·—·— Atherton 5

—··—··— Cardiff 13

+++++ Walsall 16

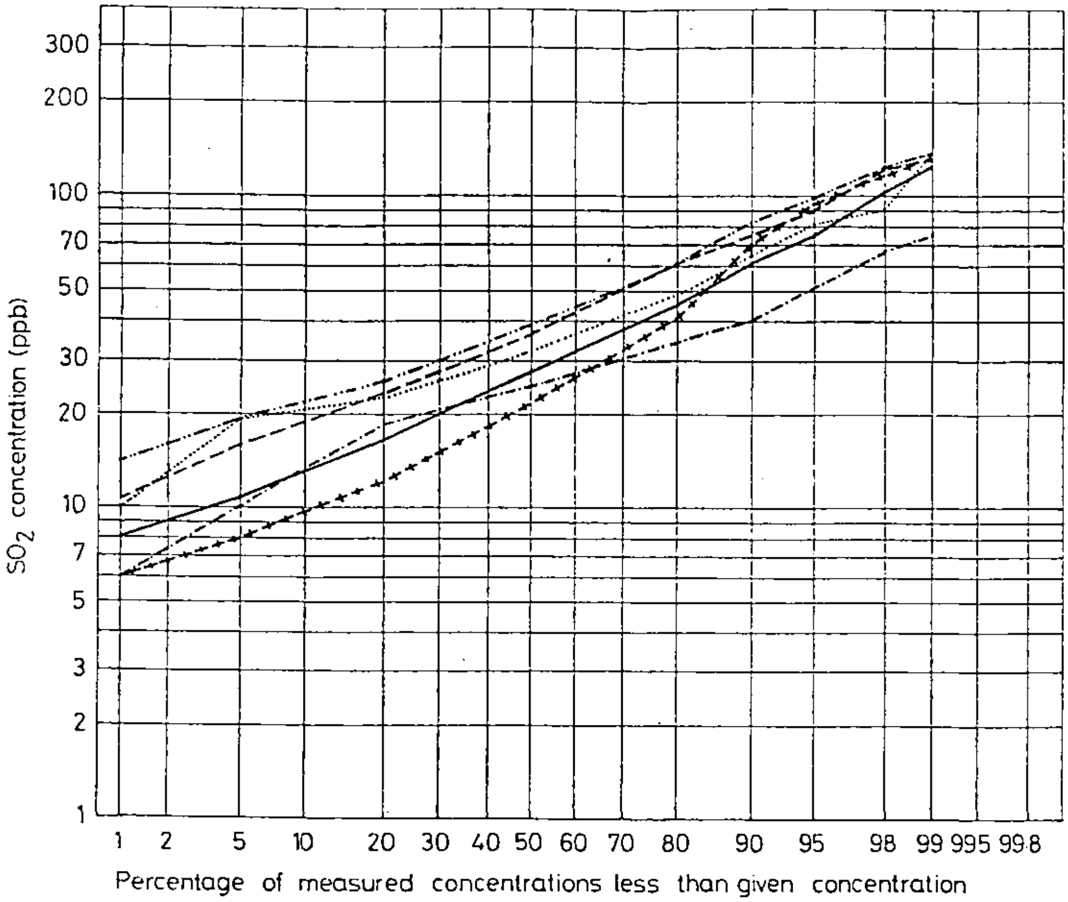


Fig. 2·9

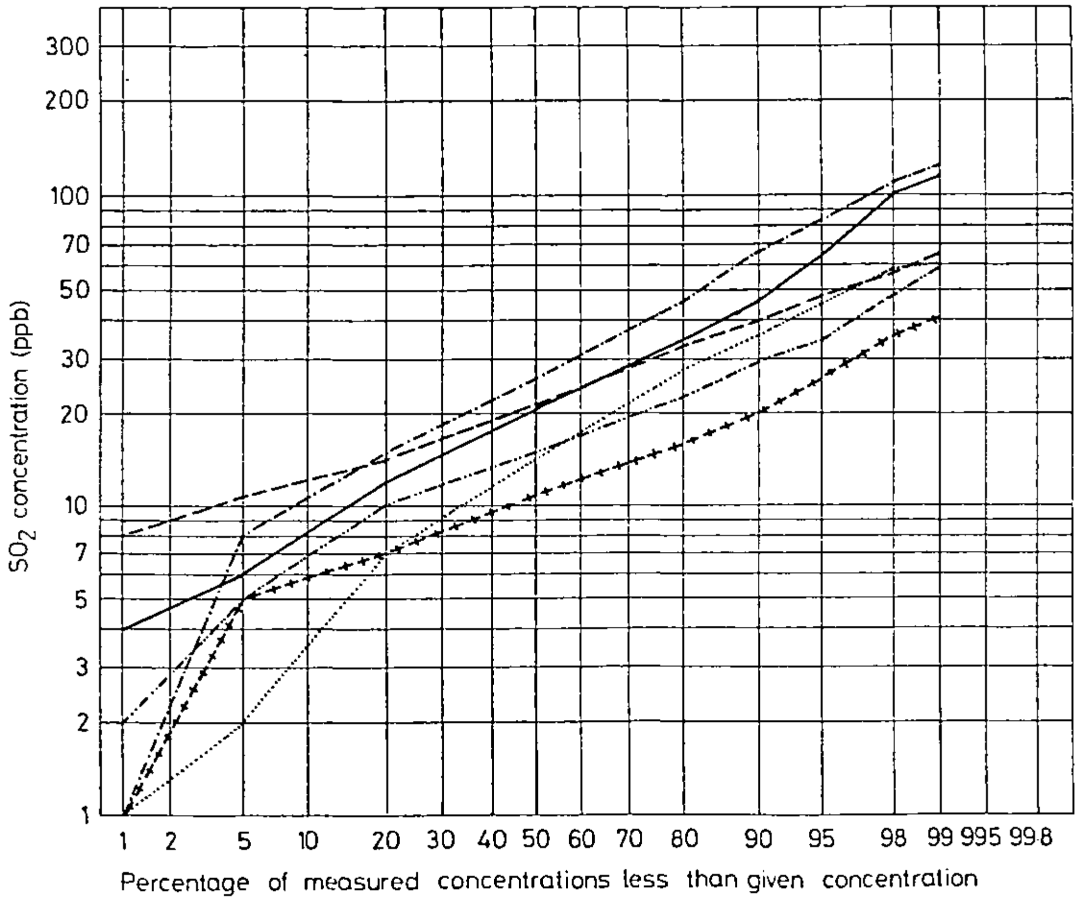


Fig. 2·10

Figure 2.11 : Cumulative frequency distributions of daily mean SO_2 concentrations at some country sites for April 1978-March 1979. Data from WSL National Survey (1980).

——— Kirkby Underwood 1

— — – Kelvedon Hatch 1

………… Burton 2

—·—·— Helmshore 1

—··—··— Cottam 27

+++++ Didcot 1

Figure 2.12 : Average cumulative frequency distributions of daily mean SO_2 concentrations at urban, fringe and country sites (geometric means of each percentile of the cfd's used in the construction of Figs. 2.9-2.11).

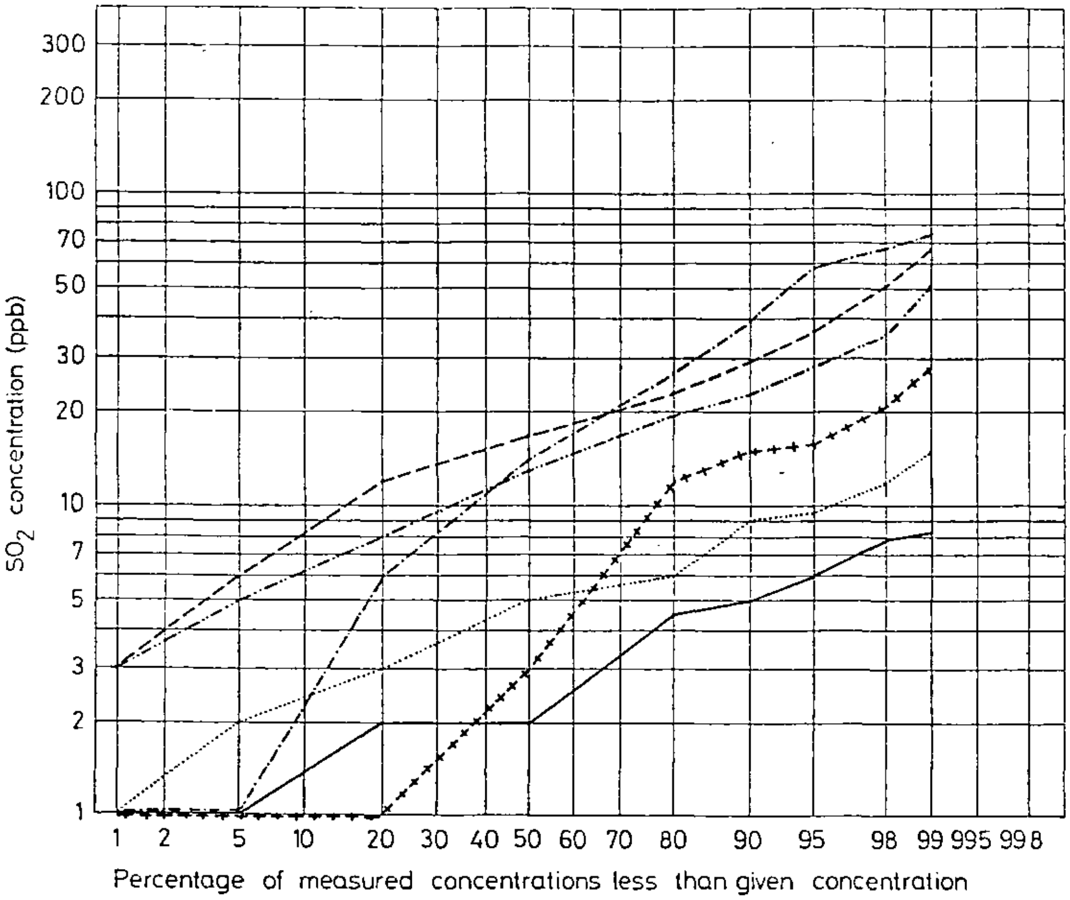


Fig. 2·11

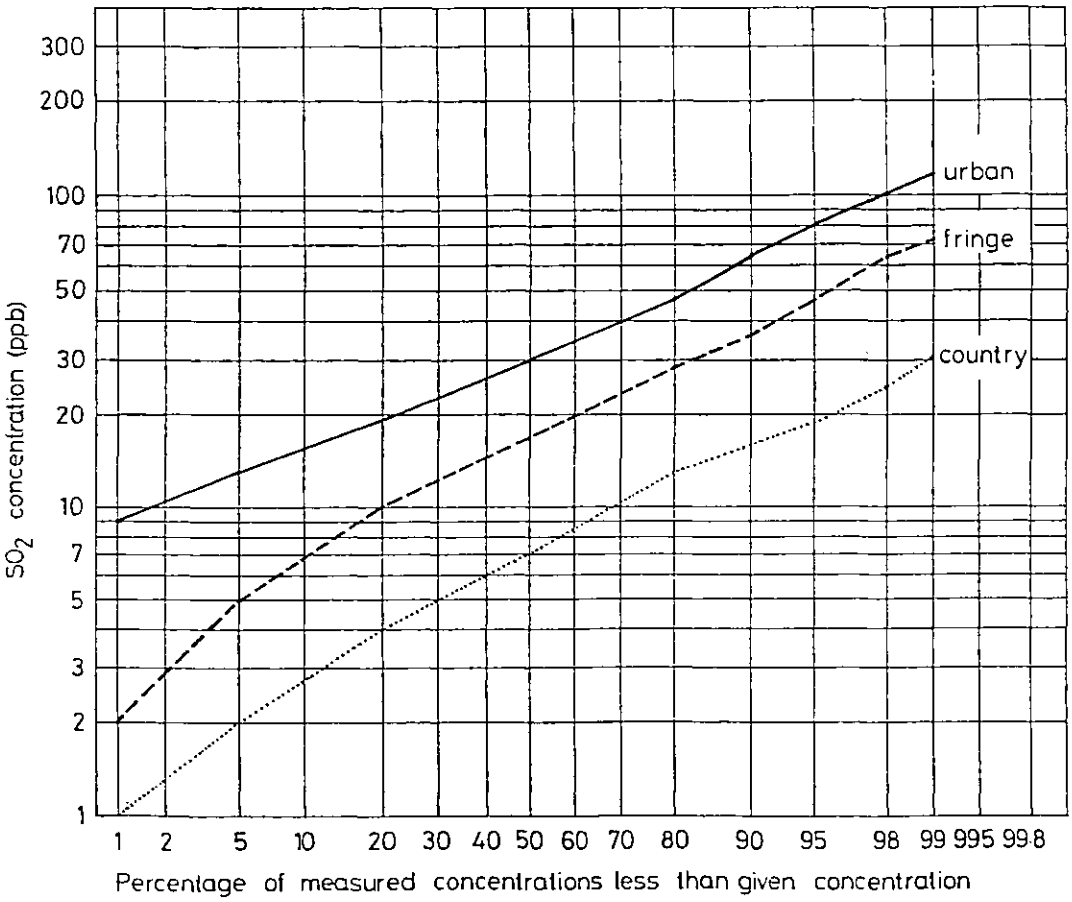


Fig. 2·12

sites (Fig. 2.11) the fit is less good, especially when the concentration falls below about 10 ppb. This may be an accurate reflection of the situation or instrument error resulting in an underestimate of SO_2 levels at low concentrations.

Figure 2.12 shows the average cfd for each site type calculated as the geometric mean of each percentile used in Figures 2.9 to 2.11. The cfd's are all approximately linear and have similar slopes. This is of particular interest when attempting to generalise about SO_2 levels over the UK since it means that the cfd's of daily mean concentrations at sites throughout the UK are approximately related to the geometric mean (= 50 percentile of a true log-normal distribution) at each site. From an experimental point of view, a range of SO_2 cfd's can be simulated by multiplying a typical cfd by suitable factors. This will be referred to again in Chapter 4 as it formed part of the experimental design.

2.2.2 Hourly mean cumulative frequency distributions

The data from the WSL national Survey constitute the most comprehensive information on SO_2 cfd's throughout the UK. However, there have been several other studies which have produced SO_2 cfd's. These studies have based their cfd's on various averaging times from 10 minutes (Nicholson, Kinnaird & Paterson, 1980) to 1 week (Cox, Derwent & Sandalls, 1976). This complicates comparison of results because the standard geometric deviation (≡ slope of a straight line on log x probability axes) decreases with increasing averaging time (see Larsen, Zimmer, Lynn & Blemel, 1967, for a practical example). The most common averaging time used is one hour, and since this averaging time was used in an experimental design (see Chapter 5), this discussion will be confined to studies using a one hour averaging time.

A summary of some data from 6 sites in the UK is shown in Table 2.4

Table 2.4 : Descriptive statistics for SO_2 hourly mean concentrations at several sites in the UK.

Location and date of survey	SO_2 concentration (ppb)					Reference
	arithmetic mean	exceeded for			maximum	
		50%	10%	1%		
LONDON: kerbside summer 1975 (all hours)	50(1)	37	120	350	-	Williams, Perry, McInnes, Spanton and Tsani-Bazaca (1980)
LONDON: off-street summer 1975 (all hours)	50(1)	40	100	270	-	"
LONDON: roof-top 1 Jan.-31 Mar. 1979	45	35	90	166	232	calculated from data supplied by the GLC
STEVENAGE: N of London Apr.-Sept. 1978	15	12	27	49	102	Apling, Dorling, Lilley, Rogers and Stevenson (1981)
BOTTESFORD: Midlands Jan. 1978-Dec. 1979	12	-	-	50	369	Martin and Barber (1981)
HEYSHAM: NW England May-Sept. 1977	7	4	19	45	70	Harrison and McCartney (1980)

(1) estimated from 63rd percentile.

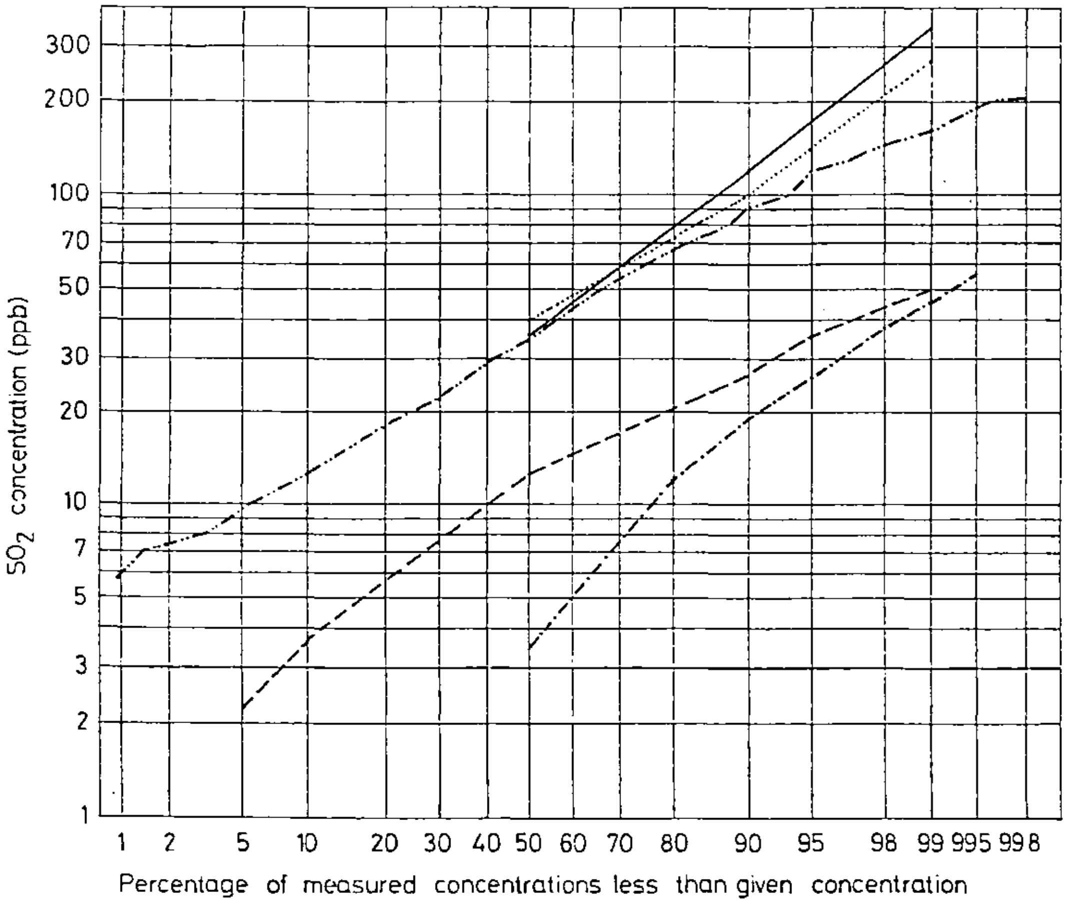


Figure 2.13 : Cumulative frequency distributions of hourly mean SO_2 concentrations at five sites in the UK.

——— London, kerbside: summer 1975 (Williams *et al.*, 1980).

········ London, off-street: summer 1975 (Williams *et al.*, 1980).

–··–··– London, roof top: 1 January-31 March 1979 (calculated from data supplied by the GLC).

– – – Stevenage, N. of London: April-September 1980 (Apling, Dorling, Lilley, Rogers & Stevenson, 1981).

–·–·– Heysham, NW England: May-September 1977 (Harrison & McCartney, 1980).

and data from five of these are illustrated in Figure 2.13. Hourly means of SO_2 exceeded about twice the long-term mean for 10% of the time, and 1% were 3-7 times the mean. Maximum concentrations have been recorded 5-30 times the long-term mean. From Figure 2.13 it is clear that the cfd's are approximately log-normal, although at the two more rural sites the cfd's are slightly curved, indicating departure from log-normality. This is similar to the situation shown by the WSL daily mean cfd's (Figs. 2.9-2.12).

The data listed as 'London: roof-top' were supplied by the Greater London Council, Scientific Branch, as hourly means. These data, from a sampling point on the roof of County Hall in central London, included means for NO, NO_2 and NO_x and have been extensively analysed here in an attempt to characterise pollutants in central London and for comparison with published accounts. Subsequently these data are referred to simply as the 'GLC data'.

2.3 NO_x: Long-Term Trends, Means and Cumulative Frequency Distributions

There have been few studies of temporal trends in ground-level concentrations of NO_x in the UK, but total emissions appear to have been fairly constant at around 2 mt per annum from 1970 to 1979 (Fig. 1.1). Studies by WSL of NO at a London kerbside and of NO and NO_2 levels at an off-street site from 1972 to 1977 (Apling, Potter & Williams, 1979) and of NO and NO_2 at several sites in and around London from 1972 to 1980 (Apling, Rogers & Stevenson, 1981) show no evidence for any trends.

There are no data on NO_x levels comparable to the WSL National Survey data for SO_2. All available information is from relatively small-scale studies carried out in several parts of the UK, of which the most comprehensive is by Apling, Rogers & Stevenson (1981). A summary of some of their data is given in Table 2.5, along with data from four other studies. At non-roadside sites mean concentrations of NO range from less than 2 to

Table 2.5 : Descriptive statistics for NO_2 and NO hourly mean concentrations at several sites in the UK.

Location and date of survey	NO_2 concentration (ppb)					NO concentration (ppb)					Reference
	arithmetic mean	exceeded for				arithmetic mean	exceeded for				
		50%	10%	1%	maximum		50%	10%	1%	maximum	
CENTRAL LONDON: Cromwell Rd., kerbside Jan. 1976-Feb. 1980	41	37	68	123	-	137	94	307	656	-	Apling, Rogers and Stevenson (1981)
CENTRAL LONDON: WSL laboratory(1) Jan. 1972-Mar. 1980	39	37	57	86	-	51	37	105	260	-	"
CENTRAL LONDON: Islington July 1976-Sept. 1978	26	24	44	74	-	28	15	60	183	-	"
CENTRAL LONDON: roof-top, County Hall 1 Jan.-31 Mar. 1979	26	25	36	62	220	29	19	64	138	474	calculated from data supplied by the GLC
OUTER LONDON: Harrow Aug. 1978-Sept. 1980	21	19	39	64	-	27	15	64	214	-	Apling, Rogers and Stevenson (1981)
STEVENAGE: N of London Apr. 1977-Sept. 1980	22	20	38	64	-	31	18	64	227	-	"
GATWICK AIRPORT: Feb.-June 1979	23	20	35	51	81	18	9	34	133	~350	Williams *et al.* (1980)
CANVEY ISLAND: E of London Sept. 1977-Aug. 1980	17	14	31	53	-	15	6	35	147	-	Apling, Rogers and Stevenson (1981)
HEYSHAM: rural NW England(2) July-Nov. 1974	10	8	22	38	~50	<2	usually near limit of detection				Harrison and McCartney (1980)
BOTTESFORD: rural Midlands Jan. 1978-Dec. 1979	9	-	-	-	137	8	-	-	50	123	Martin and Barber (1981)
SIBTON: rural East Anglia May 1977-Nov. 1979	7	5	14	29	-	3	2	6	16	-	Apling, Rogers and Stevenson (1981)

(1) NO_2 from July 1976.

(2) The influence of a local fertiliser works on ambient air quality had been eliminated from the data.

51 ppb (137 ppb at the roadside site) and those of NO_2 from 7 to 39 ppb (41 ppb at the roadside). Hourly mean concentrations of NO_2 in excess of 1.5-2 times the long-term mean occur for 10% of the time, and 1% of hourly means exceed only about 3 times the mean. NO is more variable, with 10% of hours exceeding twice and 1% exceeding 5-10 times the mean. Maximum hourly mean concentrations of NO or NO_2 may be more than 15 times the long-term mean.

From the limited amount of data available it appears that winter: summer ratios for NO_2 vary according to site type. The ratio is about 1.5:1 in rural areas and about 1.3:1 in fringe and urban areas other than central London where the ratio is about 0.9:1 (Martin & Barber, 1981; Apling, Rogers & Stevenson, 1981; Apling, Dorling, Rogers, Williams & Stevenson, 1981).

Vehicle emissions are a major source of NO (Apling *et al.*, 1979) and therefore NO concentrations may be expected to be high at roadside sites. The mean NO concentration at the kerbside of Cromwell Road (a major road near central London with a high traffic flow) is 137 ppb but NO_2 is only 41 ppb. At the other central London sites NO and NO_2 concentrations are similar to each other. Also, the NO_2 concentrations at all the central London sites, including Cromwell Road, are similar: it is only NO that is greatly increased at the roadside (Table 2.5) (see also Apling *et al.*, 1979).

At two of the rural sites (Heysham and Sibton) NO_2 concentrations are much greater than NO. Both these sites are essentially remote from large urban areas, although Heysham is influenced both by local towns and by long-distance transport of pollutants (Harrison & McCartney, 1980); the latter also influences Sibton (Apling, Rogers & Stevenson, 1981). Since most NO_x is generated in urban areas as NO, and at low concentrations NO is only slowly oxidised to NO_2 in the atmosphere, then in/near urban areas one may expect a large proportion of NO_x to be NO. As a 'pollution cloud' moves away from an urban area (and therefore as duration in the atmosphere increases) the proportion of NO_2 will increase. This may explain the high NO_2:NO ratio at rural sites. On the other hand NO and NO_2 concentrations are approximately equal at Bottesford which is also described as a rural site (Martin & Barber, 1981) but is presumably affected by its situation in the Midlands (20 km east of Nottingham).

Figure 2.14 illustrates cumulative frequency distributions of NO and NO_2 at three of the sites in Table 2.5: two in London (kerbside and rooftop) and one at Sibton in rural East Anglia. Similarly to SO_2, the cfd's are approximately log-normal. As mentioned above, NO can be seen to vary more than NO_2, particularly at the London sites.

2.4 Comparison of SO_2, NO, NO_2 and NO_x Concentrations

In view of recent work which showed severe effects of mixtures of SO_2 and NO_2 on the growth of several grass species (Ashenden & Mansfield, 1978; Ashenden, 1979b; Ashenden & Williams, 1980; Davies, 1980b) it is important to consider the proportions of SO_2 and NO_2 found in ambient UK air. Table 2.6 lists long-term mean concentrations of SO_2, NO_2, NO and NO_x at several sites in the UK. In all cases NO_x exceeds or equals SO_2. As discussed in the previous section NO concentrations vary in their proportion to SO_2 (at least partly according to distance from major NO_x sources). NO_2 concentrations are about 30% less than SO_2 at five sites but exceed SO_2 by about 50% at Stevenage and Heysham. Apling (quoted in Fowler & Cape, 1982) estimated that the ratio of SO_2:NO_2 in rural areas of the UK was 1:0.8 on a w/w basis; on a v/v basis (as in Table 2.6) this is equivalent to 1 ppb SO_2:1.1 ppb NO_2. In view of the small amount of

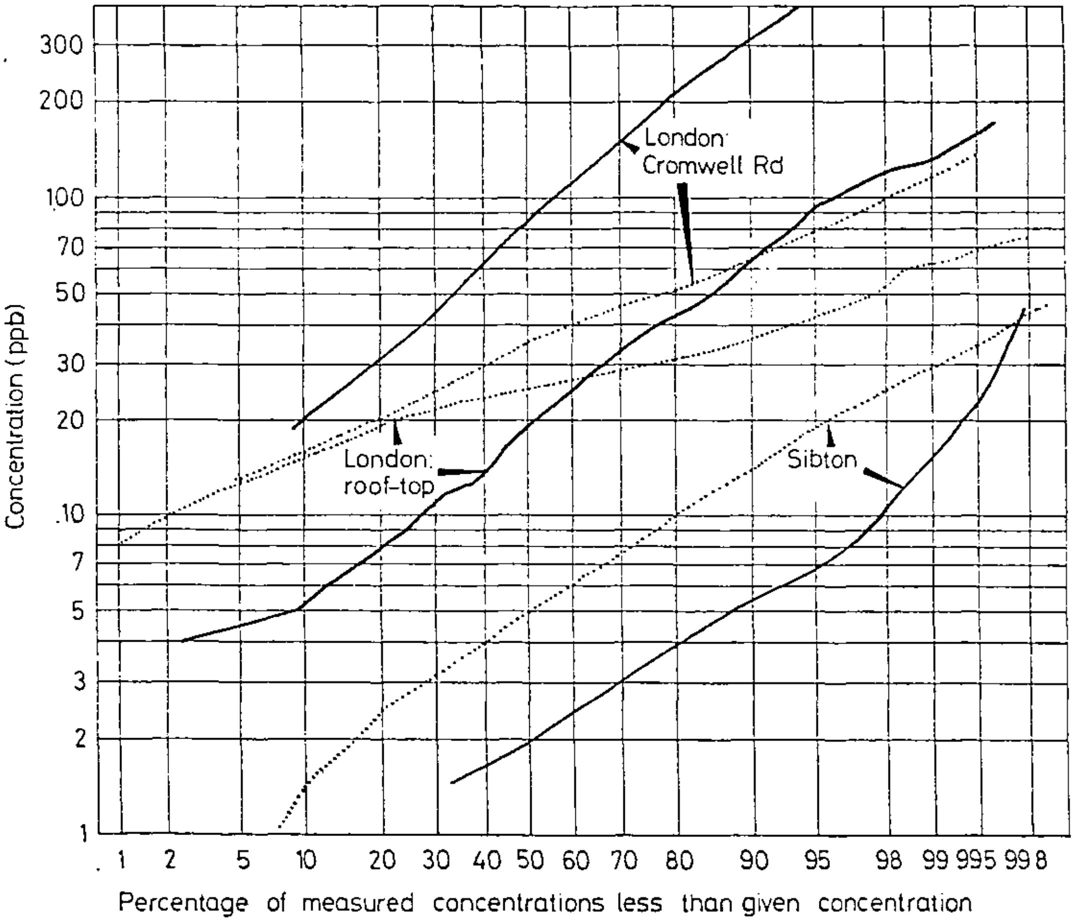


Figure 2.14 : Cumulative frequency distributions of hourly mean concentrations of NO (——) and NO_2 (┄┄) at 3 sites. Data sources are given in Table 2.5.

Table 2.6 : Arithmetic mean concentrations of SO_2, NO, NO_2 and NO_x at several sites in the UK.

Location and date of survey	Mean concentration (ppb)				Reference
	SO_2	NO	NO_2	NO_x	
LONDON: kerbside 1974-1975 (working week)(1)	50(2)	78(2)	34(3)	112	Apling, Potter and Williams (1979)
LONDON: off-street 1974-1975 (working week)(1)	50(2)	38(2)	34	72	"
LONDON: roof-top 1 Jan.-31 Mar. 1979	45	29	26	52	calculated from data supplied by the GLC
STEVENAGE: N of London Apr. 1977-Sept. 1978	15	29	23	52	Apling, Dorling, Lilley, Rogers and Stevenson (1981)
BOTTESFORD: Midlands Jan. 1978-Dec. 1979	12	8	9	17	Martin and Barber (1981)
HEYSHAM: NW England May-Sept. 1977	7	<2	10	~12	Harrison and McCartney (1979)
HARWELL: S England May 1973-July 1974	8	2	6	8	Cox, Derwent and Sandalls (1976)
DEVILLA: Central Scotland Jan.-Dec. 1978	~7	-	-	~16	Nicholson, Fowler, Paterson, Cape and Kinnaird (1980)

(1) SO_2 sample period was summer 1975 all hours. (2) Estimated from 63rd percentile. (3) Estimated from 57th percentile.

available data on NO_2 levels the only conclusion that can be drawn is that NO_2 and SO_2 concentrations are similar on a v/v basis.

In comparison, the emissions of SO_2 are about 2.5 times greater than those of total NO_x (Fig. 1.1). Fowler & Cape (1982) suggested that one of the reasons for the difference between the ratios of emissions and observed concentrations may be a longer residence time in the atmosphere for NO_2, due to smaller deposition velocities and less efficient scavenging by rain of NO_2 than SO_2.

The discussion above has considered ratios between long-term means but it is also important to consider the subject on a short-term basis. Nicholson *et al.* (1980) gave correlation coefficients for ten-minute means of pollutants at Devilla, central Scotland: for SO_2 and NO_x $r = 0.58$; for SO_2 and NO $r = 0.51$; for O_3 and NO_x $r = -0.50$ and for O_3 and NO $r = -0.37$. The correlation coefficients are all fairly low (although highly significant) and in the absence of further information no conclusions can be drawn.

An informative type of analysis is that carried out by Docherty (1974) around a small industrial area in north-west England. Daily means of SO_2 and NO_2 were measured over 2.5 years and tabulated against each other. For example, there were 15 days when the daily mean SO_2 concentration exceeded 94 ppb and 51 days when NO_2 exceeded 104 ppb, but on no occasion did this occur simultaneously. This was explained by the fact that the major sources of NO_2 and SO_2 were separate and some distance apart. If the pollutants were emitted from the same source then one would expect the SO_2 and NO_2 levels to peak simultaneously.

An analysis of the GLC hourly mean data for central London was carried out similarly to Docherty (1974) (except that hourly rather than daily means were used). Figure 2.15a shows, for 9 concentration categories

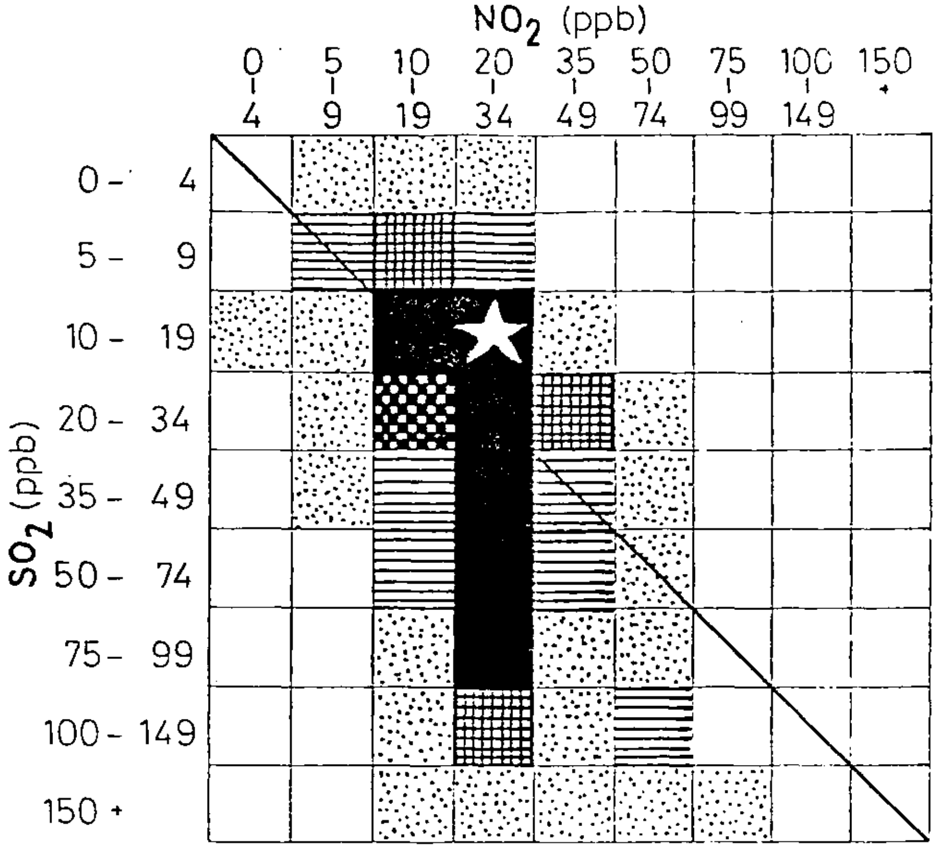
Figure 2.15 : Correlation of hourly mean concentrations of SO_2 with NO_2 (a) and SO_2 with NO (b). Central London, roof-top, 1 January-31 March 1979. (Calculated from GLC data)

The diagonal lines represent 1:1 correlation.

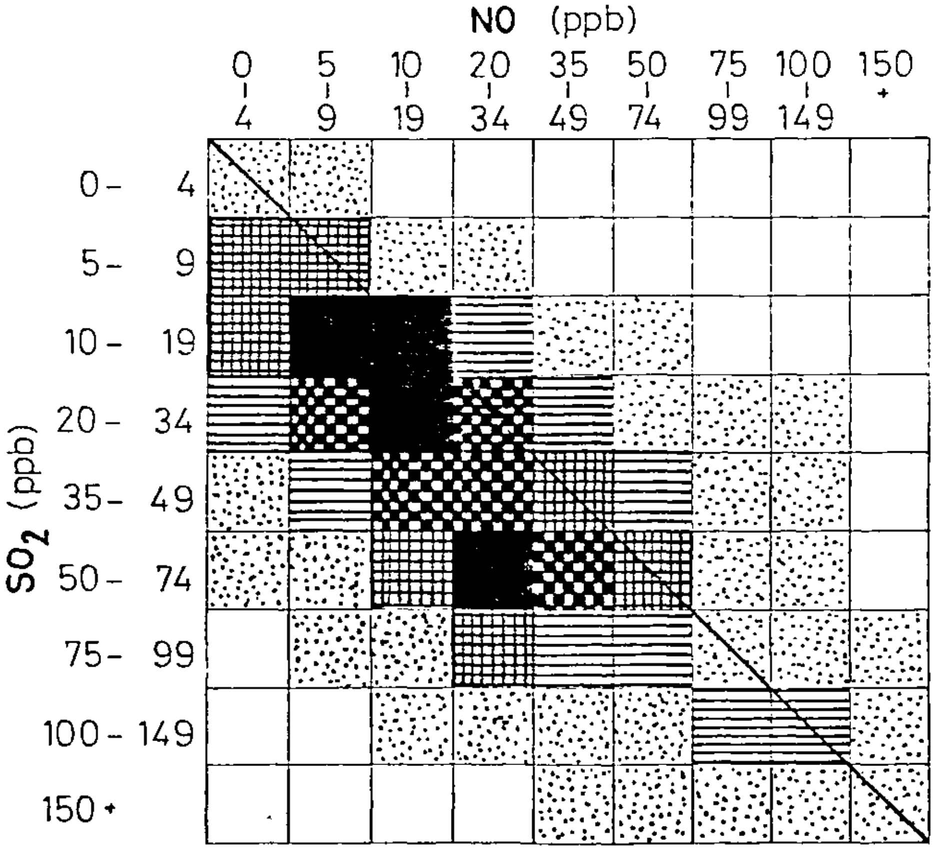
Individual squares represent the percentage of total hours in each combination of concentrations.

	%
☐	0
░	0 < – ≤ 1
▤	1 < – ≤ 2
▦	2 < – ≤ 4
▩	4 < – ≤ 6
■	6 <

For example the ★ indicates that for > 6% of hours SO_2 was 10-19 ppb and NO_2 was 20-34 ppb.


NO2 (ppb)
0-4
5-9
10-19
20-34
35-49
50-74
75-99
100-149
150+
SO2 (ppb)
0- 4
5- 9
10- 19
20- 34
35- 49
50- 74
75- 99
100- 149
150+

(a)


NO (ppb)
0-4
5-9
10-19
20-34
35-49
50-74
75-99
100-149
150+
SO2 (ppb)
0- 4
5- 9
10- 19
20- 34
35- 49
50- 74
75- 99
100- 149
150+

(b)

of SO_2 and NO_2, the percentage of hours in which the 81 possible concentrations of SO_2 and NO_2 occurred. (An example is given in the Figure legend.) Figure 2.15b is similar but for SO_2 and NO. Concentrations of NO_2 are generally independant of SO_2, e.g. a large proportion of NO_2 hourly means are in the range 20-34 ppb, and when NO_2 is in this range SO_2 concentrations may be anywhere between 0 and 150 ppb, although more probably between 10 and 100 ppb (Fig. 2.15a). SO_2 is more closely correlated with NO (Fig. 2.15b) than NO_2: as the measured SO_2 concentration increases then the expected NO concentration also increases. However, correlation is not good, and for any given SO_2 (or NO) concentration any one of a wide range of NO (or SO_2) concentrations may be present at the same time.

2.5 Ozone: Long-Term Trends and Area Means

Ozone is unusual among air pollutants in the UK in that the natural background level is 20-50 ppb, compared with less than 2 ppb for SO_2 and NO_x (Cox, 1977; Cox *et al.*, 1976). Formation of O_3 by photochemical processes is briefly described in Appendix 1, where it is also pointed out that concentrations of O_3 formed in this way are at least partly dependent upon sunlight and therefore the weather. It is generally acknowledged that the most useful expression of O_3 levels over a long time period is the number of days on which it exceeds a certain level, often 80 or 100 ppb. The assumptions being that if it does not exceed this level, then although the O_3 is not necessarily natural it is not present in high enough concentrations to reduce plant growth.

Due to its association with the weather, ozone is a summer pollutant in the UK. Table 2.7 lists, for several UK sites, the number of days per summer having peak O_3 levels in excess of 80 and 100 ppb. It is evident

Table 2.7 : Number of days each summer having the specified peak hourly ozone concentration (expanded from Martin & Barber, 1981).

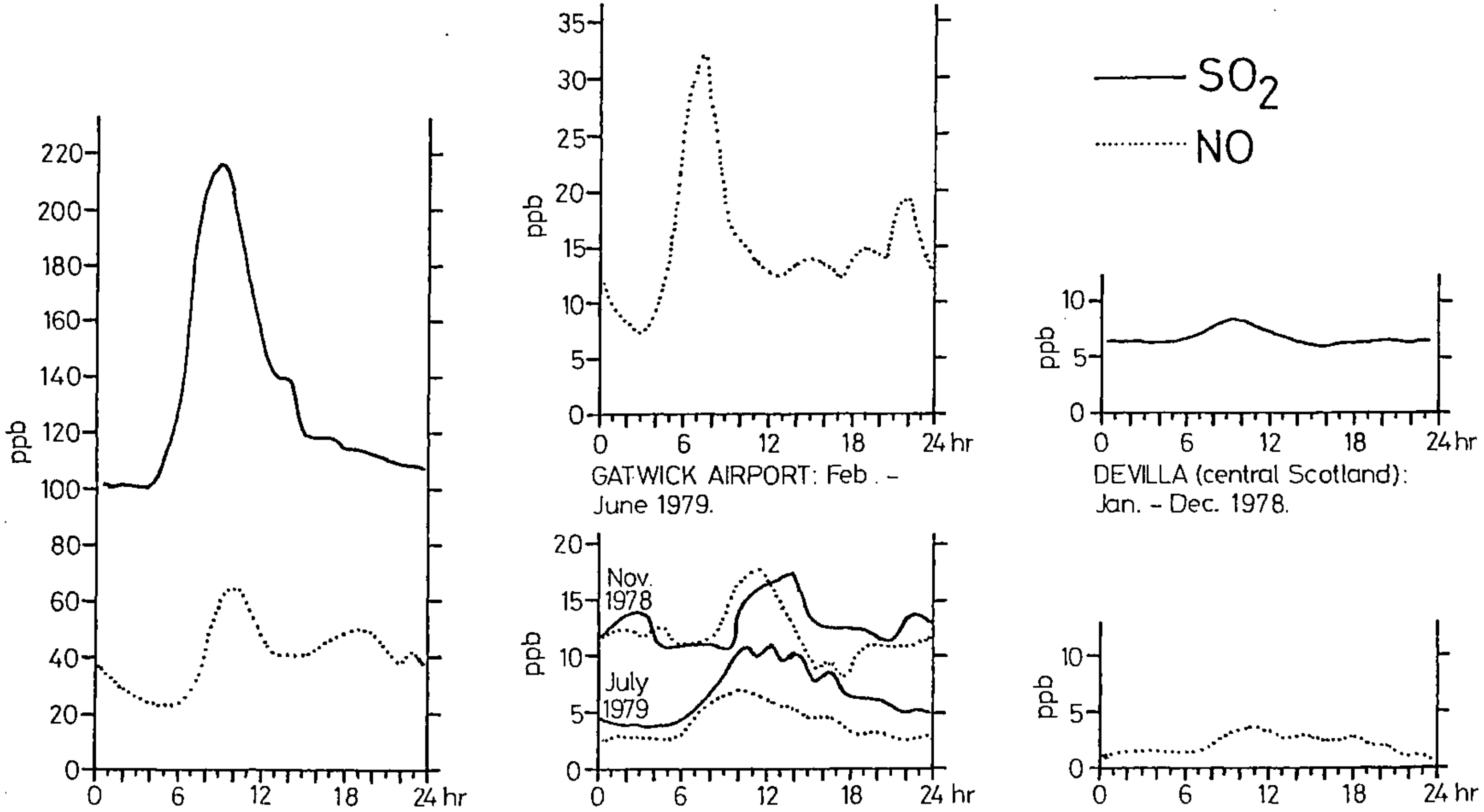
Year	Location	Days with 80 ppb or more	Days with 100 ppb or more	Maximum concentration	Mean	Reference
1973	ADRIGOLE, SW Ireland	17	4	141		Derwent *et.al.*, 1976
	HARWELL, S England	23	8			"
	SIBTON, E England	8	5			"
	LONDON, Endell St.	28	14	136		"
1974	HARWELL	17	7	120		"
	LONDON, Endell St.	14	4	164		"
1975	HARWELL	20	15	177		"
	SIBTON	22	14			"
	CHILWORTH, S England	35	22			"
	EAST KILBRIDE, Scotland	13	4			"
	LONDON, County Hall	16	13	150		"
1976	LONDON, County Hall	26	16	212		Ball and Bernard, 1978
	HARWELL	31	24			Derwent and Hov, 1979
1977	HEYSHAM, NW England	7	3	112	31	Harrison and McCartney, 1980
	HARWELL	1	1			Derwent and Hov, 1979
1978	HEYSHAM	15	8	122		Harrison and Holman, 1979
	HARWELL	1	1			Derwent and Hov, 1979
	BOTTESFORD, Midlands	10	5	144	24	Martin and Barber, 1981
1979	BOTTESFORD	25	11		34	"
1981	LEATHERHEAD, S England	6	0	96	24	Roberts (unpubl.)

that there is variation from site to site within each year, but often there is more variation at the same site from year to year. Using Harwell as an example, O_3 exceeded 80 ppb on 31 days in 1976 but on only one day in each of 1977 and 1978, a reflection of the summer weather in those years: hot in 1976, cooler in 1977 and 1978. Trends in O_3 are therefore as unpredictable as trends in the weather.

During the summer of 1977 a survey of O_3 levels over the whole UK was carried out by Ashmore, Bell & Reilly (1978). In this study, plants of the O_3 - sensitive Bel W3 cultivar of *Nicotiana tabacum* were placed at 53 locations. Visible damage caused by O_3 was measured throughout the summer and compared with the number of sunshine hours. Ashmore *et al.*(1978) showed that if there were uniform levels of sunshine over the UK then maximum O_3 - induced injury could be expected in areas of high urbanisation (sources of NO_x and hydrocarbons).

2.6 Diurnal Patterns of SO_2, NO_x and O_3

Since light intensity has been shown to influence the response of plants to both SO_2 and NO_2 (Davies, 1980a; Taylor, 1968), then it is of interest to know how concentrations of pollutants vary over the course of a day. Results from several surveys have included the mean concentration at each hour of the day (i.e. the mean diurnal pattern) some of which are shown in Figures 2.16 and 2.17. A more detailed type of analysis was used by McCune, MacLean & Schneider (1976) on gaseous fluoride concentrations. They calculated, for each 2-hour period of the day, the proportion of time concentrations were found in several ranges (0; > 0 and < 0.1; > 0.1 and < 1.0; > 1.0 μg F m^{-3}). The GLC data were analysed in a similar manner, but for each hour of the day, and the results were expressed as proportion of time above given levels rather than in ranges (Figures 2.18 and 2.19).



LONDON: off-street site, weekdays, Sept. 1973–March 1974.

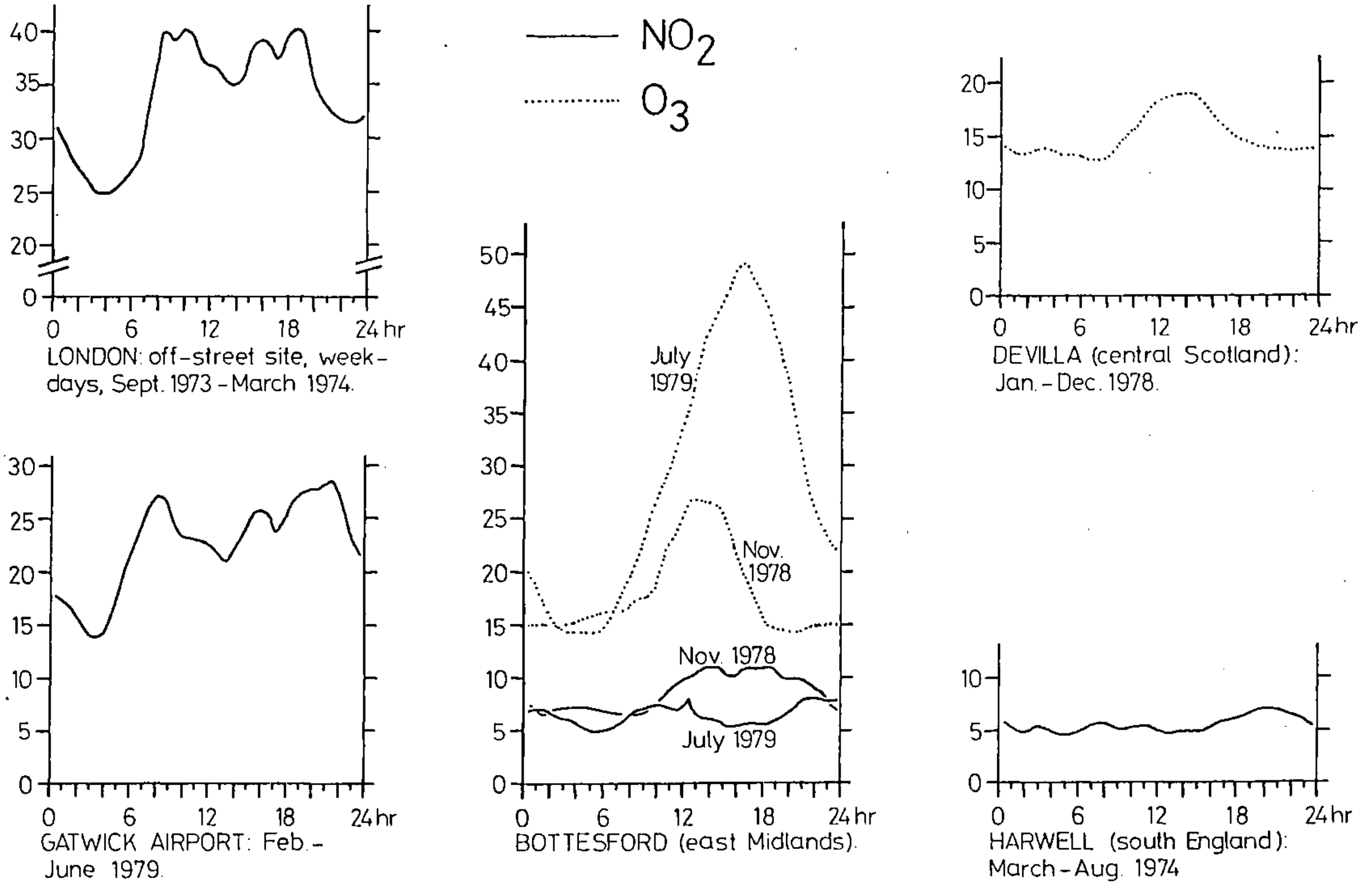
GATWICK AIRPORT: Feb. – June 1979.

BOTTESFORD (east Midlands).

DEVILLA (central Scotland): Jan. – Dec. 1978.

HARWELL (south England): March–Aug. 1974.

Figure 2.16 : Mean diurnal patterns of SO_2 and NO concentrations at several sites in the UK. (From Apling *et al.*, 1979 (London); Williams *et al.*, 1980 (Gatwick); Martin & Barber, 1981 (Bottesford); Nicholson *et al.*, 1980 (Devilla); Cox *et al.*, 1976 (Harwell)).



LONDON: off-street site, week-days, Sept. 1973 - March 1974.

GATWICK AIRPORT: Feb.-June 1979.

BOTTESFORD (east Midlands).

DEVILLA (central Scotland): Jan.-Dec. 1978.

HARWELL (south England): March-Aug. 1974

Figure 2.17 : Mean diurnal patterns of NO$_2$ and O$_3$ concentrations at several sites in the UK. (Data sources as for Fig. 2.16).

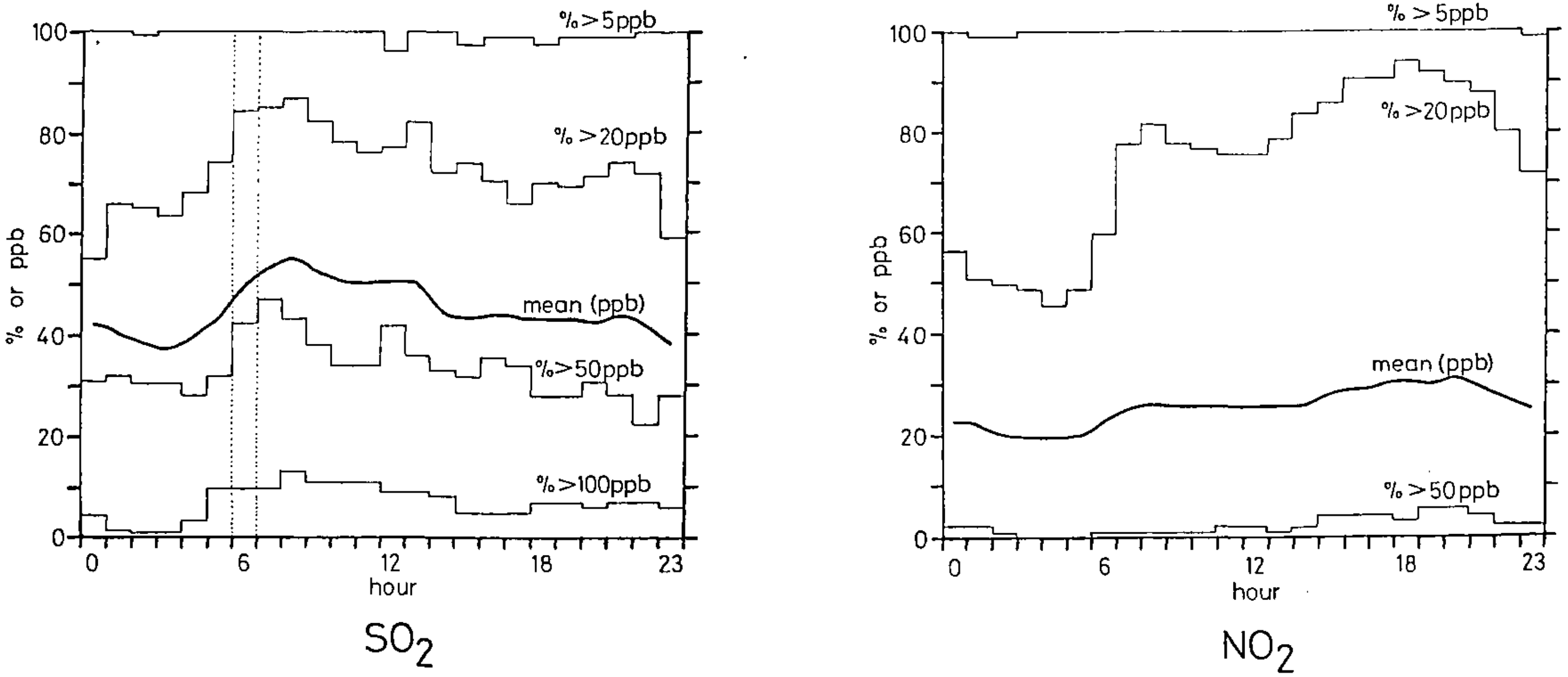


Figure 2.18 : Mean diurnal patterns of SO_2 and NO_2 at central London roof-top site, 1 January-31 March 1979. (Calculated from data supplied by the GLC)

The thick line represents the mean concentration at each hour of the day; the thin lines represent, for each hour of the day, the proportion (%) of the days during the sampling period on which the concentrations exceeded 5, 20, 50 or 100 ppb.

For example, from 0600-0700 the mean SO_2 concentration was 49 ppb, SO_2 exceeded 5 ppb every day, 20 ppb on 84% days, 50 ppb on 44% days and 100 ppb on 9% days.

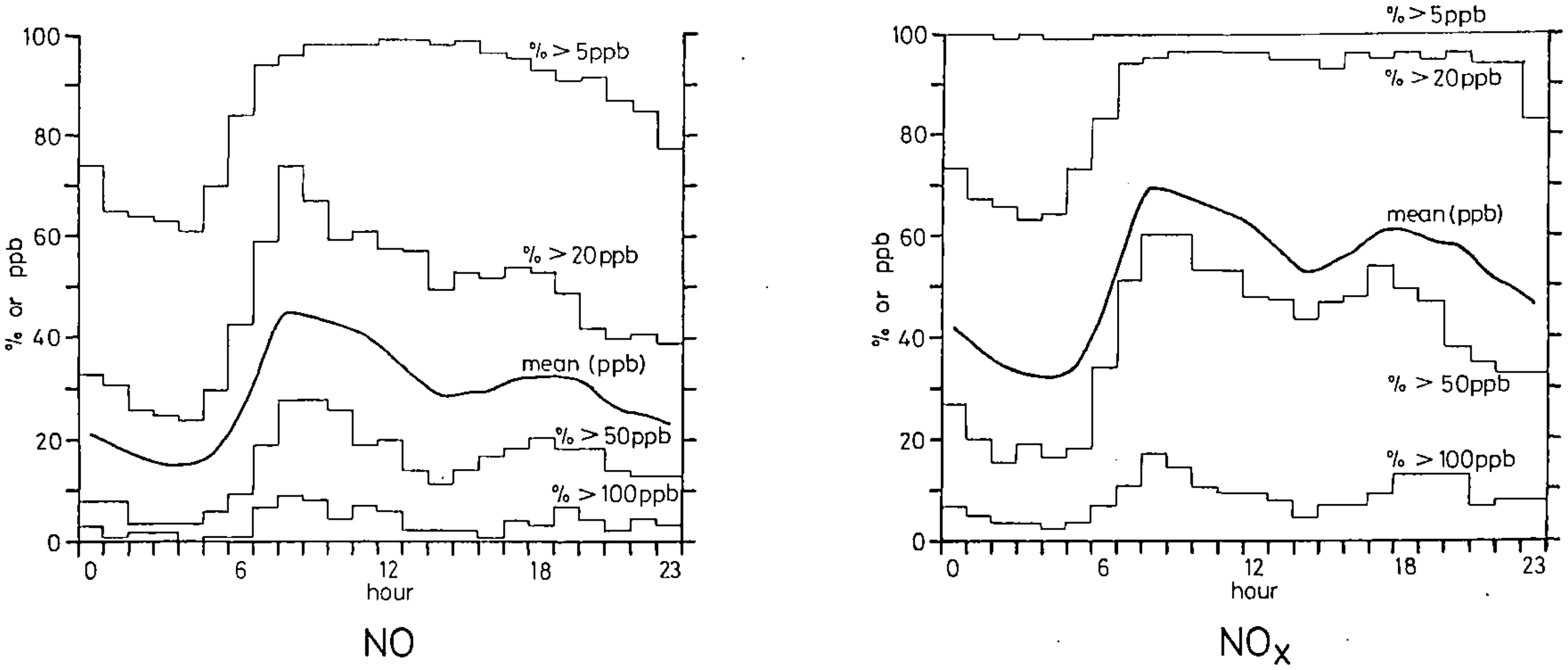


Figure 2.19 : Mean diurnal patterns of NO and NO_x at central London roof-top site, 1 January-31 March 1979. (Calculated from data supplied by the GLC) For explanatory notes, see Figure 2.18.

Since the analysis is performed on each hour of the day the proportion of time above a given level is equivalent to the proportion of days above that level (at that hour) during the sample period.

The mean diurnal patterns of SO_2 and NO tend to peak together at Bottesford and in London (Figs. 2.16, 2.18 and 2.19) (the only areas with data for both SO_2 and NO), but peaks of SO_2 and NO tend to be earlier and larger in London and at Gatwick than at Bottesford. The large urban peaks probably reflect emissions from vehicles (NO) and office heating (SO_2 and NO) at 08-0900 hours into a layer of relatively stable air below an inversion. The smaller peaks at Bottesford are probably caused by the mixing of polluted air from above the inversion layer with cleaner air below when the inversion breaks up in the late morning. Rural areas with low pollution levels have less distinct diurnal patterns (Fig. 2.16). Apling, Dorling, Rogers, Williams & Stevenson (1981) produced similar results for NO mean diurnal patterns at four sites ranging from rural (Sibton) to central London (Islington).

Mean diurnal patterns for NO_2 (Figs. 2.17 and 2.18) show less pronounced peaks, and a minimum around 0400 hours is common. Two indistinct peaks at about 0800 and 1800 hours often occur in urban areas, but again rural areas show little pattern (Fig. 2.17; Apling, Rogers & Stevenson, 1981; Apling, Dorling, Rogers, Williams & Stevenson, 1981). As expected from its mode of production O_3 concentrations peak in mid-afternoon, with peaks being much larger in summer than winter (Fig. 2.17; Apling, Dorling, Rogers, Williams & Stevenson, 1981).

The more detailed analysis of diurnal patterns of SO_2, NO_2, NO and NO_x levels (Figs. 2.18 and 2.19) shows that as the mean concentration increases then the proportion of the time above a given concentration also increases. For example, when the mean concentration of SO_2 is at its lowest there are few days on which the concentration exceeds 100 ppb; when the mean is high then concentrations exceed 100 ppb on about 10% of days. Similarly following the mean diurnal pattern, NO_2 exceeds 20 ppb from midnight to 0600 on only about 50% of days, but on 80-90% of days from 0700-2300 hours (Fig. 2.18). Corresponding statements could be made about either NO or NO_x (Fig. 2.19) and other levels of SO_2 and NO_2.

2.7 Duration of Peaks

The final point to be considered is the duration a pollutant remains above a given concentration. The term 'peak' will be used for the time during which a pollutant remains continually above a given 'base' level. Larsen (1961) calculated the lengths of time for which SO_2 remained above 200, 300, 400, 500 and 1000 ppb in six American cities. Peak durations were found to be log-normally distributed at each base level. Drufuca & Giuliano (1977), analysing SO_2 concentrations over three winters in Milan found similar results to Larsen (1961).

A similar analysis for UK air monitoring data appears to be lacking, as do analyses for NO_x concentrations. Analysis of the GLC data shows that, even with the small data set, peak durations are approximately log-normally distributed; the results for SO_2 and NO_2 are illustrated in Figure 2.20 and for NO and NO_x in Figure 2.21. Generally, for increasingly high peak base levels, the number of peaks shorter than a given duration will form a decreasing proportion of the total number of peaks at that base level. This can only be a generalisation because, although the number of peaks of a given duration will decrease at increasingly high base levels, the total number of peaks (all durations) will also decrease: this may result in a higher proportion of peaks of the given duration at a high than a low base level.

A major feature of these diagrams is that they provide an indication

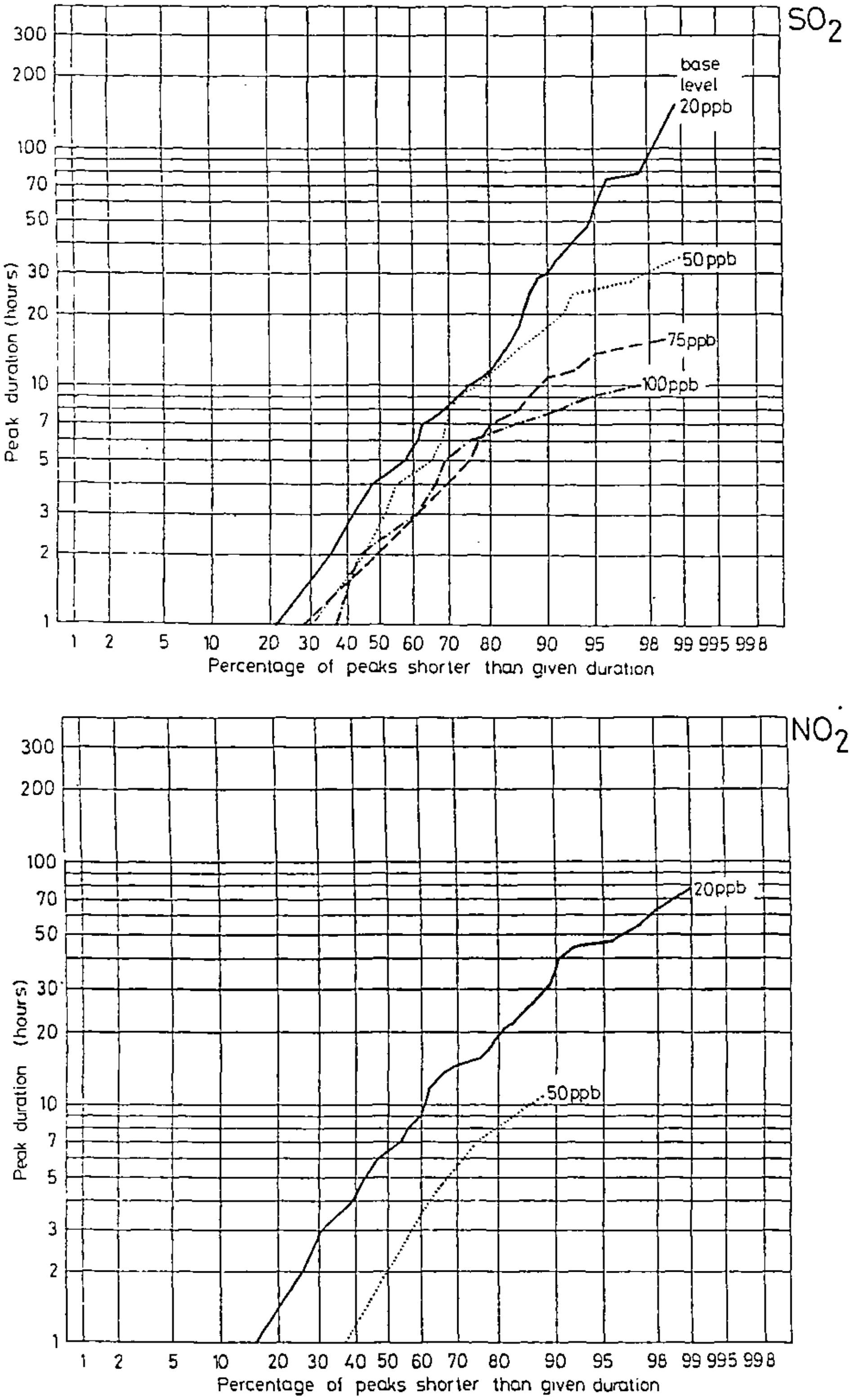


Figure 2.20 : Cumulative frequency distributions for peak durations of SO_2 and NO_2 above various base levels. Central London roof-top, 1 January-31 March 1979.

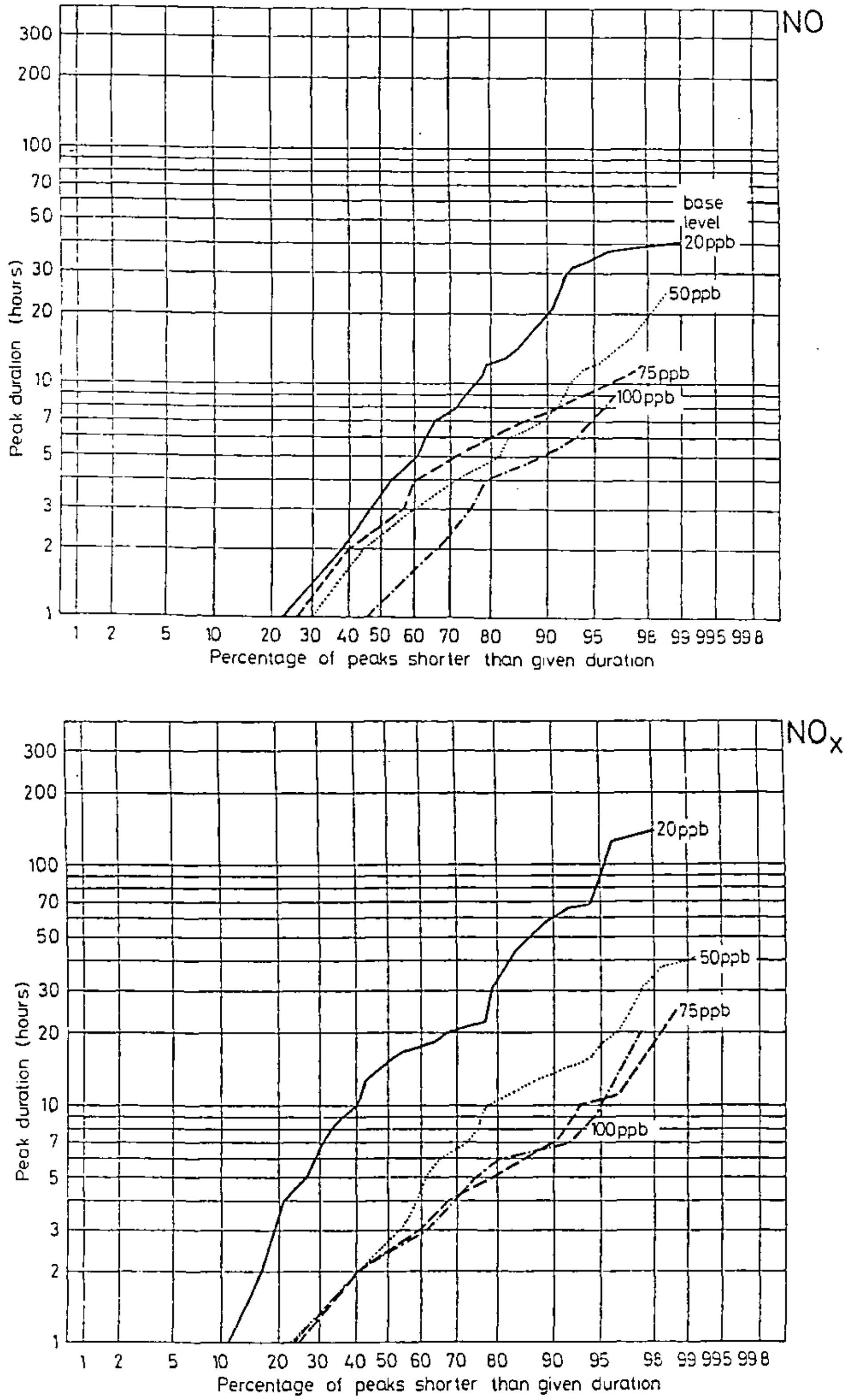


Figure 2.21 : Cumulative frequency distributions for peak durations of NO and NO_x above various base levels. Central London roof-top, 1 January-31 March 1979.

of the maximum length of time a pollutant is likely to remain above a given level. For example, few peaks of SO_2 above 100 ppb last for longer than 10 hours, nor does NO_2 often remain above 50 ppb for more than 11 hours (Fig. 2.20). About 50% of peaks over 100 ppb SO_2 or NO_x were of only 2 hours duration. After each peak the pollutant concentration will not immediately go down to zero (or even near zero) and so care must be exercised in using such diagrams in, for example, experimental design or interpretation of results.

2.8 Conclusions

Ambient concentrations of SO_2 declined over the decade 1969 to 1979, particularly in urban and fringe areas. Data on NO_x are available for a few sites from 1972 to 1980 but there is no evidence for a decrease in ambient concentrations. In 1979 annual mean SO_2 concentrations in urban areas were about 35 ppb with winter and summer means of approximately 45 and 25 ppb respectively. Fringe sites, which probably represent the more polluted agricultural areas, had an annual mean of 23 ppb SO_2 with winter and summer means of around 28 and 17 ppb. Most of the UK has an annual mean SO_2 concentration less than 15 ppb.

A reasonable estimate of the v/v ratio of SO_2:NO_2 is 1:1 but the NO:NO_2 ratio varies, with NO greater than NO_2 at roadside sites, NO less than NO_2 at very rural sites and NO approximately equal to NO_2 elsewhere.

SO_2 daily mean cfd's are log-normal and, when plotted on log x probability axes, lines representing cfd's from different site types are approximately parallel. Hourly mean cfd's of SO_2, NO and NO_2 are also log-normally distributed. SO_2 and NO hourly means exceed twice the long-term mean for 10% of hours and 3-7 (SO_2) or 5-10 (NO) times the mean for 1% of hours. NO_2 concentrations are less variable, hourly means exceeding the overall mean by 1.5-2 times for 10% but only about 3 times for 1% of hours.

Comparison of hourly mean concentrations of SO_2 with NO or NO_2 shows that SO_2 and NO_2 are essentially independant of each other but that SO_2 and NO are significantly correlated. This is supported by mean diurnal patterns with coincident peaks of SO_2 and NO but NO_2 patterns have no distinct peaks.

O_3 is essentially a summer pollutant, concentrations depending largely on the weather. O_3 levels rise to over 80 ppb on from 1 to more than 30 days per summer and less frequently to over 100 ppb.

The general conclusions mentioned above, and some of the details discussed earlier in the chapter, were used as the basis for experimental designs (described in Chapters 4 and 5). Reference will be made to these findings where appropriate. In addition, some of the general conclusions should be borne in mind when reading Chapter 3, concerning the effects of SO_2 and NO_2 on crop growth.

CHAPTER 3

THE EFFECTS OF AMBIENT UK SO_2 AND NO_x POLLUTION ON CROP GROWTH

3.1 Introduction

In Chapter 2 the concentrations of SO_2 and NO_x in the UK were described fully. It was concluded that the levels of SO_2 and NO_2 were often similar, while NO concentrations may be greater or less than NO_2, depending on location. The relative phytotoxicities of these gases with respect to growth have not been established conclusively, but recent work by Ashenden (1979b) and Ashenden & Williams (1980) suggests that, for a given concentration, the growth of grass is reduced less by NO_2 than SO_2. Mansfield & Freer-Smith (1981) discussed the problems of determining the phytotoxicity of NO since it is spontaneously oxidised to NO_2 in air. They concluded that NO and NO_2 probably cause effects by similar mechanisms, but that because NO is taken up more slowly than NO_2 (about one third as fast in *Capsicum annuum*) then NO will be less toxic than NO_2 for a given atmospheric concentration.

The effects of SO_2 on crop growth have been extensively studied, but less attention has been paid to the effects of NO_x or mixtures of SO_2 and NO_x. During this century, the effects of SO_2 on plant growth have been the subject of much debate. Thomas (1951) concluded firmly that SO_2 would not reduce the growth of plants unless visible damage was present. This conclusion was in contrast to the earlier suggestion by Stoklasa (1923) that growth reduction may occur in the absence of visible symptoms (i.e. 'invisible injury'). Until the early 1970's a long-term threshold of 200-300 ppb SO_2, below which visible injury was thought unlikely to occur, was commonly accepted as the threshold for growth reduction (Bell, 1982). This compares with a winter mean SO_2 concentration of ~45 ppb in UK urban areas in 1978 (Figure 2.1). However, recent research, reviewed below, has shown that SO_2 can reduce the growth of many plants without visible injury.

Ayazloo & Bell (1981) and Horsman, Roberts, Lambert & Bradshaw (1979) showed that there was no relationship between the sensitivity of clones of several grass species to chronic injury (yield reduction with no necrosis) and acute injury (necrosis, with or without yield reduction) caused by exposure for long periods to low (usually < 150 ppb) or for shorter periods to very high (> 1000 ppb) SO_2 concentrations, respectively. Garsed & Rutter (1982) have shown a similar lack of relationship for several *Pinus* and *Picea* species. Information on this subject is otherwise lacking, but it is interesting that these two widely diverse groups (grasses and conifers) both show no correlation between resistance to acute and chronic SO_2 injury. There is no comparable information for NO_x or pollutant mixtures. For the reason above, and since the present work is concerned with effects of pollutants on crop growth, only studies of growth effects, rather than visible injury, will be considered in detail in the following review.

The majority of studies on the effects of SO_2 and/or NO_x on plant growth have been undertaken by exposing plants to controlled concentrations of pollutants in closed chambers of various designs. So far, only two British studies have used 'open-air' fumigation systems to release SO_2 over field-grown crops (Greenwood, Greenhalgh, Baker & Unsworth, 1982; McLeod, pers. comm.) but no results of such long-term fumigations have yet been published. Open-air fumigation systems have been developed and used elsewhere (e.g. Lee & Lewis, 1978; Miller, Sprugel, Muller, Smith & Xericos, 1980; Runeckles, Palmer & Trabelsi, 1981) but, with the exception of the latter, have not been used on UK crop species.

An alternative approach is to grow crops in chambers receiving filtered or unfiltered polluted air, but this has been done in the UK on relatively few occasions.

The fumigation and filtration experiments are reviewed separately.

3.2 Fumigation Experiments

3.2.1 The effects of SO_2 on the growth of grass

The effects of SO_2 on grass growth have been comprehensively reviewed by Bell (1982). When studying the published accounts of the effects of SO_2 on *Lolium perenne*, Bell (1982) distinguished between results gained from plants grown as dense swards and those from plants grown individually or planted well apart (spaced plants). He concluded that for spaced *L. perenne* plants there was no relationship between the percentage reduction in shoot dry weight due to SO_2 and the dose of pollutant (concentration x time). Bell (1982) also pointed out that, assuming there is a constant difference in relative growth rate between fumigated and control plants, the percentage difference in dry weights will increase with time. However, the logarithm of the ratio of the dry weights will be linearly related to time, and therefore the effect of time may be removed by dividing by the duration of the fumigation. Thus, yield reduction per day (termed Ry from hereon) may be expressed as:

$$Ry = \log_{10} \frac{\text{dry weight of control plants}}{\text{dry weight fumigated plants}} \times \frac{1000}{\text{time}},$$

where time = duration of fumigation in days.

When Bell (1982) plotted Ry against SO_2 concentration, also for spaced plants of *L. perenne*, he again found no correlation. Subsequently, Mansfield & Freer-Smith (1981) re-examined the same data, but excluded plants fumigated for < 40 and > 160 days, and found a significant ($p < 0.02$) positive correlation between Ry and SO_2 concentration.

Bell (1983a) commented on the discarding of short and long fumigations and agreed that "fumigations of very young plants, and of more mature plants over periods greater than 6 months are not comparable with those of intermediate duration." This suggestion was based on the findings of Whitmore & Freer-Smith (1982) who, after fumigating *Poa pratensis* for 11 months with a mean concentration of 62 ppb SO_2, showed an overwinter yield reduction of ~50%, but this changed to a 17% stimulation by the following autumn (see Fig. 3.1a). From their work it is clear that the effect of SO_2 changed with time (a factor which involves both plant age and season) but this change did not become apparent until after 160 days fumigation.

Fewer experiments have been performed on *L. perenne* swards than on spaced plants (Bell, 1982), but workers using swards have often carried out more than one harvest, allowing regrowth in between. Following the example of both Bell (1982) and Mansfield & Freer-Smith (1981), the published data on the effects of fumigating *L. perenne* with SO_2 in closed chambers were studied. Only the ryegrass cultivar S23 was considered and, for the swards, data from each harvest were included: data for successive harvests were calculated as the total to that harvest, e.g. yield for the second harvest = the sum of the yields at the first and second harvests. Yields between successive harvests were not used because at the start of the growth period the swards were not necessarily the same size. The results of this survey are listed in Tables 3.1 (for spaced plants) and 3.2 (for swards). In the following analysis, harvests of plants < 50 days old were excluded (rather than fumigations of < 40 days), as were fumigations of > 160 days.

Figure 3.2 illustrates Ry plotted against SO_2 concentration for

Figure 3.1 : % change in dry weight of *Poa pratensis* cv. Monopoly caused by SO_2, NO_2 or SO_2 + NO_2 compared with controls.

(a) Large symbols represent total plant weight, small symbols represent shoot weight of plants grown in 62 ppb NO_2 (○——○), 62 ppb SO_2 (□- -□), 62 ppb SO_2 + 62 ppb NO_2 (△——△).

(The vertical dotted line is included to facilitate comparison with (b)).

(b) Total plant weight in 68 ppb NO_2 (○——○), 68 ppb SO_2 (□- -□), 68 ppb SO_2 + 68 ppb NO_2 (△——△).

(Redrawn from Whitmore & Freer-Smith, 1982, (a); and from data in Ashenden, 1979b, (b))

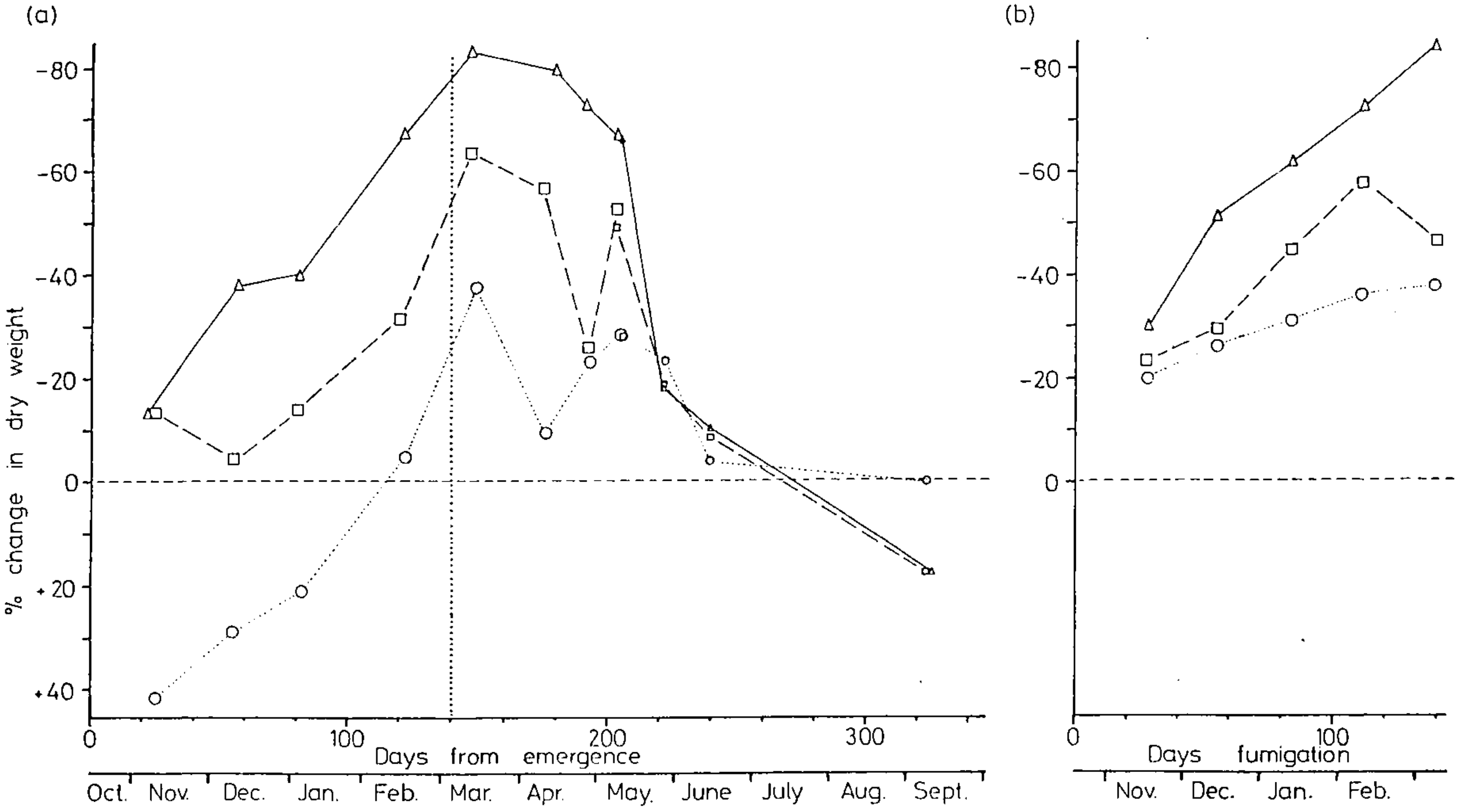

(a)
% change in dry weight
-80
-60
-40
-20
0
+20
+40
0
100
200
300
Days from emergence
Oct.
Nov.
Dec.
Jan.
Feb.
Mar.
Apr.
May.
June
July
Aug.
Sept.
(b)
-80
-60
-40
-20
0
0
100
Days fumigation
Nov.
Dec.
Jan.
Feb.

Table 3.1 : Summary of conditions used to fumigate spaced plants of *L. perenne* cv. S23 with SO_2 and the results obtained.

Experiment number	SO_2 (ppb)	Duration (days)	Age at start (days)	Season or light intensity(1)	Shoot dry wt (mg plant^{-1})			Ry(3)	Reference
					Control	$+SO_2$	%(2)		
1	16	173	0	winter	-	-	-68	2.86	Bell, Rutter and Relton (1979)
2	23	42	0	summer	-	-	+11	-1.08	"
3	25	144	25	winter	-	-	+8	-0.23	"
4	40	194	-	summer	-	-	-24	0.61	"
5	83	133	-	winter	1889	1486	-21	0.78	"
6	159	108	-	winter	626	359	-43	2.23	"
7	72	180	0	winter	1296	652	-50	1.66	Bell and Clough (1973)
8	129	62	0	autumn	502	299	-40	3.63	"
9	110	28	21	81 W m^{-2}	1006	829	-16	3.00	Ashenden and Mansfield (1977)
10	110	28	21	81 W m^{-2}	799	529	-34	6.40	"
11	130	61	T(4)	summer	1379	1080	-22	1.74	Ayazloo and Bell (1981)
12	136	105	T	summer	1921	1561	-19	0.86	"
13	143	64	-	-	737	589	-20	1.52	Ayazloo, Bell and Garsed (1980)
14	226	42	T	30 W m^{-2}	-	-	-16	1.80	R.M. Bell in Horsman, Roberts, Lambert and Bradshaw (1979)
15	244	35	T	30 W m^{-2}	53(5)	44(5)	-16	2.16	Horsman, Roberts, Lambert and Bradshaw (1979)
16	263	56	T	30 W m^{-2}	330	231	-30	2.77	"

(1) season for outdoor chambers, light intensity for controlled environment

(2) % change in shoot dry weight in SO_2

(3) see text for definition

(4) tillers or young plants (age assumed ≡ 15 days minimum)

(5) mg tiller^{-1}

Table 3.2 : Summary of conditions used to fumigate swards of *L. perenne* cv. S23 with SO_2 and the results obtained.

Experiment number	SO_2 (ppb)	Duration (days)	Age at start (days)	Season or light intensity(1)	Shoot dry weight				Ry(3)	Reference
					Control	$+SO_2$	Units	%(2)		
1	46	44	0	summer	138	110	$g\ m^{-2}$	-20	2.24	Bell, Rutter and Relton (1979)
	46	44	0	"	117	87	"	-25	2.56	"
	56	78*	0	"	230	191	"	-17	1.03	"
	56	78*	0	"	203	179	"	-12	0.70	"
2	51	136	12	winter	-	-	-	-5	0.14	"
3	69	183	18	winter	-	-	-	+1	-0.03	"
4	19	29	21	summer + minimum 30 $W\ m^{-2}$	222	224	$mg\ pl^{-1}$	+1	-0.13	Cowling and Koziol (1978)
	150	29	21	"	222	218	"	-2	0.27	"
	19	51*	21	"	645	632	"	-2	0.17	"
	150	51*	21	"	645	622	"	-4	0.31	"
5	17	22	76	summer + minimum 30 $W\ m^{-2}$	~209	~209	$mg\ pl^{-1}$	0	0	Lockyer, Cowling and Jones (1976)
	39	22	76	"	~209	~209	"	0	0	"
	78	22	76	"	~209	~212	"	+2	-0.28	"
	156	22	76	"	~209	~176	"	-16	3.39	"
	17	50*	76	"	~491	~470	"	-4	0.38	"
	39	50*	76	"	~491	~480	"	-2	0.20	"
	78	50*	76	"	~491	~497	"	+1	-0.11	"
	156	50*	76	"	~491	~370	"	-25	2.46	"
	17	77*	76	"	~794	~745	"	-6	0.36	"
	39	77*	76	"	~794	~764	"	-4	0.22	"
	78	77*	76	"	~794	~842	"	+6	-0.33	"
	156	77*	76	"	~794	~588	"	-26	1.69	"
6	19	24*	111	summer	247	276	$mg\ pl^{-1}$	+12	-2.01	Cowling and Lockyer (1976)
	19	45*	111	"	687	754	"	+10	-0.90	"
	19	66*	111	"	1228	1314	"	+7	-0.45	"
	19	87*	111	"	1597	1700	"	+6	-0.31	"
7	49	17	25	110 $W\ m^{-2}$	1600	1486	$mg\ pl^{-1}$	-7	1.89	Cowling, Jones and Lockyer (1973)
	49	38*	25	"	3914	3700	"	-5	0.64	"
	49	59*	25	"	6671	6014	"	-10	0.76	"
8	21	56	54	winter/spring + 30 $W\ m^{-2}$	553	533	$mg\ pl^{-1}$	-4	0.29	Cowling and Lockyer (1978)
	21	85*	54	"	1472	1428	"	-3	0.16	"

* harvested after cutting and allowing regrowth

(1) to (3) see Table 3.1

Figure 3.2 : Yield reduction ($Ry = \log \left[\frac{\text{dry wt control plants}}{\text{dry wt fumigated plants}}\right] \times \frac{1000}{\text{time}}$) versus SO_2 concentration for spaced plants (●) and swards (○) of *L. perenne* cv. S23. Data from Tables 3.1 and 3.2 excluding plants harvested when younger than 50 days or fumigated for more than 160 days.

The regression lines are:

(1) ———, from Mansfield & Freer-Smith (1981), spaced *L. perenne* plants fumigated for between 40 and 160 days.

$Ry = -0.230 + 0.0111x$ ($p < 0.02$)

($x = SO_2$ concentration, ppb)

(2) ———, for spaced plants as defined in figure title.

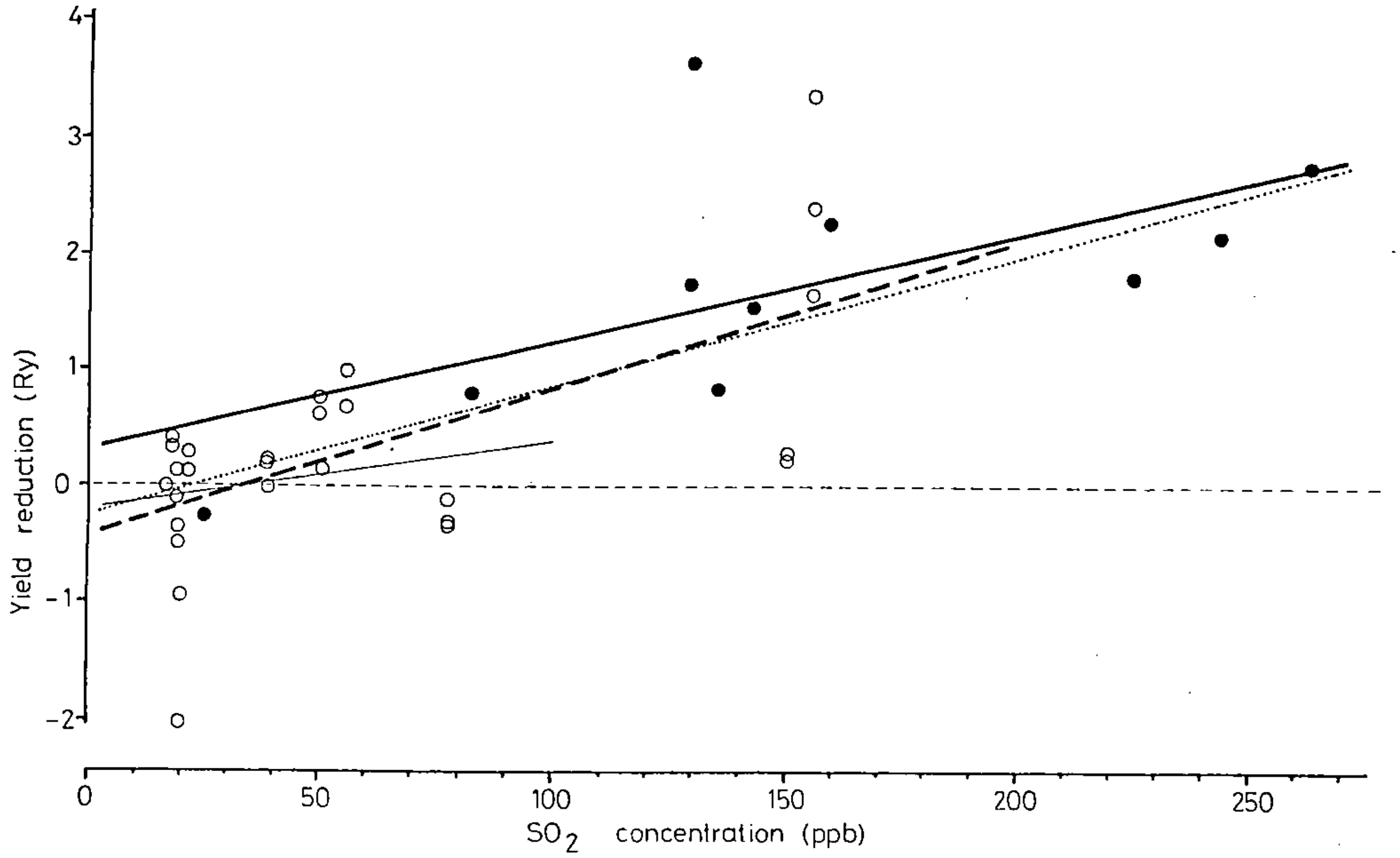
$Ry = 0.299 + 0.0093x$ ($p = 0.05$, $r = 0.63$)

(3) — — —, for swards as defined in figure title.

$Ry = -0.446 + 0.0128x$ ($p < 0.005$, $r = 0.64$)

(4) ———, as line (3) but fumigated with < 100 ppb SO_2.

$Ry = -0.204 + 0.0059x$ (N.S., $r = 0.21$)


4
3
2
1
0
-1
-2
Yield reduction (Ry)
0
50
100
150
200
250
SO$_2$ concentration (ppb)

spaced plants and swards of *L. perenne* S23. The 'spaced plant' regression line (line 2 on Fig. 3.2) is slightly different from that obtained by Mansfield & Freer-Smith (1981) for spaced *L. perenne* plants fumigated for between 40 and 160 days (line 1 on Fig. 3.2): line 1 indicates the possibility of a stimulation of yield below 20 ppb SO_2, whereas line 2 suggests no threshold before yield reduction occurs.

The regression line for swards (line 3 on Fig. 3.2) suggests the possibility of an increased yield caused by SO_2 below 35 ppb. This line is heavily influenced by the five points corresponding to ~150 ppb, and although their inclusion is valid statistically it is of interest to note that the exclusion of these data produces a non-significant regression (line 4 on Fig. 3.2).

For any given SO_2 concentration the time required to produce a certain percentage drop in yield may be calculated from the regression lines. Table 3.3 illustrates this for both swards and spaced plants. For example, at 50 ppb SO_2 it would take 54 days to produce a 10% reduction in shoot yield of spaced plants and a 25% reduction would occur after 127 days. Swards take longer than spaced plants to respond to SO_2 and a 10% reduction in yield would not occur for 214 days at 50 ppb SO_2 (a time outside the limits of the original data). At higher SO_2 concentrations the effect on swards and spaced plants becomes similar.

At this point it must be emphasised that Table 3.3 was produced only for interest and should not be taken too literally. Clearly the data on which the regression lines are based vary greatly ($r \approx 0.64$ in both cases), at least partly due to different experimental techniques and times of year for fumigations (Tables 3.1 and 3.2). For example, Horsman, Roberts, Lambert & Bradshaw (1979) used a light intensity of 30 W m^{-2}, whereas Ashenden & Mansfield (1977) used 81 W m^{-2}. Davies (1980a) has shown for

Table 3.3 : Estimated length (days) of fumigation with SO_2 required to produce 10, 25 and 50% reductions in shoot yield of spaced plants and swards of *L. perenne* cv. S23 of harvested when more than 50 days old.

	SO_2 concentration (ppb)				
	50	75	100	125	150
Spaced plants					
Length of fumigation (d) for 10% reduction	54	42	34	28	24
" " " " " 25% "	127	97	79	66	57
" " " " " 50% "	(230)	(177)	143	120	104
Swards					
Length of fumigation (d) for 10% reduction	(214)	81	50	36	28
" " " " " 25% "	(502)	(189)	117	84	66
" " " " " 50% "	(912)	(344)	(212)	153	120

Calculated from regression lines 2 and 3 on Figure 3.1. Data in brackets are outside the limit of 160 days fumigation in the original data.

Phleum pratense that, at a low light intensity (40 W m^{-2}), 120 ppb SO_2 caused a 50% reduction in yield compared with no effect at a high light intensity (130 W m^{-2}). Unexpectedly, growth reductions in Horsman *et al.*'s (1979) experiments appear, if anything, less than predicted from the regression line (Fig. 3.2: the data points being those > 200 ppb). It is possible that *L. perenne* is not affected in the same way as *P. pratense* by light intensity.

So far the discussion has centred on *L. perenne*. Published reductions in shoot dry weight for fumigations of other grass species with SO_2 refer only to spaced plants and are listed in Table 3.4. Only for *Phleum pratense* is there much information, but there is no relationship between Ry and SO_2 concentration, even if growth experiments using a light intensity of less than 40 W m^{-2} (or ~150 µE m^{-2} s^{-1}) are excluded. In the experiments conducted by Ashenden (1979b) and Ashenden & Williams (1980) with 68 ppb SO_2, sequential harvests were obtained (experiment numbers 5, 10, 11 and 13 in Table 3.4). *Dactylis glomerata* (expt. 5) showed an approximately 50% reduction of shoot dry weight throughout the winter, and therefore Ry decreased with increasing duration. The shoot dry weight reduction of *Poa pratensis* (expt. 10) increased for the first 4 harvests (up to 112 days) but recovered slightly at the last harvest. (Similarly, Whitmore & Freer-Smith (1982), after fumigating *Poa pratensis* with 62 ppb SO_2, found a maximum reduction of total plant weight after about 150 days, although this was followed by a recovery.) *Lolium multiflorum* (expt. 11) showed a maximum yield reduction after 56 and 84 days and then began to recover; Ry decreased throughout the fumigation period. The reductions in shoot dry weight of *Phleum pratense* (expt. 13) may be best described as having remained around 35% for the duration of the fumigation and therefore Ry tended to decrease with increasing length of

Table 3.4 : Summary of conditions used to fumigated spaced plants of several grass species with SO_2 and the results obtained.

Expt. number	Species	SO_2 (ppb)	Duration (days)	Age at start(d)	Season or light intensity(1)	Shoot dry wt (mg pl^{-1})			Ry(3)	Reference
						Control	+SO_2	%(2)		
1	*Dactylis glomerata* - wild(4)	138	131	T(5)	winter	1680	1240	-26	0.96	Ayazloo and Bell (1981)
2	*D. glomerata* cv. S37	173	180	T	winter	1516	1190	-22	0.61	"
3	*D. glomerata* cv. S37	110	28	20	81 W m^{-2}	780	458	-41	8.26	Ashenden (1978)
4	*D. glomerata* cv. S37	110	28	20	81 W m^{-2}	1631	1015	-38	7.36	"
5	*D. glomerata* cv. S37	68	28	42	winter	209	100	-52	11.43	Ashenden (1979b)
		68	56	42	"	363	195	-46	4.82	"
		68	84	42	"	492	226	-54	4.02	"
		68	112	42	"	601	303	-50	2.66	"
		68	140	42	"	743	416	-46	1.80	"
6	*Festuca rubra* - wild	138	131	T	winter	900	740	-18	0.65	Ayazloo and Bell (1981)
7	*F. rubra* cv. Engina	181	105	T	spring/summer	1581	1139	-28	1.36	"
8	*Holcus lanatus* - wild	138	131	T	winter	1180	660	-44	1.93	Ayazloo and Bell (1981)
9	*H. lanatus* - wild	94	133	T	winter	1937	1522	-21	0.79	
10	*Poa pratensis* cv. Monopoly	68	28	42	winter	91	74	-19	3.21	Ashenden (1979b)
		68	56	42	"	176	132	-25	2.23	"
		68	84	42	"	255	157	-38	2.51	"
		68	112	42	"	356	160	-55	3.10	"
		68	140	42	"	558	343	-38	1.51	"
11	*Lolium multiflorum* cv. Milano	68	28	38	winter	435	357	-18	3.07	Ashenden and Williams (1980)
		68	56	38	"	875	637	-27	2.47	"
		68	84	38	"	1433	1053	-27	1.59	"
		68	112	38	"	1441	1132	-21	0.94	"
		68	140	38	"	1917	1651	-14	0.46	"
12	*Phleum bertolonii* cv. S50	120	72	T	spring/summer	1677	1331	-21	1.39	Ayazloo and Bell (1981)
13	*Phleum pratense* cv. Eskimo	68	28	38	winter	110	63	-43	8.64	Ashenden and Williams (1980)
		68	56	38	"	176	134	-24	2.11	"
		68	84	38	"	247	180	-27	1.64	"
		68	112	38	"	387	239	-38	1.87	"
		68	140	38	"	489	313	-36	1.38	"
14	*P. pratense* cv. S48	120	35	7	130 W m^{-2}	504	507	+1	-0.07	Davies (1980)
		120	35	7	40 "	26	13	-50	6.84	"
15	*P. pratense* cv. S48	120	44	10	100 μE m^{-2} s^{-1}	227	171	-25	2.80	Jones and Mansfield (1982a)
		120	44	10	400 "	1964	2405	+22	-2.00	"
		120	44	10	100 "	78	49	-37	4.59	"
		120	44	10	400 "	681	516	-24	2.74	"
16	*P. pratense* cv. S48	120	10	10	220 μE m^{-2} s^{-1}	4.0	3.4	-15	7.06	Jones and Mansfield (1982a)
		120	20	10	"	30	18	-41	11.38	"
		120	30	10	"	175	98	-44	8.39	"
		120	40	10	"	789	387	-51	7.73	"
17	*P. pratense* cv. S48	100	21	14	180 μE m^{-2} s^{-1}	64	55	-14	3.11	Jones and Mansfield (1982b)
		100	14	21	"	64	62	-4	1.23	"
		100	7	28	"	64	54	-16	10.70	"
18	*P. pratense* cv. S48	60	41	7	195 μE m^{-2} s^{-1}	320	310	-3	0.35	Jones and Mansfield (1982b)
		60	41	7	"	320	289	-10	1.09	"
		60	41	7	"	320	291	-9	1.03	"

(1) to (3) see Table 3.1; (4) natural population; (5) tiller.

fumigation. These results contrast with Bell's (1982) assumption that Ry would remain constant with respect to time and therefore casts some doubt on its usefulness as a measure of yield reduction. On the other hand, the reaction of various species to SO_2 differs and there is the circumstantial evidence that, for *L. perenne* cv. S23, Ry is correlated with SO_2 concentration.

Shoot dry weight is not the only factor that may be affected by SO_2 fumigations. Bell (1982) tabulated the changes in several parameters caused by fumigating spaced plants with SO_2, and a modified version of his table is given here as Table 3.5. In many cases a reduction in shoot dry weight was accompanied by a reduction in tiller number, but often the percentage reduction of shoot dry weight was greater than that of tiller number. Only with *L. multiflorum* was tiller number reduced substantially more than shoot dry weight. In most experiments the proportion of dead leaves was significantly increased by the presence of SO_2, often by a factor of 2-3, regardless of SO_2 concentration. Exceptions to this were the experiments of Jones & Mansfield (1982a) where the proportion of dead leaves increased by 8-17 times, but these represented an increase of from < 1% to only 1-6% dead leaves. Root dry weight was often reduced by a larger proportion than shoot dry weight and this was reflected by decreases in the root/shoot ratio in most cases when it was measured.

Comparable data for swards are available only for *L. perenne* and there is insufficient information from which to draw conclusions (Table 3.6).

The only open-air fumigation of a commonly grown UK grass was that of *L. perenne* cv. S23 by Runeckles *et al.* (1981). These authors exposed individually potted plants for 10 weeks (August to October) to mean concentrations of 106 and 198 ppb SO_2. As a consequence of the type of fumigation system used, the concentrations of SO_2 varied to give log-normal

Table 3.5 : Effects of SO_2 on several yield parameters of grass species.

Species	SO_2 (ppb)	Duration (days)	% change in SO_2 fumigated plants					Reference
			Tiller no.	Proportion of dead leaves (% total shoot wt)	Root dry wt	Shoot dry wt	Root/shoot dry wt	
Lolium perenne	129	62	-42	+207		-40		Bell and Clough (1973)
	72	180	-41	+247		-50		
	159	108		+142	-60	-43	-32	Bell, Rutter and Relton (1979)
	81	133		+124		-25		
	85	133		+12		-20		
	143	64	-11	+47	-48	-23	-37	Ayazloo, Bell and Garsed (1980)
	136	105		+54	-33	-19	-20	Ayazlood and Bell (1981)
	130	61		+129	-12	-22	+11	
	110	28	-8		-48	-18	-35	Ashenden and Mansfield (1977)
	110	28	-14		-60	-34	-42	
	263	56		+67		-30		Horsman *et al.* (1979)
L. multiflorum	68	140	-23		+8	-14		Ashenden and Williams (1980)
Festuca rubra	138	131		+270	-40	-18		Ayazloo and Bell (1981)
	181	105		+160	-39	-28	-14	
Holcus lanatus	94	133		+62	-20	-21	-1	Ayazloo and Bell (1981)
	138	131		+53	-58	-44		
Phleum bertolonii	120	72		+99	-38	-20	-24	Ayazloo and Bell (1981)
Phleum pratense	68	140	-33		-58	-36		Ashenden and Williams (1980)
	120	35	-8	+100	+1	-11		Davies (1980)
	120	44	+3	+1070	-48	+22		Jones and Mansfield (1982a)
	120	44	-22	+1674	-29	-24		
	120	40	-14	+794	-62	-51		
	60	41	+1	+90	-17	-3	-15	Jones and Mansfield (1982b)
Poa pratensis	68	140	-27		-54	-39		Ashenden (1979b)
Dactylis glomerata	138	131		+130	-51	-26		Ayazloo and Bell (1981)
	173	180		+90	-44	-22		
	110	28	-12		-52	-41	-27	Ashenden (1978)
	110	28	-13		-45	-38	-13	
	68	140	-10		-37	-44		Ashenden (1979b)

Blanks indicate the parameter was not measured.

Table 3.6 : Effect of SO_2 on several yield parameters of swards of *Lolium perenne* cv. S23.

SO_2 ppb	Duration (days)	% change in SO_2-fumigated plants				Reference
		Tiller no.	Proportion of dead leaves (% total shoot) wt.	Root dry wt.	Shoot dry wt.	
19	51	-3			-2	Cowling and Koziol (1978)
150	51	-5			-4	"
21	56		-11		-4	Cowling and Lockyer (1978)
21	85		-10	-1	-3	"
49	59			-14	-10	Cowling, Jones and Lockyer (1973)
19	87			+17	+6	Cowling and Lockyer (1976)

Blanks indicate the parameter was not measured.

distributions. There were no significant effects of SO_2 on shoot dry weight, but root weight was reduced by ~17 and 36% after exposure to mean concentrations of 106 and 198 ppb SO_2, respectively. The lack of effect on shoot dry weight was surprising: the authors suggested that it may have been a result of the open-air conditions (in contrast to the chambers used in all the other studies discussed above). However, in a similarly designed fumigation system it has been shown that the SO_2 concentrations at night were about twice those during the day (Lee, Preston & Weber, 1979). If this was the case in Runeckles *et al.*'s (1981) study it may affect the interpretation of their results. The effect on root weight without an effect on shoot weight is consistant with several reports from studies using chambers (Table 3.5).

3.2.2 Effects of NO_x on crop growth

All work concerning the effects of NO_2 on the growth of grass has been in conjunction with SO_2 and will be discussed in the next section. Studies on the effects of NO_x on the growth of tomato (*Lycopersicon esculentum*) have been carried out by several workers (e.g. Spierings, 1971; Troiano & Leone, 1977; Capron & Mansfield, 1977; Anderson & Mansfield, 1979) but these are only applicable to a glasshouse situation and will not be discussed here. Other work devoted to the effects of NO_2 on arable crops has involved higher than UK ambient concentrations, often resulting in acute effects.

3.2.3 The effects of SO_2 + NO_2 on grass growth

Most fumigations of grasses with SO_2 and NO_2 have used both single pollutants and their combination. Comparison of results allows estimation of the interaction (if any) of the effects of individual pollutants when they are applied simultaneously. Studies by several workers on the production of visible injury have often shown that a mixture of SO_2 + NO_2 either caused greater injury than the sum of the injuries caused by the individual gases at the same concentrations, or that injury was produced by concentrations at which the individual gases caused no damage (a 'greater than additive' effect) (e.g. Heck, 1968; Matsushima, 1971; Tingey, Reinert, Dunning & Heck, 1971; Bennett, Hill, Soleimani & Edwards, 1975). Similarly, White, Hill & Bennett (1974) found evidence for greater than additive inhibition of photosynthesis in *Medicago sativa* by 250 ppb SO_2 + 250 ppb NO_2, although Bull & Mansfield (1974) showed only additive effects of 50-250 ppb SO_2 and NO_2 on photosynthesis of *Pisum sativum*. Only rarely have studies found evidence for a combination of SO_2 + NO_2 causing a significantly less than additive effect. For example Amundson & Weinstein (1981) exposed *Glycine max* to 2000 ppb SO_2 and/or 500 ppb NO_2 for 4 hours and found that only those plants exposed to SO_2 singly developed necrotic lesions, i.e. the presence of NO_2 prevented SO_2 causing visible damage.

Work on the effects of relatively low levels of SO_2 and/or NO_2 on grass growth was first published by Ashenden & Mansfield (1978) and later described in more detail by Ashenden (1979b) and Ashenden & Williams (1980). In their study, carried out at the University of Lancaster, Ashenden and co-workers exposed spaced plants of four grass species (*Dactylis glomerata, Poa pratensis, Lolium multiflorum* and *Phleum pratense*) to pollutants for 103.5 hours and clean air for 64.5 hours per week. SO_2 and NO_2 were applied at 110 ppb, resulting in a weekly mean concentration of 68 ppb. Their experiment began in October and continued for 20 weeks; harvests were carried out at 4 week intervals and the results are summarised in Tables 3.7 to 3.10.

NO_2 applied singly reduced the shoot dry weight of *D. glomerata* and *Poa pratensis* by about 30% by the end of the experiment, although it had

Table 3.7 : Percent reduction in shoot and root dry weights and tiller number of *Dactylis glomerata* exposed to 68 ppb NO_2, 68 ppb SO_2 or 68 ppb SO_2 + 68 ppb NO_2. (From Ashenden, 1979b).

	Pollutant	% reduction compared with control(1) exposure period (days)				
		28	56	84	112	140
shoot dry weight(2)	NO_2	41	24	27	12	33
	SO_2	52	46	54	50	46
	$SO_2 + NO_2$	35	52	60	64	72
root dry weight	NO_2	13	20	12	19	11
	SO_2	51*	59***	52**	53***	37**
	$SO_2 + NO_2$	21	59***	68***	66***	85***
number of tillers	NO_2	9	5	17	5	1
	SO_2	19	13	24	10	10
	$SO_2 + NO_2$	21	+3	33**	41**	32*

(1) significant differences from control are: *, $p < 0.05$; **, $p < 0.01$; ***, $p < 0.001$; increases are prefaced by '+'.

(2) statistics not available as reductions were calculated from 'green leaf wt' plus 'dead leaves and stubble', see original paper.

Table 3.8 : Percent reduction in shoot and root dry weights and tiller number of *Poa pratensis* exposed to 68 ppb NO_2, 68 ppb SO_2 or 68 ppb SO_2 + 68 ppb NO_2. (From Ashenden, 1979b)

	Pollutant	% reduction compared with control(1) exposure period (days)				
		28	56	84	112	140
shoot dry weight(2)	NO_2	14	29	29	31	28
	SO_2	19	25	38	55	38
	SO_2 + NO_2	25	44	56	67	76
root dry weight	NO_2	33**	23*	37***	42***	47***
	SO_2	33**	37**	54***	63***	54***
	SO_2 + NO_2	39***	62***	68***	79***	91***
number of tillers	NO_2	0	14	15	19	9
	SO_2	9	15	35**	40***	27**
	SO_2 + NO_2	16	15	34**	55***	61***

(1) and (2) see Table 3.7.

Table 3.9 : Percent reduction in shoot and roof dry weights and tiller number of *Lolium multiflorum* exposed to 68 ppb NO_2, 68 ppb SO_2 or 68 ppb SO_2 + 68 ppb NO_2. (From Ashenden & Williams, 1980)

	Pollutant	% reduction compared with control$^{(1)}$ exposure period (days)				
		28	56	84	112	140
shoot dry weight$^{(2)}$	NO_2	4	8	18	13	8
	SO_2	18	27	27	21	14
	SO_2 + NO_2	+17	27	39	39	48
root dry weight	NO_2	14	+4	47***	17	+35
	SO_2	12	32*	33***	16	+8
	SO_2 + NO_2	0	29*	47***	43**	58*
number of tillers	NO_2	21	+6	+10	3	17
	SO_2	26	1	22*	24*	23*
	SO_2 + NO_2	17	6	15	7	32**

(1) and (2) see Table 3.7.

Table 3.10 : Percent reduction in shoot and root dry weights and tiller number of *Phleum pratense* exposed to 68 ppb NO_2, 68 ppb SO_2 or 68 ppb SO_2 + 68 ppb NO_2. (From Ashenden & Williams, 1980)

	Pollutant	% reduction compared with control (1) exposure period (days)				
		28	56	84	112	140
shoot dry weight (2)	NO_2	23	+6	27	7	+1
	SO_2	43	24	27	38	36
	SO_2 + NO_2	33	29	50	62	74
root dry weight	NO_2	25	+12	30*	25*	+1
	SO_2	59***	36*	45**	52***	58**
	SO_2 + NO_2	48***	28*	72***	78***	92***
number of tillers	NO_2	3	+2	17	+11	6
	SO_2	18	0	13	22	33*
	SO_2 + NO_2	9	7	24*	27*	55***

(1) and (2) see Table 3.7.

no effect on the shoot dry weight of *L. multiflorum* or *Phleum pratense*. Root dry weights were largely unaffected by NO_2, with only that of *Poa pratensis* reduced by the end of the experiment. Tiller number was not affected by NO_2 in any of the four species.

The mixture of SO_2 + NO_2 reduced the shoot and root dry weights of all four species, usually from the first harvest and with the percentage reductions increasing throughout the experiment. Also, root weights were often reduced by a greater proportion than shoot weights. At the first harvest of all four species, SO_2 + NO_2 appeared to have a less than additive effect on root and shoot dry weight reduction (although the interaction may not be statistically significant, see Table 3.7). At the harvests after 56, 84 and 112 days the reductions in root and shoot dry weights were generally additive in comparison with the single-pollutant effects. Only at the final harvest, after 140 days fumigation, was there much evidence for a greater than additive effect: root and shoot dry weights of *L. multiflorum* and *Phleum pratense*, and root dry weight of *D. glomerata* were reduced more than expected from the effects of the individual gases. By the end of the experiment all species showed a large (50-90%) yield reduction caused by 68 ppb SO_2 + 68 ppb NO_2; Ashenden (1979b) and Ashenden & Williams (1980) suggested this may have been partly due to the fact that exposure to the pollutants was overwinter when the plants were growing slowly. (Indeed, Davies (1980b) has subsequently shown that the yield of *Phleum pratense* was reduced more by SO_2, NO_2 and SO_2 + NO_2 at low than at high light intensity.) Tiller number was generally reduced by the mixture of pollutants after 84 days, and a greater than additive effect was seen after 140 days in all species except *L. multiflorum*.

Davies (1980b) exposed individual plants of *Phleum pratense* cv. S48 to 120 ppb SO_2 and/or 120 ppb NO_2 for 35 days. She found that NO_2 increased shoot dry weight by 28% and that SO_2 reduced root dry weight by ~40% but did not affect shoots. The fact that 68 ppb SO_2 reduced shoot weight after only 28 days (Table 3.10), whereas after 35 days 120 ppb SO_2 had no effect may be attributable to the high light intensity used by Davies (1980b) (a photon flux density of 410 $\mu E\ m^{-2}\ s^{-1}$) compared with the winter conditions in Ashenden & Williams' (1980) study (probably about 110 $\mu E\ m^{-2}\ s^{-1}$, see footnote). Davies (1980b) found no evidence for SO_2 and NO_2 interacting in their effects on shoot or root dry weights.

In another study, Davies (1980b) grew *Phleum pratense* (six plants per 15 cm diameter pot) in the same outdoor chambers that were used by Ashenden & Williams (1980) and used similar pollutant concentrations (~100 ppb SO_2 and/or NO_2 for 104 hours per week, giving a mean weekly concentration of ~64 ppb of each pollutant). Plants were placed in the chambers for 56-day periods at four times of year: summer (May to July), autumn (October to December), winter (December to February) and spring (March to April). Results from this study showed that NO_2 produced essentially no effect on shoots at any season, except for a 27% reduction in tiller number in summer. SO_2 alone reduced shoot weight by 23% in winter and $SO_2 + NO_2$ reduced shoot weight by ~25% in winter and spring. Davies (1980b) also found that in all seasons $SO_2 + NO_2$ caused a large increase in leaf senescence (dead leaf dry weight increased to 2-4 times that of the control). Root growth was not measured.

Whitmore & Freer-Smith (1982), again using the chambers at Lancaster,

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The mean total short-wave radiation at Kew Observatory, London, from November to January (averaged from 1956-60) was 2.2 $MJ\ m^{-2}\ day^{-1}$ (Monteith, 1973). Photosynthetically active radiation (PAR) comprises 50% of the total radiation (Szeicz, 1974). From this it may be calculated that, from November to January, the mean PAR at Kew was 12.7 $J\ m^{-2}\ s^{-1}$ (for 24 h day^{-1}), and since the mean daylength during the relevant period is ~8.5 h, then the average PAR during daylight hours was ~36 $J\ m^{-2}\ s^{-1}$ ($\approx$ 110 $\mu E\ m^{-2}\ s^{-1}$).

exposed *Poa pratensis* cv. Monopoly to mean concentrations of 62 ppb SO_2 and/or NO_2 (100 ppb for 104 hours per week), beginning in October and continuing for 11 months. Their results are illustrated in Figure 3.1a. NO_2 initially increased total plant weight by ~40% but in late winter and early spring a 30% decrease in yield with respect to control occurred; plants recovered during the summer to yield similar shoot dry weights to the controls. SO_2 alone and $SO_2 + NO_2$ consistently decreased yield over-winter but by September the shoot dry weights in both these treatments exceeded that in the control by ~17% ($p < 0.05$). At the beginning of the experiment the $SO_2 + NO_2$ treatment showed a greater than additive effect (in contrast to Ashenden's (1979b) results, Figure 3.1b), but subsequently the effects of SO_2 and NO_2 became additive. After 140 days, the % reductions in dry weights obtained by Ashenden (1979b) and Whitmore & Freer-Smith (1982) were similar in all respective treatments (Fig. 3.1). In addition, the reductions caused by the $SO_2 + NO_2$ treatments were similar throughout the first 140 days of each experiment.

3.2.4 Summary of fumigation experiments

There is good evidence that SO_2 alone at mean concentrations in excess of 50-60 ppb will reduce the shoot weight of many grass species by 20-40% in long-term exposures. This is similar to the concentration (68 ppb) suggested by IERE (1981) as the threshold above which crop yield reductions will occur consistently. There have been few fumigations of spaced *L. perenne* plants with less than 60 ppb SO_2 (and none using the other grass species listed in Table 3.4), and although the regression lines (Fig. 3.2) suggest a low/zero threshold for growth reduction, there are little supporting data (Table 3.1). Even with swards of *L. perenne* it is not until the SO_2 concentration exceeds ~50 ppb that consistent growth reductions were found.

In all the grass species studied, reductions in shoot dry weight due to SO_2 were often accompanied by a decrease in tiller number, but a reduction in mean tiller weight also occurred in most cases. Roots were reduced proportionately more than shoots by SO_2 pollution, presumably indicating an effect on the partitioning of assimilates between shoots and roots (see Jones & Mansfield, 1982b). The percentage of dead material was usually increased by the presence of SO_2 but there was no apparent relationship to SO_2 concentration.

In general the effects of NO_2 on shoot and root dry weight of grass species were less than those caused by similar concentrations of SO_2. In many cases there was no effect and occasionally NO_2 caused increased yield.

The simultaneous fumigation of grass plants with SO_2 and NO_2 often produced an additive effect on shoot and root weight reduction, occasionally the effects were more than additive but evidence on this point was conflicting. However, there was no evidence for a less than additive effect occurring after a long-term fumigation with SO_2 + NO_2. The reduction in root weight was often proportionally greater than that of the shoot, similar to the situation found when fumigating with SO_2 alone. Most studies involving mixtures of SO_2 and NO_2 have used 100-110 ppb of each pollutant for ~104 hours per week, resulting in mean weekly concentrations of 62-68 ppb SO_2 and/or NO_2. Changes in shoot dry weight caused by this mixture of pollutants have varied from a 17% stimulation in summer to more than 70% reduction in late winter, although overwinter fumigations have consistently resulted in a decrease in yield. Both species (and possibly cultivar) and time of harvest (length of fumigation or season) appear to be very important in determining the observed effect.

3.3 Filtration Experiments

In the UK, relatively little work has been carried out on the effects of SO_2-polluted air on crop growth using chambers receiving filtered or unfiltered air. Indeed, at only three sites has this approach been used to study grass yield, and in one other area, the growth of barley. The first study was that by Bleasdale (1952) who grew *L. perenne* cv. S23 in glasshouses ventilated with water-scrubbed or polluted air in Manchester in the early 1950's. Although mean SO_2 concentrations were not included in his later publication (Bleasdale, 1973), Bleasdale (1952) originally reported daily mean SO_2 concentrations for the duration or part-duration of most of his experiments. At the start of his work he measured the SO_2 concentration of the ambient air at the site, rather than in the glasshouse receiving polluted air, but subsequently he measured the SO_2 concentrations in both ambient air and the glasshouse. Concentrations in the polluted glasshouse were, on average, about 50% of those in ambient air. (This factor has been used to estimate SO_2 concentrations during his earlier experiments.) Results from Bleasdale's (1952) studies are summarised in Table 3.11 (expts. 1 to 5). On four occasions reductions of approximately 30% in shoot dry weight were found in the polluted air compared to the scrubbed air; in each case the mean SO_2 concentration was estimated to be in the region of 20 ppb. Surprisingly, in the experiment with the highest mean SO_2 concentration (65 ppb) there was no effect on shoot dry weight (although the amount of dead leaves increased and there was a significant 17% reduction in green leaf dry weight).

In more recent work, Crittenden & Read (1978a, b; 1979) and Awang (1979) have used charcoal-filtered and unfiltered sections of a single glasshouse in Sheffield. Concentrations of SO_2 in the unfiltered section were similar to some of those in Bleasdale's (1952) study (Table 3.11). Crittenden & Read (1978b, expts. 9-11 in Table 3.11) found ~25% reductions in shoot dry weight of *L. perenne* cv. S23 in the presence of about 24 ppb

Table 3.11 : Summary of results from filtration experiments using grass species.

Expt. number	Species	SO_2 (ppb)	Duration (days)	Season or light intensity	% change in unfiltered air(1)				Reference
					Tiller no.	Proportion of dead leaves (% total shoot wt)	Root dry wt	Shoot dry wt	
1	*Lolium perenne* cv. S23	–	~105	winter	-18			-27	Bleasdale (1952)
		~20(2,3)	~187*	"				-33	"
2		~22(4)	187	summer	-30			-33	Bleasdale (1952)
3		~25	78	spring-summer				+ 1 N.S.	Bleasdale (1952)
4		16	59	summer				-32	Bleasdale (1952)
5		65	104	winter		+26		– 1 N.S.	Bleasdale (1952)
6	*L. perenne* cv. S23	64	~135	winter				– 5 N.S.	Roberts *et al.* (1983)
		47	~240*	winter-summer				-18 N.S.	"
7		31	207*	winter				0 N.S.	Colvill *et al.* (1983)
		27	332*	winter-summer				+ 3 N.S.	"
8		46	~180*	winter				+ 7 N.S.	Colvill *et al.* (1983)
		39	~300*	winter-summer			+20 N.S.	+18 N.S.	"
9	*L. perenne* cv. S23	26	56	spring	-20		-36	-36	Crittenden and Read (1978b)
		22	131	spring-summer		+3 N.S.	-20	-20	"
10		26	86	spring	-25		-23	-25	Crittenden and Read (1978b)
11		24	117	spring-summer	-15	-7 N.S.	-26	-25	Crittenden and Read (1978b)
12	*L. perenne* cv. S23	17	42	summer				-14 N.S.	Awang (1979)
13		15	56	32 klux				-24	Awang (1979)
14	*L. multiflorum* cv. S22	35	24	spring				-33	Crittenden and Read (1979)
		25	57	spring-summer	-24			-32	"
15	*L. multiflorum* cv. S22	16	42	summer				-16 N.S.	Awang (1979)
16		15	56	32 klux				-38	Awang (1979)
17	*Dactylis glomerata* cv. S143	23	23	spring-summer				-22	Crittenden and Read (1979)
		17	72	"	-28			-42	"
18	*D. glomerata* cv. S143	17	42	summer				-29	Awang (1979)

* Harvested after cutting and allowing regrowth.

(1) all % changes significant at $p = 0.05$ or greater unless marked with N.S. (not significant).

(2) estimated as 50% ambient concentration - see text for reasons.

(3) measured over last 62 days only.

(4) measured over last 110 days only.

Blanks indicate data not available

Note: all plants were grown as spaced plants with the exception of experiment 5 (10 plants per 18 cm diameter pot)

SO_2, similar to Bleasdale's (1952) results. Unlike many fumigation experiments, the roots and shoots were affected to an equal extent.

In one summer experiment (number 12 in Table 3.11) Awang (1979) found no effect of 17 ppb SO_2 on shoot dry weight of *L. perenne* cv. S23 after 42 days. On the other hand, in an experiment in which the glasshouse was lined with aluminium foil, and illuminated at 32 klux for 12 hours per day, plants of S23 that received 15 ppb SO_2 in unfiltered air showed a reduction in shoot dry weight of 24% compared with those in filtered air (Awang, 1979).

Crittenden & Read (1978b) grew clones of both *L. perenne* cv. S23 and plants from a natural population of *L. perenne* from Helmshore, Lancashire, thought to be tolerant to SO_2 pollution. The experiment began in July 1974 and continued for 43 weeks; SO_2 concentrations and percent reductions of total plant weight in unfiltered air are listed in Table 3.12. With the exception of during February and March the SO_2 concentrations were low. Air containing a mean of 9 ppb SO_2 caused a reduction of ~36% in the total weight of S23 and had no effect on the Helmshore population; later in the experiment the Helmshore (SO_2 tolerant) population showed a reduced dry weight in the polluted air whereas the S23 plants were unaffected by the treatment.

The growth of *L. multiflorum* and *D. glomerata* was also shown to be depressed, to a similar extent to *L. perenne* cv. S23, by low concentrations of SO_2 in the unfiltered glasshouse (Table 3.11, expts. 14-18). In addition to the experiments listed in Table 3.11, Crittenden & Read (1979) grew *L. multiflorum* cv. S22 for 35 days in unfiltered air containing 4-19 ppb SO_2 (overall mean not given); by the end of the experiment there was no difference (at $p = 0.05$) between plants grown in filtered or unfiltered air.

Table 3.12 : Percentage reduction of total live plant weight of *L. perenne* cv. S23 and Helmshore (SO_2 tolerant) populations grown in unfiltered Sheffield air for 43 weeks, compared with charcoal-filtered air. (From Crittenden & Read, 1978b)

		Monthly mean SO_2 (ppb)	% reduction of total live plant dry weight in unfiltered air (1)	
			S23	Helmshore
July	1974	~9		
August		~9		
September		~9	36	N.S.
October		~15	39	N.S.
November		~15		
December		~8		
January	1975	~8	N.S.	30
February		60		
March		24	N.S.	34
April		15		
May		18	N.S.	28

(1) N.S. = differences in weight are not given, but are noted as not significant by the authors; the % decreases given are significant at $p = 0.05$ or greater.

Most recently, Roberts, Bell, Horsman & Colvill (1983) and Colvill, Bell, Roberts & Bradshaw (1983) grew *L. perenne* cv. S23 in filtered and unfiltered open-top chambers in St. Helens, Lancashire. In three experiments (numbers 6-8 in Table 3.11) they found no overall effect (at $p = 0.05$) of filtering the air on shoot dry weight. However, it should be noted their experimental method resulted in SO_2 concentrations of 8-30 ppb in the filtered chambers (25-50% of that in the respective unfiltered chambers). Colvill *et al.* (1983) have suggested that the lack of a true control (near zero SO_2) may have lead to an underestimate of yield reduction. This view is supported by the large decreases in shoot dry weight reported by Crittenden & Read (1978b, 1979) and Awang (1979) at SO_2 concentrations similar to those in the filtered chambers of Roberts *et al.* (1983) and Colvill *et al.* (1983). Nevertheless, it must be remembered that both the latter groups of authors did achieve an average 56% reduction in SO_2 concentration with no apparent effect.

In all the studies discussed above, SO_2 was considered to be the pollutant of primary importance, although both NO_x and O_3 (in summer) were probably present (see Chapter 2). Several experiments have shown that polluted ambient air containing mean SO_2 concentrations of 15-26 ppb may significantly reduce the shoot yield of three grass species. The experiments of Roberts *et al.* (1983) and Colvill *et al.* (1983) were exceptions to this but interpretation of their results was complicated by the relatively high pollution levels in their filtered chambers. The SO_2 concentrations quoted here for Bleasdale's (1952) Manchester experiments may be an underestimate due to the assumption that the SO_2 concentrations in the glasshouse were half those in ambient air, but it is highly unlikely that the SO_2 concentrations in the Sheffield studies are incorrect (Crittenden & Read, 1978a; Awang, 1979). There is only one record of about 20 ppb SO_2 causing a large yield reduction in a fumigation experiments (Tables 3.1, 3.2 and 3.4), but there have been few fumigations at this low concentration. Mansfield & Freer-Smith (1981) have suggested that the yield reductions found in filtration experiments were due to interaction of SO_2 with NO_2 (see Section 3.2.3), but there have been no reports of fumigation experiments using about 20 ppb SO_2 with similar concentrations of NO_2. In addition, in summer experiments the presence of O_3, as well as SO_2 and NO_2, may increase the yield reduction in unfiltered air (e.g. Reinert & Gray, 1981; Reinert & Sanders, 1982; see also Chapter 7).

In experiments growing spring barley (*Hordeum vulgare* cv. Magnum) in filtered and unfiltered open-top chambers Buckenham, Parry & Whittingham (1982) have shown that the grain yield was increased by 59% in 1979 but was not affected in 1980 by filtering air containing 17 and 18 ppb SO_2 respectively. An experiment in 1976 by Brough, Parry & Whittingham (1978) in the same area showed that filtering air containing 23 ppb SO_2 improved the yield of spring barley (cv. Abacus) by 40%. In the area in which both teams conducted their experiments (the Bedfordshire brickfields), in addition to SO_2, fluoride pollution is also present (mean concentrations of 0.8 $\mu g\ m^{-3}$ in 1976, 0.15 $\mu g\ m^{-3}$ in 1980, not measured in 1979) and may have increased the yield depression in unfiltered air. However, as with the studies on grass, there is evidence that filtering air containing low levels of pollution significantly improved crop growth.

3.4 Summary and Conclusions

In many fumigation experiments, mean concentrations of 50-60 ppb SO_2 alone have been shown to reduce grass yield, whereas lower concentrations had little or no effect. The presence of similar concentrations of NO_2 in addition to SO_2 usually further reduced yield, occasionally more than additively, particularly overwinter. In filtration experiments, SO_2 has been considered in most detail, although NO_x and O_3 will have been present in the unfiltered air. On several occasions, unfiltered air containing ~20 ppb SO_2 has been found to reduce the yield of grasses. In general, therefore, it may be noted that yield reductions have been found at lower SO_2 concentrations in filtration experiments than in fumigations, but there have been few fumigation experiments using levels of SO_2 typical of areas in which the filtration experiments were carried out (and none that included NO_2 at similar levels). Also, it has been noted that a probable explanation for at least part of the discrepancy between results obtained from many fumigation and filtration experiments is the presence of SO_2 alone in the former and a mixture of pollutants (SO_2, NO_x and O_3) in the latter.

Another cause of variation between the results obtained from fumigation and filtration experiments may be the existence of continually fluctuating concentrations of pollutants in the field, in comparison with relatively constant levels during fumigation experiments. However, fluctuating concentrations of SO_2, with a mean of 60 ppb or less, have produced relatively little evidence that use of varying levels produces different results from constant concentrations with the same mean (Garsed, Mueller & Rutter, 1982; Jones & Mansfield, 1982b). In addition, the effects of pollutants depend on environmental conditions such as light intensity, temperature and windspeed (Jones & Mansfield, 1982a; Ashenden & Mansfield, 1977). It may be important, for example, that in filtration experiments, pollutant concentrations vary with time of day (and therefore light intensity and temperature) and with the weather.

All these points are discussed in detail in Chapter 7.

From the summary above, it is clear that several aspects of the effects of ambient levels of pollution on crops are poorly understood. As a result, it is not possible to predict accurately the effects of ambient pollution on crop yield in the UK. In the present study, fumigation experiments were carried out with low mean concentrations (15-50 ppb) SO_2 and/or NO_2, the levels of which were fluctuated to give typical log-normal distributions. Furthermore, in one set of fumigation experiments the pollutant concentrations were varied according to the time of day, although in no case were the pollutant levels related to the weather. In addition, two overwinter filtration experiments were conducted in an area of low pollution. It was intended that these experiments would provide insight into the effects of ambient UK levels of SO_2 and NO_2 on the growth of crops, particularly grass species.

CHAPTER 4

FUMIGATION EXPERIMENTS, I

DOSE-RESPONSE WITH SO_2 + NO_2

4.1 Introduction

A review of previous fumigation work on the effects of SO_2 and NO_2 on crop growth is contained in Chapter 3. Most of these studies have used essentially constant or regularly intermittent concentrations and it was suggested that chronic injury (growth effects) caused by fumigation regimes and pollutant levels used to date cannot be related to growth effects caused by pollutants as they are experienced in the field.

One of the objects of this project was to study, as far as possible, the effects of ambient UK air pollution on crop growth. In view of the uncertainties involved in using more or less constant levels of pollutants it was decided to simulate ambient pollution levels as closely as possible, with the equipment available. Two sets of chambers were used (described fully in Sections 4.2 and 5.2). In a set of four chambers at the Central Electricity Research Laboratories (CERL) both SO_2 and NO_2 were added to three chambers at three concentrations designed to represent increasingly polluted environments, the fourth chamber acted as control. In these chambers the concentrations of pollutants were fluctuated on a daily basis to give the desired frequency distributions of daily means. Two experiments were performed, from November 1980 to August 1981 and from October 1981 to June 1982, and these form the subject of this chapter. In a set of six chambers at Imperial College, Silwood Park, SO_2, NO_2 and NO were added singly or as mixtures and fluctuated on an hourly basis to give suitable frequency distributions. Also, an attempt was made to simulate diurnal patterns and peak durations. Again two major experiments were carried out and these are described in Chapter 5.

In neither set of chambers was any attempt made to fluctuate concentrations according to the weather and it should also be noted that controlled fumigations add only 1, 2 or 3 pollutants to the 'background' levels that pass through the filters. Thus, even in chambers polluted with, say, SO_2, NO_2 and NO added at urban concentrations, the atmosphere is not the same as in an urban environment where other pollutants will be present; particularly O_3 (in summer), but also hydrocarbons, carbon monoxide and particulates. Plants growing in the field may also be subjected to acid rain as well as to dry deposition of the above-mentioned pollutants. In addition, the environmental conditions in the chambers, other than pollutant concentrations, may be different from ambient. Even using outdoor chambers (as in the present work), temperatures within the chambers will be higher than ambient and light intensity lower (Crittenden & Read, 1978a; Farrar, Relton & Rutter, 1977; Bell, 1980). Windspeed in the chambers will be constant and therefore may be more or less than ambient. Whether extrapolation is possible from results obtained under chamber conditions to a field situation is discussed in Chapter 7. However, it seems reasonable to suggest that the use of fluctuating concentrations, at realistic ambient levels of pollutants, is one step nearer to achieving an understanding of the effects of air pollution on crops.

4.2 Materials and Methods

The chambers used in these experiments were designed by Dr. T.M. Roberts and built at CERL. The use of hemispherical glasshouses was suggested by a system used for similar experiments at the University of Lancaster (Ashenden, Tabner, Williams, Whitmore & Mansfield, 1982), but modified to improve charcoal filtering, minimise environmental differences between the chambers and ambient air and to allow plants to be grown in the ground, as well as in pots. Staff from CERL maintained and monitored the pollutant levels and did the majority of the routine watering of the crops.

4.2.1 Chamber design and position

Each of the four chambers was based on a hemispherical glasshouse 4.4 m in diameter. These bear the tradename 'Solardome' and are referred to as such, or as 'domes', throughout this thesis. Each dome had a 30 cm high aluminium wall around the base, the rest was glass with thin aluminium struts that cast little shadow. The door was positioned on the north side.

The chambers were ventilated at a rate of about 4 air changes per minute: air was drawn through a block of charcoal filters and passed through a 75 cm diameter duct underground to be blown upward into each dome from its centre (Fig. 4.1). Vents in the aluminium wall around the base of each dome allowed the air out. A 'diffuser' was positioned above the mouth of the air duct to disperse the air-flow evenly around the dome and across the crop. The height of the diffuser could be adjusted according to crop height to give a suitable air flow. The diffuser cast a fairly large shadow over the crops in the north half of the dome. There was no artificial lighting or temperature control. Watering was by means of a spray system built into each dome: a fine spray could be turned on simultaneously in all the domes as required. Soil within each dome had been removed to a depth of 60 cm and replaced with a sandy loam.

The four domes were located on an east-west line, with dome 1 on the east and dome 4 on the west end.

4.2.2 Control experiment

Before conducting the long-term growth experiments in the Solardomes a soil analysis and short-term growth experiment were carried out by

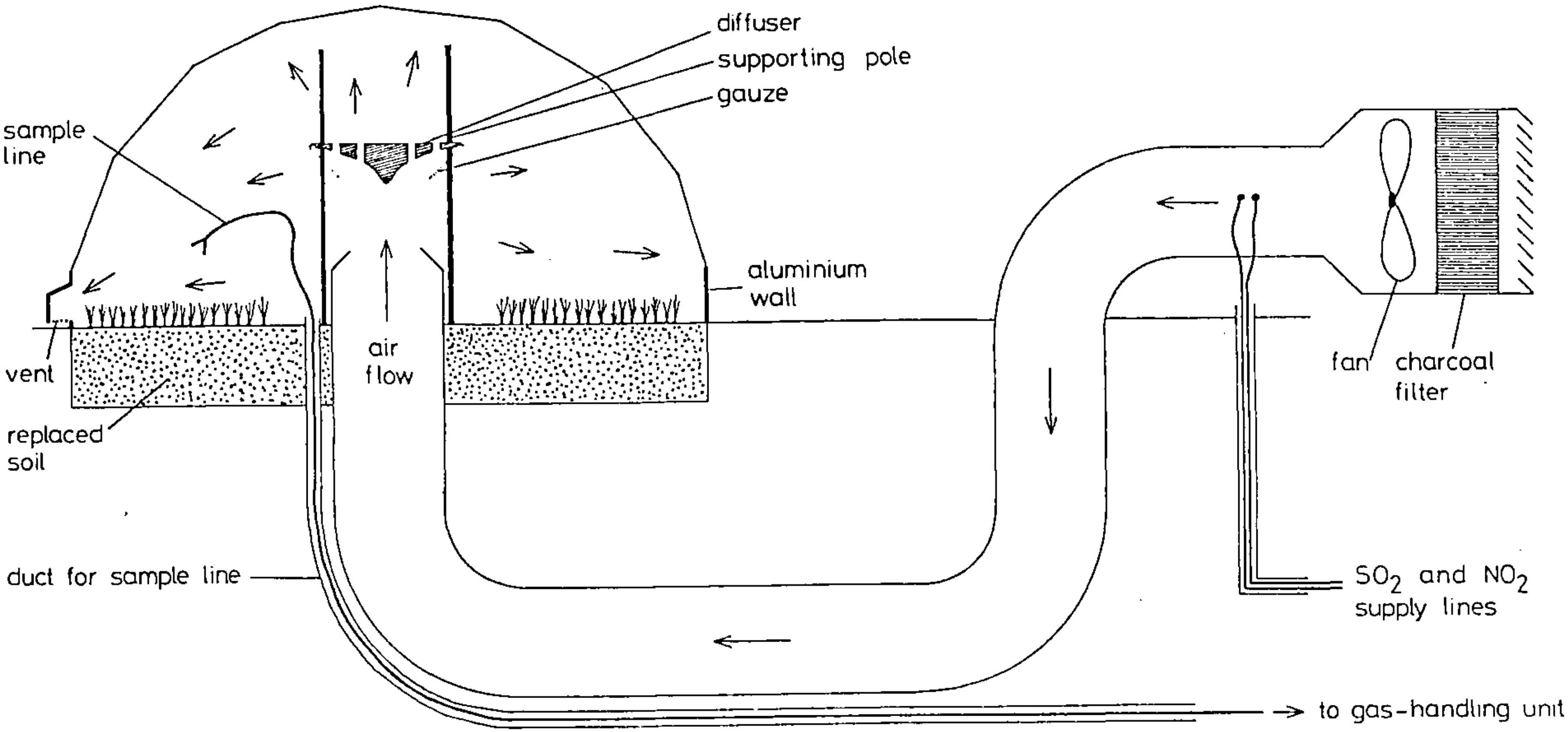


Figure 4.1 : Schematic diagram of Solardome.

Roberts (unpubl.) to check that, in the absence of added pollutants, conditions were equal in all the domes. The results of the soil analysis are shown in Table 4.1: there were no significant differences between any domes. To test environmental differences other than the soil, six tillers of *L. perenne* cv. S24 were planted in each of 16 crates of well-mixed soil. Four crates were placed in each dome on 1 September 1980 and removed after 53 days on 24 October. The dry weights per crate and S and N content of *L. perenne* are given in Table 4.1. None of the means were significantly different at $p < 0.05$.

4.2.3 Pollutant supply

In each experiment one dome received only filtered air and acted as a control chamber; SO_2 and NO_2 were added at three concentrations to the remaining domes. Pollutants were supplied from cylinders of 100% SO_2 or NO_2 (British Oxygen Company) kept in a heated (35°C) storeroom adjacent to the main shed which housed all the control and monitoring equipment for the domes. The store required heating because NO_2 liquifies below 22°C. Pressure from the SO_2 and NO_2 cylinders was controlled by stainless steel regulators (BOC Spectrol series) which led to 0.25 inch stainless steel tubing. In the case of SO_2, the tubing went directly into the main shed where it was divided into three lines, each with a mass-flow controller (Fig. 4.2). Shortly after passing through the mass-flow controller the SO_2 (flowing at 1-50 cm^3 per minute) was diluted with ambient air (4-5 litres per minute) and pumped along 0.25 inch diameter PTFE tubing into the main ducts (Figs. 4.1 and 4.2). The mass-flow controllers would not function with 100% NO_2 which therefore had to be diluted to about 20% with dry nitrogen (also from a cylinder). NO_2 and N_2 were fed into a mixing vessel at constant rates, using flowmeters to monitor and control their flow. From the mixing vessel a stainless steel 0.25 inch diameter tube

Table 4.1 : Results of analysis of soils from the Solardomes and from the control experiment (no added pollutants)
1 September-24 October 1980.
(Data from Roberts, pers. comm.)

		Dome			
		1	2	3	4
Soil	pH	7.3	7.4	7.4	7.2
	Total S content (%)	0.12	0.12	0.13	0.13
	Exchangable P content (ppm)	52	55	59	53
	Exchangable Mg content (ppm)	56	52	47	49
L. perenne cv. S24	Yield (g crate^{-1})	6.4	6.7	7.8	7.3
	Total S content (%)	0.48	0.47	0.50	0.48
	Total N content (%)	3.39	3.48	3.49	3.51

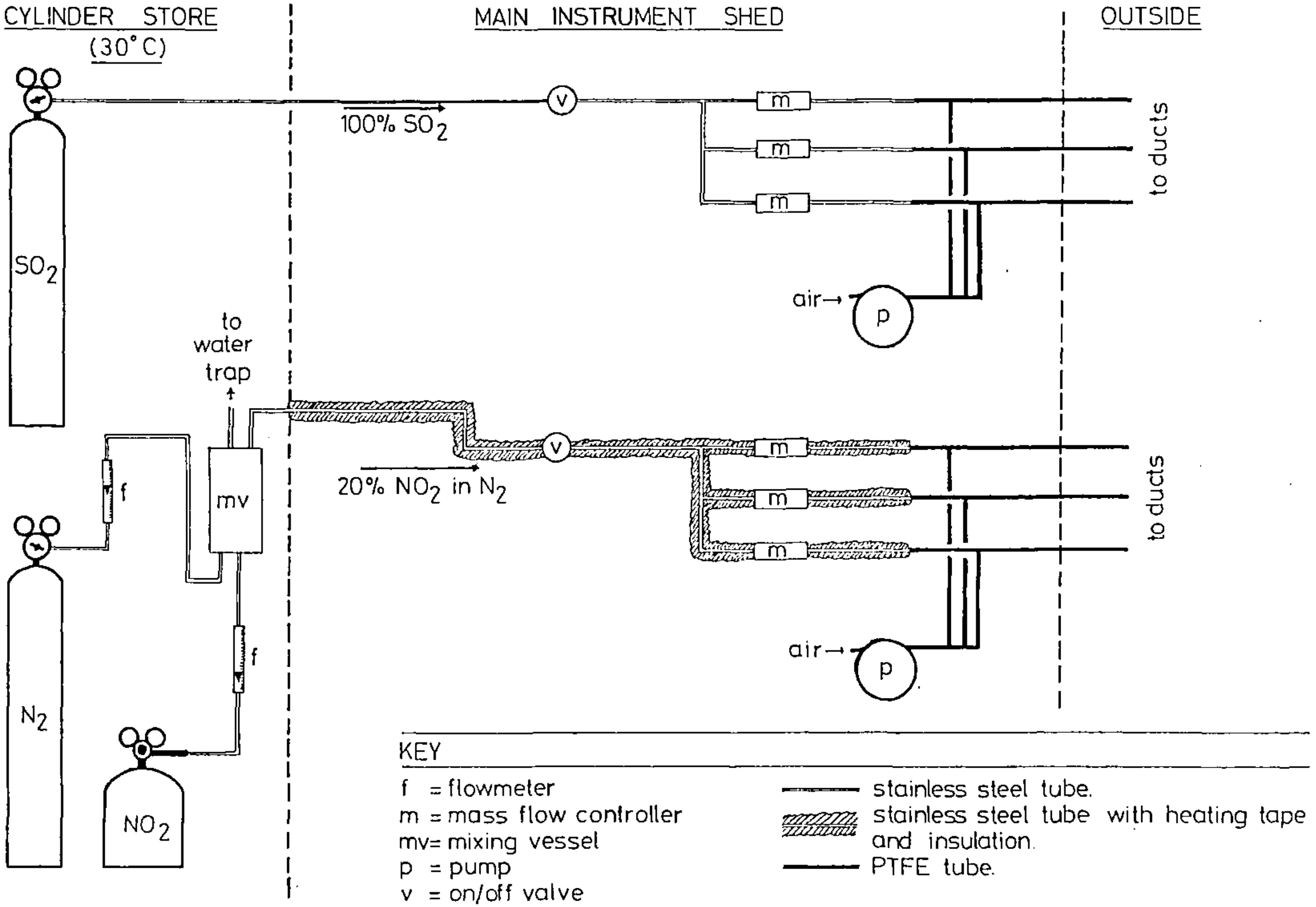


Figure 4.2 : Schematic diagram of pollutant control system for Solardomes.

lead into the main shed and divided into three, as with SO_2. This tubing was warmed to about 30°C using heating tape and insulated with standard pipe insulation (Figure 4.2). In addition, a by-pass line took excess NO_2/N_2 from the mixing vessel to a running-water trap. All the mass-flow controllers could be set independently to provide the desired concentrations of SO_2 or NO_2 in the domes.

As a safety precaution, if the measured concentration of SO_2 or NO_2 in any dome exceeded 250 ppb, or if the air flow in a main duct stopped, or a power failure occurred, a solenoid valve in each of the two main pollutant supply lines would close (Fig. 4.2).

Initial problems with controlling NO_2 delayed its supply to the domes until 13 February 1981. SO_2 was supplied from the start of each experiment, as was NO_2 from the start of the 1981-82 experiment. Gases were occasionally turned off due to instrument failure, and also in very cold weather both gases and fans were turned off. (It was felt that relatively fast-moving air and very low temperatures were not typical of a UK winter, i.e. in very cold weather the air is usually still. Also, in 1981-82 the temperatures dropped so low that gases and moisture froze in the pollutant supply lines and snow blocked the inlets and outlets to the chambers.) Otherwise pollutants were supplied essentially continuously, including weekends.

4.2.4 Choice of pollutant concentrations

The target long-term mean concentrations of both SO_2 and NO_2 in the three polluted domes were 20, 40 and 60 ppb, which will be referred to as the 'low', 'medium' and 'high' treatments respectively (cf. 35 ppb SO_2 and 25 ppb NO_2 are typical urban annual means, see Chapter 2). To achieve this, the daily mean concentrations at Bottesford during 1978-79 (supplied by CEGB, Midland Region, Scientific Services Dept.) were taken as a base from which to work. Mean concentrations at this site over 1978 and 1979 were 12 ppb SO_2 and 9 ppb NO_2 (Table 2.6). To give the required long-term means, each daily mean SO_2 and NO_2 concentration from Bottesford was multiplied by three factors (approximately 1.6, 3.2 and 4.8). The justification for using this approach with SO_2 is discussed in Section 2.2.1: its use for NO_2 is assumed since the SO_2:NO_2 ratio is often about 1:1 (Section 2.4). The domes receiving clean air and the three pollutant concentrations were altered from the first experiment to the second. In 1980-81 dome 2 acted as control and domes 4, 1 and 3 received low, medium and high levels of pollution respectively. In 1981-82 dome 1 received clean air, and increasing concentrations of SO_2 and NO_2 were given in domes 3, 2 and 4 respectively.

4.2.5 Pollutant monitoring

A 0.25 inch diameter PTFE sample line was placed in each of the domes with added pollutants, halfway between the centre and the edge and just above crop height (there was no spatial variation in concentration), a fourth sample line was used either to sample ambient air or the control dome. The lines were connected to a gas-handling unit (The Analytical Development Co. Ltd.) which pumped air along each line in turn at 15-20 litres per minute, changing from one line to the next every 5 minutes. The sample passed through the gas-handling unit and into a small, partially closed, container from which gas monitors subsampled for SO_2, NO_x and O_3 analysis. A flame photometric total sulphur analyser (Meloy, model SA285), a chemiluminescent nitrogen oxides analyser (Monitor Labs, model 8440) and an ultraviolet light ozone analyser (Dasibi, model 1003 HC) were used. The SO_2 and NO_x monitors were calibrated using an SO_2 calibrator (Meloy, model CS 10-2X) and a cylinder containing 240 ppb NO_2 (BOC Spectrol). The calibration of the O_3 monitor was checked against a known accurate O_3

analyser at AERE, Harwell. O_3 concentrations were monitored only as a check and were generally found to be less than 10 ppb in the chambers.

NO_2 monitoring did not begin until supply began on 13 February 1981. Prior to this a concentration of 5 ppb NO_2 in all domes was assumed. Outputs from the monitors were to chart-recorders from which daily means were read. Monthly means and means corresponding to each harvest period were calculated, as were cumulative frequency distributions, over each experimental period.

Comparisons were made between pollutant concentrations in ambient air and filtered air in the domes. The filtering efficiency for SO_2 was greater than 80%, but for NO_2 was about 50%. These efficiencies were used to calculate pollutant concentrations inside the control dome when ambient air was being monitored.

At all stages of the sampling operation the sample was only in contact with stainless steel or PTFE in order to minimise loss of pollutants by adsorption. The lines to the domes were 15-20 m long but pollutant loss was found to be less than 10% (Roberts, pers. comm.).

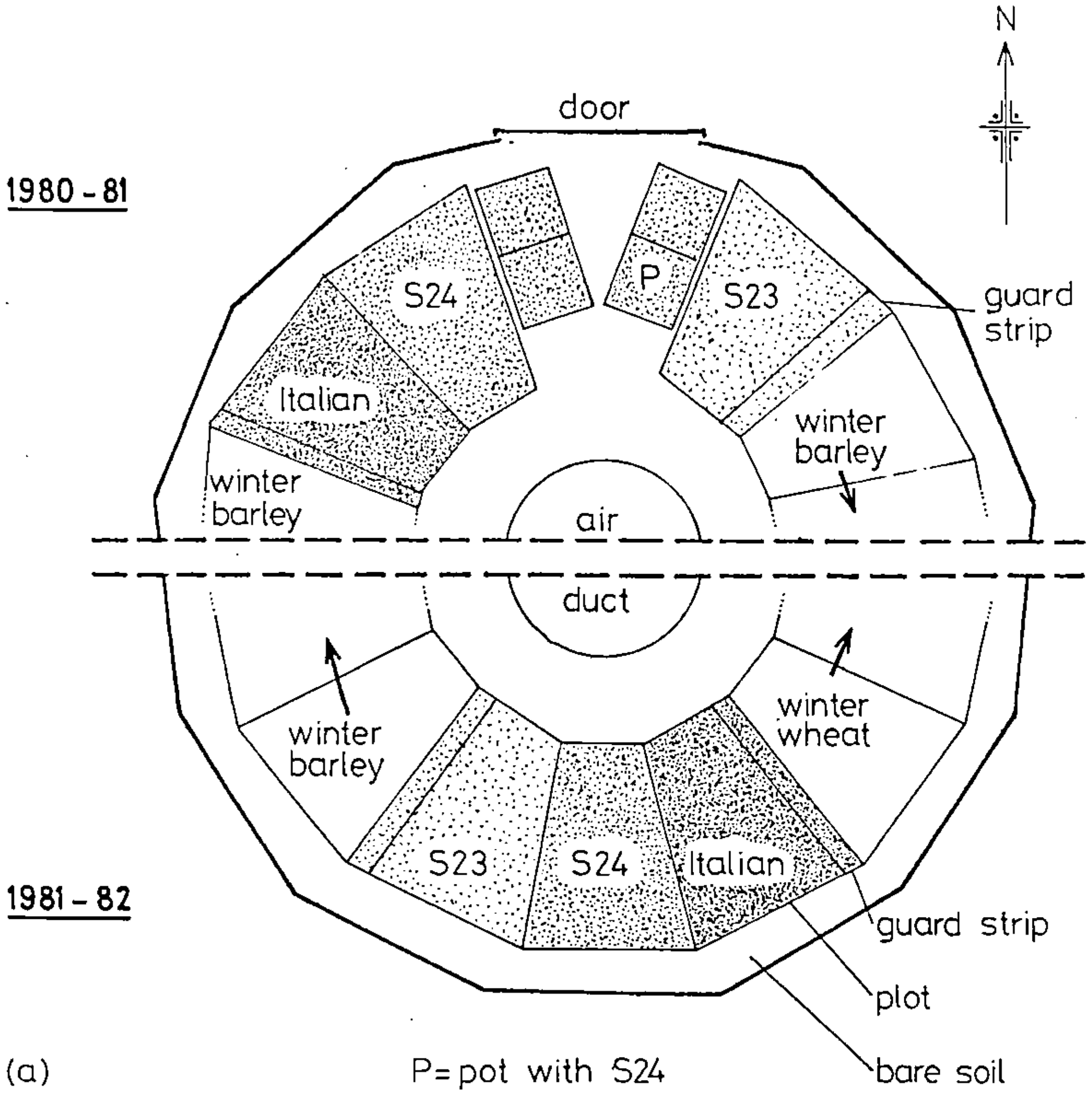
4.2.6 Species, planting and harvesting

For both major experiments three species/cultivars were grown in each dome: *Lolium perenne* cvs S23 and S24 (perennial ryegrass) and *L. multiflorum* cv. RvP (Italian ryegrass). For convenience these cultivars will be referred to as 'S23', 'S24' and 'Italian' respectively. Plots of each cultivar were sown in the north half of each dome in 1980 but in the south half in 1981 (Fig. 4.3a). Guard strips (approximately 10 cm wide) of S23 or Italian were sown where the plots of these cultivars were adjacent to wheat or barley being grown by Dr. T.M. Roberts (Fig. 4.3a). Each plot was subdivided into ten 20 x 20 cm subplots, permanently marked with small plastic labels at each corner (Fig. 4.3b). These subplots formed the

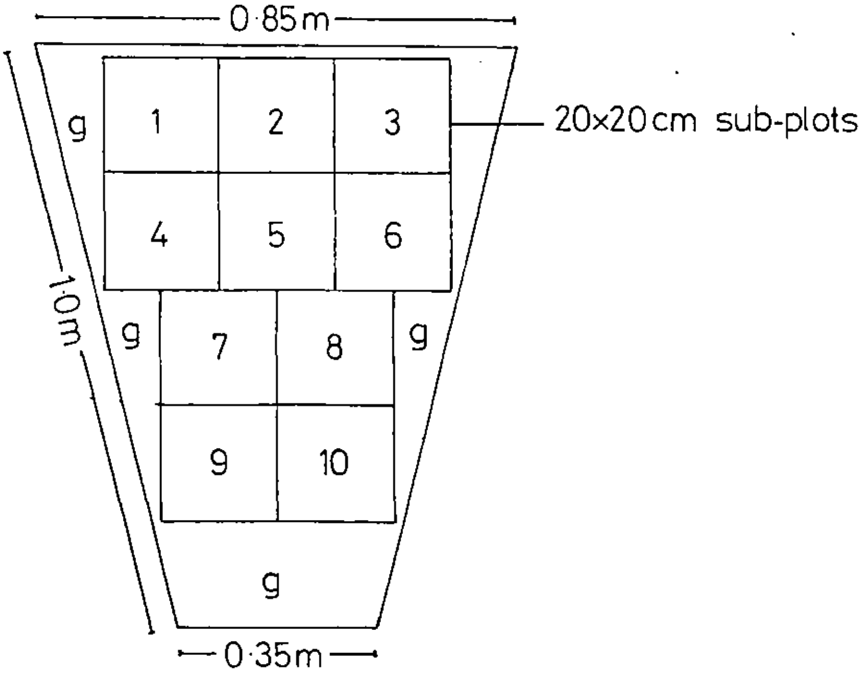
Figure 4.3 : Position of crops within the Solardomes.

(a) Areas of ground sown with *Lolium perenne* cvs S23 and S24 and *L. multiflorum* (Italian ryegrass) in 1980-81 and 1981-82. (Crops adjacent to the ryegrasses in each year are also indicated. The pots containing S24 were sunk into the ground so that the top of the pots were 3 cm above soil level. They are not part of the present experiment.)

(b) Subplot designation within each plot. The area in the plot marked 'g' was sown with seed as a guard area but discarded at harvests.



(a) P = pot with S24



(b)

'replicates' for each cultivar/treatment.

All three cultivars were treated in a similar manner in both years.

1980-81

Prior to sowing seed the soil was dug and raked level. Seed (obtained from Parkwood Feeds Ltd.) was sown 1 cm deep on 7 November 1980 at 30 kg ha^{-1}, at the same time standard 15:15:15 NPK granular fertiliser was applied at a rate of 60 kg N ha^{-1}. Germination had occurred by 21 November 1980. In order to standardise the plant densities, seedlings were thinned to 46 plants per 20 x 20 cm subplot ($\equiv$ 1150 plants m^{-2}) on 17 December 1980. On 6 January 1981 21 plants per plot were pulled up and dried; roots were removed prior to weighing the shoots individually. (The plant nearest to each of the 21 marker pegs was chosen to 'randomise' the sample.) On 9 March 1981 60 kg N ha^{-1} 15:15:15 NPK fertiliser was added to each plot.

Four major harvests were carried out: 25-27 March, 11-13 May, 15-17 June and 10-12 August 1981. Each harvest took three days as only one cultivar could be harvested per day, but subsequent references to harvest dates will refer to the middle day only, or simply to the month. Harvests were done by cutting each subplot to 4 cm. The removed shoot material from five subplots per cultivar per dome was divided into 'dead leaves' and 'live leaves plus stem' at the June and August harvests (at the March and May harvests there was essentially no dead material). All shoot material was dried at 80°C for at least three days before weighing. Spike numbers were counted when present and plant numbers were counted after the final harvest. The 'guard area' around the subplots ('g' in Fig. 4.3b) and the guard strips were also cut to 4 cm at each harvest but the material was discarded.

Fertiliser (60 kg N ha^{-1}) was added to each plot immediately after the May harvest and on 7 July, about three weeks after the June harvest. Over the season as a whole 240 kg N ha^{-1} was applied. A summary of all major dates, and age of the sward, is given in Table 4.2.

1981-82

Between the end of the 1980-81 experiment and the start of the 1981-82 experiment the soil was removed from the domes, thoroughly mixed, and then returned. Treatments were similar to the previous year. Seed was sown and fertiliser applied (at 30 kg ha^{-1} and 60 kg N ha^{-1} respectively) on 15 October 1981. No thinning was carried out because it had been suggested that it may have affected the results: for example, if germination or seedling establishment was affected by the treatments, then thinning to a constant density would mask such effects. Twenty one single plants were removed on 16 February 1982, dried and weighed.

Three major harvests were carried out, centred on 24 March, 19 May and 9 July 1982. Plant numbers were counted at each harvest. At the March harvest there was no dead shoot material, but dead leaves were present at the May and July harvests. After the final harvest the remaining 'stubble' in each subplot was cut to soil level, dried and weighed. Root samples were taken after the final harvest by removing two 3.75 cm diameter x 15 cm deep cores from each of 5 subplots per cultivar per treatment. The two cores were bulked to give one sample per subplot. The roots were separated from the soil by placing the sample in a sieve where the soil was gently removed under running water. Inevitably a large proportion of fine roots were lost, but this loss was assumed to be equal between treatments.

No fertiliser was applied in March, but 60 kg N ha^{-1} 15:15:15 NPK fertiliser was applied immediately after the May harvest. A summary of all major events is given in Table 4.2.

Table 4.2 : Summary of major events in the Solardomes, with dates and age of sward (days) for 1980-81 and 1981-82. The swards were fumigated from emergence.

Event	1980-81		1981-82	
	Date	Age of sward	Date	Age of sward
Sow seed and apply fertiliser	7 November 1980	-	15 October 1981	-
Germination	21 November 1980	1	26 October 1981	1
Thin to 46 plants/subplot	17 December 1980	27	not carried out	-
Harvest 21 single plants	6 January 1981	46	16 February 1982	114
Apply fertiliser (60 kg N ha^{-1})	9 March 1981	108	none applied	-
Major harvest	27 March 1981	126	24 March 1982	150
Major harvest	12 May 1981	172	19 May 1982	206
Apply fertiliser (60 kg N ha^{-1}	12 May 1981	172	19 May 1982	206
Major harvest	16 June 1981	207	9 July 1982	257
Apply fertiliser (60 kg N ha^{-1})	7 July 1981	228		
Major harvest	11 August 1981	263		

In subsequent sections parameters are referred to by the following abbreviations:

DW = dead leaf dry weight (above 4 cm),
TW = total shoot dry weight (above 4 cm),
RW = root dry weight,
%D = % dead material, (DW/TW) x 100.

N.b. a 'leaf' is defined as only the lamina
and does not include the leaf sheath.

4.2.7 Maintenance

Watering was carried out as necessary to maintain moist soil. Weeds were removed as required. Plants were sprayed against aphids with Metasystox 55 (Bayer, UK Ltd.) and against powdery mildew with Benlate (Pan Britannica Industries Ltd.). Infection was never severe and differential infection between treatments was not observed.

4.2.8 Nitrogen and sulphur analysis

Dried samples from harvests in March 1981 (S23 only) and May 1981 (S23, S24 and Italian) were analysed for sulphur and nitrogen content. About 4 g of dried shoot material from each of 6 subplots per cultivar per treatment was ground to a fine powder. Sulphur analysis was performed on all 6 subsamples per cultivar per treatment, but nitrogen analysis on only 3 subsamples per cultivar per treatment from the May harvest. Prior to analysis the powder was redried at 80°C. A member of the technical staff at CERL performed all the sulphur and nitrogen analyses using a LECO total sulphur analyser and the kjeldahl method for nitrogen analysis (Allen, Grimshaw, Parkinson & Quarmby, 1978).

4.2.9 Analysis of results and statistics

All cultivars were treated similarly in both years.

The first harvests in each experiment (single plants) were tested for differences using analysis of variance (anovar). The weight m^{-2} was calculated assuming a density of 1150 plants m^{-2} in 1981 and using the plant densities at the March harvest in 1982. Significant differences in weight m^{-2} were assumed to be the same as those for weight $plant^{-1}$.

Data from each harvest were analysed separately, but results from consecutive harvests were also summed to give 'results to date'. With results on a m^{-2} basis this was done simply by adding the results for each respective subplot and using the totals thus obtained for analysis. In 1981 plant numbers were counted only at the final harvest and cumulative total mean yields $plant^{-1}$ per subplot were calculated as cumulative total shoot weight in subplot divided by the number of plants in subplot at the final harvest. However, in 1982 the plants were counted at each harvest and the mean weight $plant^{-1}$ per subplot at each harvest was calculated. These were then summed for their respective subplots for analysis. Similar techniques were used for spike number. The cumulative %D was defined as total dead weight to final harvest x 100, divided by total shoot weight to final harvest. %D data were arcsine transformed before analysis.

Weight $plant^{-1}$ was calculated as weight in subplot divided by the number of plants in subplot and should strictly be referred to as a mean weight $plant^{-1}$. Describing results for treatments would then require such parameters as 'average mean weight $plant^{-1}$'. In these experiments the word mean is only used for the average of 10 (or 5) subplots.

Each parameter was tested for having a normal distribution and equal variances in all treatments. Most of the data satisfied these criteria ($p < 0.05$). Several statistical tests were performed on a few parameters that did not fit the requirements for anovar: two-way anovar and t-tests were employed on raw data and $\log_{10}$ raw data; Friedman two-way anovar and Wilcoxon matched pairs, signed ranks, tests were used on the unconverted data. The significant differences found were essentially the same whichever test was used. Since most raw data satisfied the requirements for anovar (normal, equal variances), and other tests gave similar results to anovar, it was decided to use two-way anovar on all parameters, with treatment and subplot position as factors. Means were compared using least significant difference (LSD) for $p = 0.05$. Strictly, LSDs should only be used to make a priori comparisons, but they were used here to make all possible comparisons. The small error thus introduced was not considered important.

The arcsine transformed data were tested for significant differences using anovar and LSDs as above, but the means were back-transformed to percent for convenience. The back-transformed means have asymmetrical standard errors and so the latter are not quoted in the results.

4.3 Results

4.3.1 Pollutant concentrations

Monthly mean concentrations of SO_2 and NO_2 in each treatment for the duration of both experiments are shown in Figure 4.4. Mean concentrations from the start of the experiments until each harvest, and between consecutive harvests, are listed in Tables 4.3 and 4.4 for 1980-81 and 1981-82 respectively. Over the whole period of each experiment mean SO_2 concentrations in the control, low, medium and high treatments were 2, 17, 34 and 51 ppb in 1980-81 and 3, 18, 34 and 52 ppb in 1981-82 (Tables 4.3 and 4.4). The actual treatment concentrations are below the designed levels of 20, 40 and 60 ppb because of unavoidable 'downtime' (control

Figure 4.4 : Monthly mean concentrations of SO_2 and NO_2 in each treatment during the 1980-81 and 1981-82 experiments in the Solardomes.

——— control treatment

- - - low treatment

----- medium treatment

——— high treatment

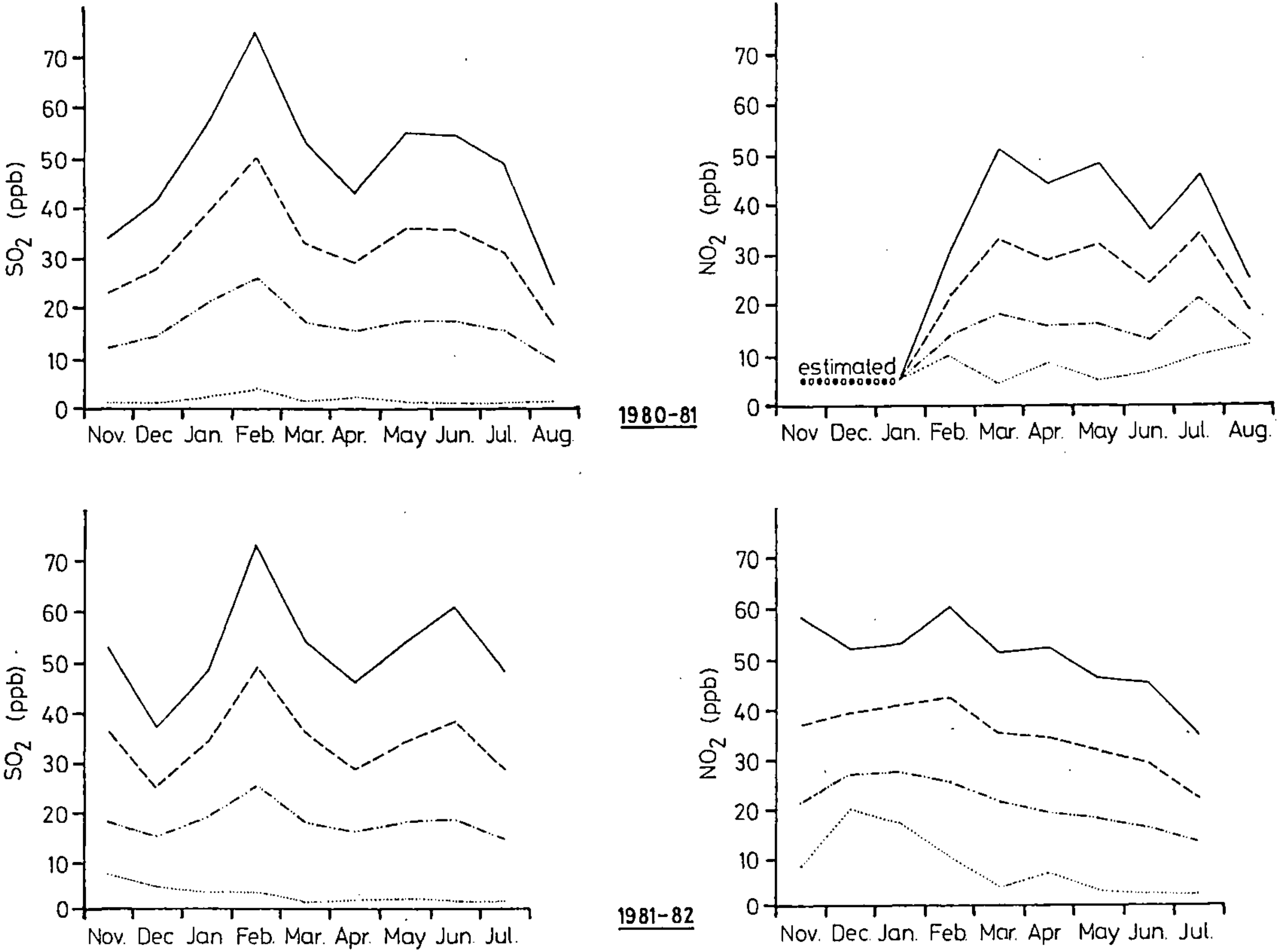

SO2 (ppb)
0
10
20
30
40
50
60
70
Nov. Dec Jan. Feb. Mar. Apr. May Jun. Jul. Aug.
1980-81
NO2 (ppb)
0
10
20
30
40
50
60
70
estimated
Nov Dec. Jan. Feb. Mar. Apr. May Jun. Jul. Aug.
SO2 (ppb)
0
10
20
30
40
50
60
70
Nov. Dec Jan Feb. Mar. Apr. May Jun. Jul.
1981-82
NO2 (ppb)
0
10
20
30
40
50
60
70
Nov. Dec. Jan. Feb. Mar. Apr May Jun. Jul.

Table 4.3 : Mean concentrations (ppb) of SO_2 and NO_2 in each treatment for the periods up to each harvest and between consecutive harvests during 1980-81.

Period	SO_2 (ppb)				NO_2 (ppb)			
	Control	Low	Medium	High	Control	Low	Medium	High
20 November 1980-6 January 1981	1.3	12.9	24.6	36.3	5.0(1)	5.0(1)	5.0(1)	5.0(1)
20 November 1980-26 March 1981	2.1	19.1	36.2	54.9	6.0	9.4	13.9	19.2
27 March-12 May 1981	2.3	16.1	30.0	45.6	8.1	18.7	34.5	52.0
13 May-16 June 1981	1.0	17.5	35.5	55.0	4.4	11.7	22.4	33.5
17 June-11 August 1981	1.2	14.9	29.9	45.8	10.0	18.2	29.7	41.7
20 November 1980-12 May 1981	2.2	18.2	34.7	52.4	6.9	11.9	19.5	28.1
20 November 1980-16 June 1981	2.0	18.1	34.8	52.8	6.0	11.9	20.0	29.0
20 November 1980-11 August 1981	1.8	17.4	33.8	51.4	7.3	13.2	22.0	31.7

(1) estimated (see text)

Table 4.4 : Mean concentrations (ppb) of SO_2 and NO_2 in each treatment for the periods up to each harvest and between consecutive harvests during 1981-82.

Period	SO_2 (ppb)				NO_2 (ppb)			
	Control	Low	Medium	High	Control	Low	Medium	High
1 November 1981-16 February 1982	3.5	19.1	35.6	52.0	14.3	24.4	38.5	54.1
1 November 1981-24 March 1982	3.6	19.0	35.8	53.0	13.1	24.2	38.6	54.5
24 March-18 May 1982	1.9	16.2	30.1	48.0	7.8	20.4	35.8	52.5
19 May-9 July 1982	1.9	18.1	37.3	58.9	3.7	14.9	27.0	41.2
1 November 1981-18 May 1982	3.2	18.1	34.1	51.4	11.6	23.1	37.8	54.0
1 November 1981-9 July 1982	3.0	18.0	34.4	52.5	10.6	21.5	35.6	51.5

failure, pollutants and fans off in very cold weather). Mean NO_2 concentrations in 1981-82 were 10, 21, 36 and 51 ppb which, with the exception of the control treatment were similar to their respective SO_2 levels. In the 1980-81 experiment mean NO_2 concentrations were only 7, 13, 22 and 32 ppb, the low, medium and high treatments being greatly influenced by the lack of NO_2 supply for the first three months. Means from 13 February to 11 August 1981 were 17, 30 and 44 ppb NO_2 in the low, medium and high treatments respectively, similar to those in 1981-82 over the same period (compare data in Tables 4.3 and 4.4 for March harvest onwards; also see Figure 4.4).

Concentrations of NO_2 and SO_2 were fluctuated daily and the cumulative frequency distributions for daily mean SO_2 and NO_2 concentrations in all treatments for 1980-81 (NO_2 from 13 February only) and 1981-82 are illustrated in Figures 4.5 and 4.6. In all cases the cfd's are approximately log-normal over the upper 80% of their ranges. On about 18% of days in 1980-81 the pollutants were off and concentrations in the domes were near zero, hence the abrupt 'cut-off' point in the low, medium and high treatments. In 1981-82, more experience with the fumigation system reduced downtime to about 10%. Higher background concentrations of SO_2 and NO_2 resulted in less distinct departures from log-normality at low concentrations. The slopes of the cfd's are similar to those illustrated in Figure 2.12 for cfd's of daily mean SO_2 concentrations averaged over several sites.

4.3.2 Effects of treatments on yield

The yield results are all presented in essentially the same manner: for the control treatment the mean yields at each harvest and cumulative yields to date are given, but yields in the low, medium and high treatments are expressed as percent of control. Results are presented in this way,

<u>Figure 4.5</u> : Cumulative frequency distributions of SO_2 and NO_2 daily means in the Solardomes:

SO_2, 20 November 1980-11 August 1981

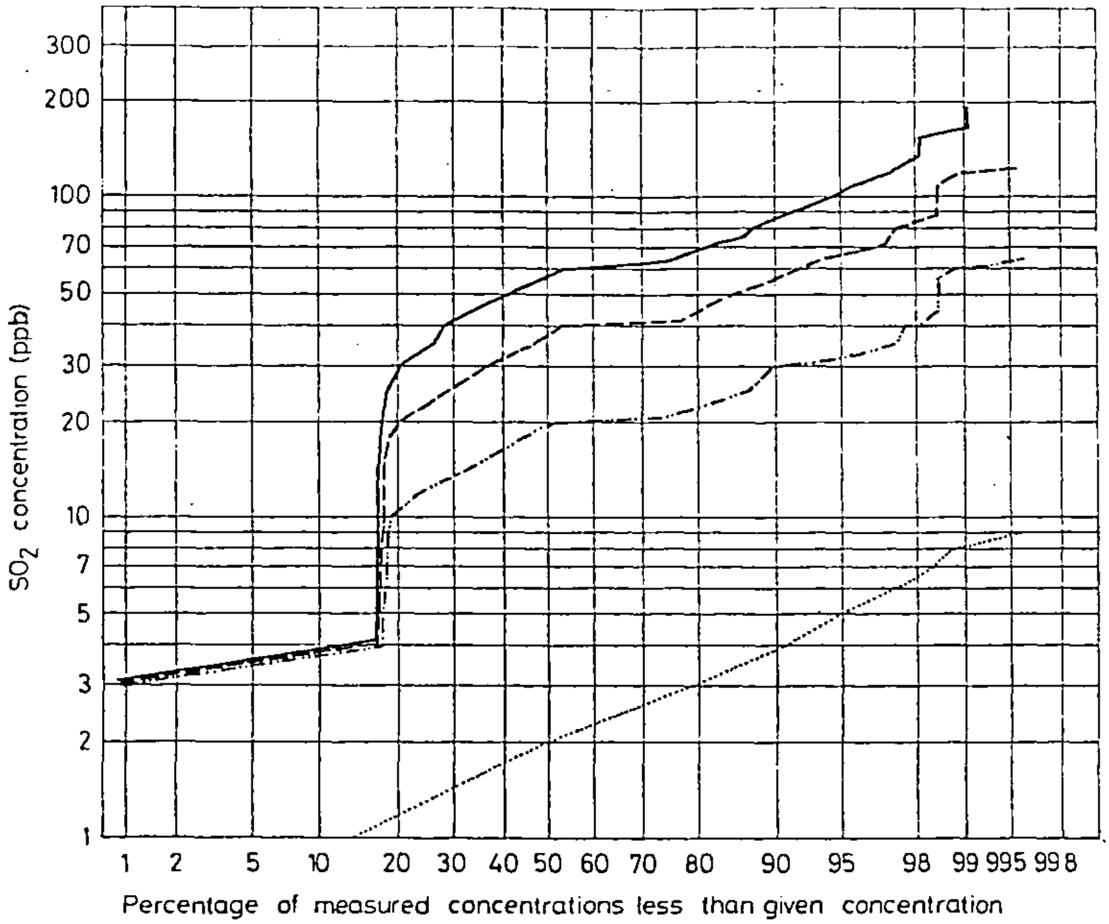
NO_2, 13 February-11 August 1981

········ control treatment

\- - - low treatment

\----- medium treatment

——— high treatment


300
200
100
70
50
30
20
10
7
5
3
2
1
SO$_2$ concentration (ppb)
1 2 5 10 20 30 40 50 60 70 80 90 95 98 99 995 99 8
Percentage of measured concentrations less than given concentration

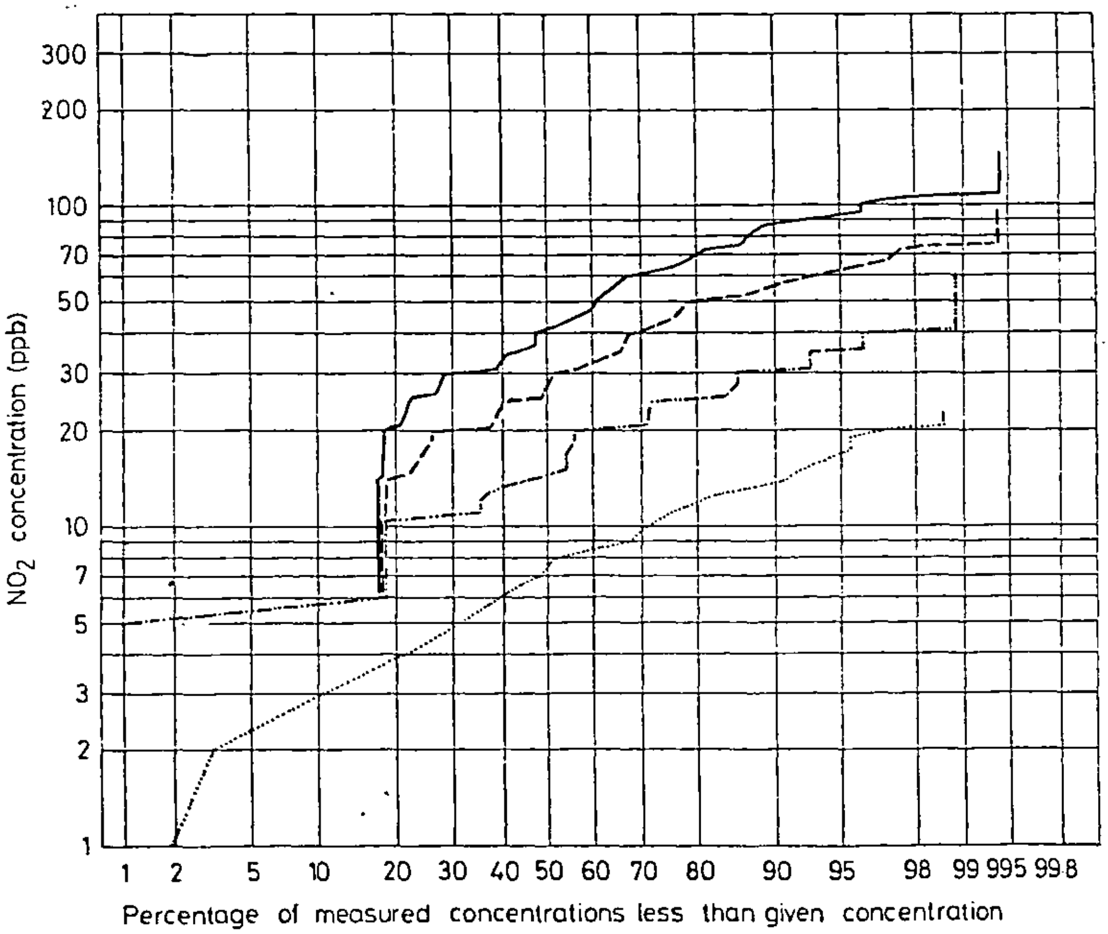

300
200
100
70
50
30
20
10
7
5
3
2
1
NO$_2$ concentration (ppb)
1 2 5 10 20 30 40 50 60 70 80 90 95 98 99 995 99 8
Percentage of measured concentrations less than given concentration

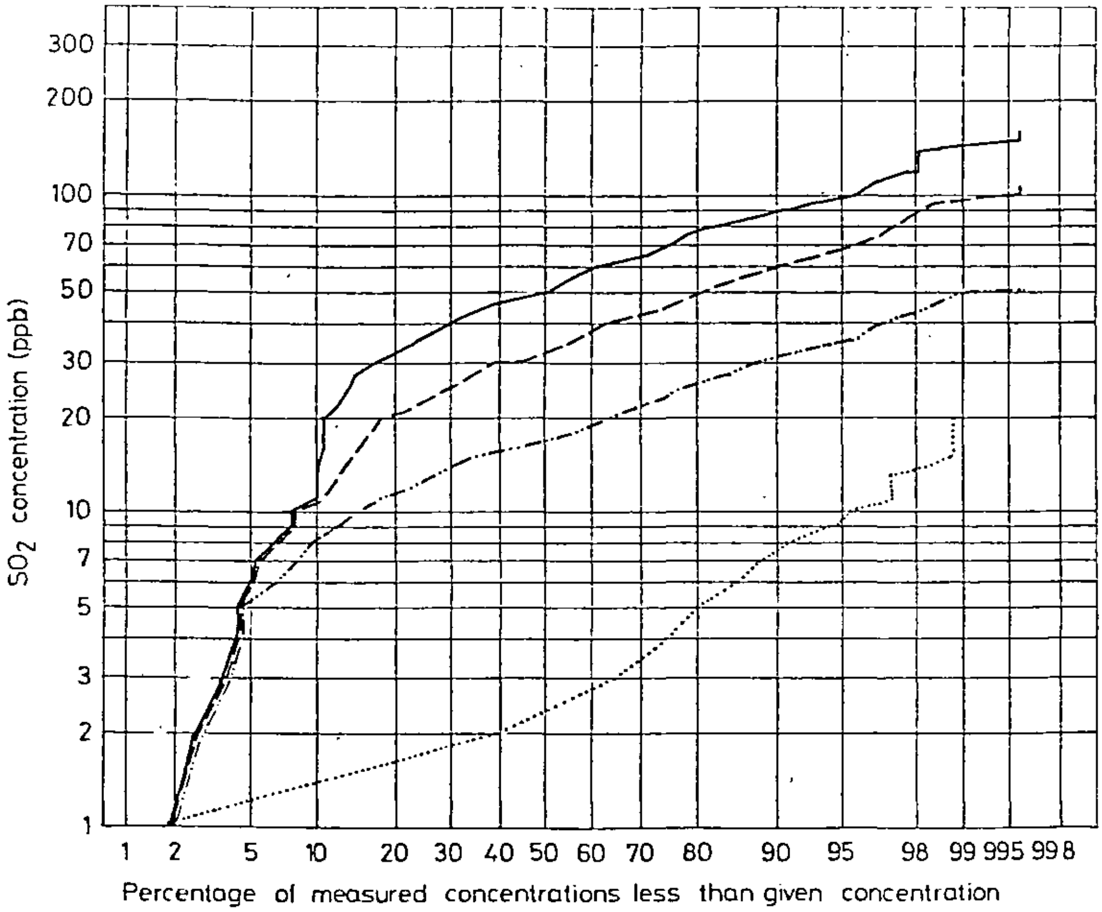
Figure 4.6 : Cumulative frequency distributions of SO_2 and NO_2 daily means in the Solardomes: SO_2 and NO_2 both from 1 November 1981-9 July 1982.

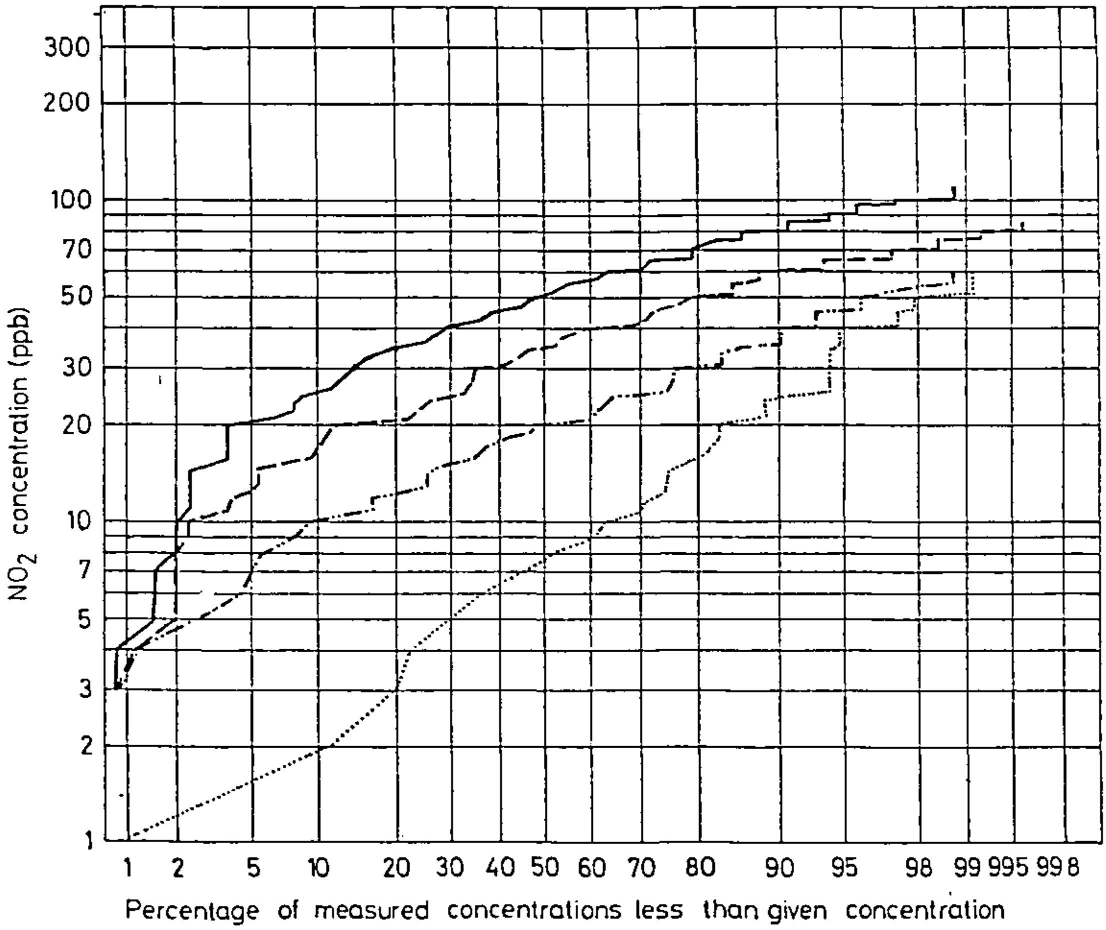
——— control treatment

– – – low treatment

----- medium treatment

——— high treatment


300
200
100
70
50
30
20
10
7
5
3
2
1
SO2 concentration (ppb)
1
2
5
10
20
30
40
50
60
70
80
90
95
98
99
995
998
Percentage of measured concentrations less than given concentration


300
200
100
70
50
30
20
10
7
5
3
2
1
NO2 concentration (ppb)
1
2
5
10
20
30
40
50
60
70
80
90
95
98
99
995
998
Percentage of measured concentrations less than given concentration

rather than listing all the mean weights (although these are included in Appendix 3), since it facilitates comparison between treatments within each harvest, and relative changes in treatment effect from one harvest to the next can easily be seen. Consideration of the percentage changes due to treatment in conjunction with the relevant control mean gives information on the importance of the effects from the point of view of total crop yield.

Yields for each cultivar within each treatment and at each harvest varied greatly between subplots. In the first experiment, subplots adjacent to the barley (Fig. 4.3) grew relatively poorly in comparison with other subplots. This was attributed to shading by the barley rather than root competition. In 1981-82 the plots near the outside of the domes yielded least. Again shading was thought to be the explanation, but by the aluminium wall around the base of the domes, rather than adjacent crops. Indeed, subplots next to the wheat or barley (Fig. 4.3) did not grow noticeably less than more central subplots. The effect of shading in 1981-82 was more pronounced over winter than in summer because, due to the fast summer growth, after harvesting the swards quickly became taller than the wall.

Total shoot dry weight

Total shoot (above 4 cm) dry weights (TW) of *L. perenne* cv. S23 for 1980-81 and 1981-82 are given in Table 4.5. By the final harvest in both experiments TWs m^{-2} in all treatments were not significantly different at $p = 0.05$. On 6 January 1981, when the sward was 46 days old and had only been subjected to SO_2, the low and medium treatments reduced TW m^{-2} of S23 by 29 and 23% respectively, but the high treatment had no effect. A similarly early harvest was not carried out in 1982 but in February, when the sward was 114 days old, there were no treatment effects. By March

Table 4.5 : TW of *L. perenne* cv. S23 grown in the Solardomes: (a) 1980-81, (b) 1981-82.

(a)

Harvest date	Days growth	TW (mean ± S.E.M.) in control (g m^{-2})	n	TW as % control(2)			
				Control	Low	Medium	High
6 Jan. 81	46	5.3(1)	21	100 a	71 b	77 b	85 ab
26 Mar. 81	125	21.4 ± 1.1	10	100 a	273 c	204 b	252 c
12 May 81	47	201 ± 14	10	100 a	152 b	144 b	133 b
16 June 81	35	328 ± 24	10	100 a	98 a	138 b	74 a
11 Aug. 81	56	349 ± 78	10	100 -	105 -	94 -	90 -
Total to:							
12 May 81	172	222 ± 14	10	100 a	163 b	150 b	144 b
16 June 81	207	550 ± 32	10	100 a	125 b	143 b	102 a
11 Aug. 81	263	900 ± 95	10	100 -	117 -	124 -	98 -

(b)

Harvest date	Days growth	TW (mean ± S.E.M.) in control (g m^{-2})	n	TW as % control(2)			
				Control	Low	Medium	High
16 Feb. 82	114	38.4(1)	21	100 -	123 -	108 -	100 -
24 Mar. 82	150	96 ± 15	10	100 -	86 -	110 -	105 -
19 May 82	56	190 ± 27	10	100 a	170 b	158 b	181 b
9 July 82	51	625 ± 35	10	100 -	92 -	88 -	82 -
Total to:							
19 May 82	206	286 ± 39	10	100 a	141 b	141 b	155 b
9 July 82	257	911 ± 43	10	100 -	107 -	104 -	105 -

(1) estimated from individual plant weights.

(2) percentages in each row are not significantly different when above the same letter ($p = 0.05$); '-' indicates no significant differences; exact results for all treatments are in Appendix 3, Table A3.1.

1981 (Table 4.5a) all three treatments with added SO_2 and NO_2 yielded at least twice as much as the control treatment, but in March 1982 (Table 4.5b) there were no effects on TW m^{-2}. The TW in the control treatment in March 1981 was 21 g m^{-2} compared with 96 g m^{-2} in March 1982, although the harvesting dates were similar, suggesting that the large effects seen in 1981 were due to very slow growth in the control chamber (for an unknown reason) rather than due to pollutants increasing growth in the other chambers.

From March to May in both experiments S23 produced about 200 g m^{-2} in the control treatments. Addition of SO_2 and NO_2 resulted in an increase in TW m^{-2} of about 40% in 1981 and 70% in 1982, but there was otherwise no apparent relationship between TW m^{-2} and pollutant concentration. After the May harvests, TWs m^{-2} of S23 in all treatments (within each harvest) were not significantly different from control, except for the medium treatment in June 1981.

The cumulative total yields reflect the individual harvests proportionately: larger individual harvest yields having greater influence. The growth from 12 May-11 August 1981 (about 670 g m^{-2} in control) and from 19 May to 9 July 1982 (about 625 g m^{-2}) represents approximately 75% of the total yield in each experiment, and during these months there was generally no treatment effect on TW m^{-2}, explaining the lack of treatment effect over each season as a whole.

TWs m^{-2} for *L. perenne* cv. S24 in both experiments are given in Table 4.6. As with S23, by the final harvest there were no significant treatment effects on cumulative TW m^{-2} in either experiment. On 6 January 1981 the low and high treatments yielded 22 and 26% less than control respectively. In February 1982 there were no treatment effects. By 26 March 1981 swards of S24 in the low, medium and high treatments all yielded significantly

Table 4.6 : TW of *L. perenne* cv. S24 grown in the Solardomes: (a) 1980-81, (b) 1981-82.

(a)

Harvest date	Days growth	TW (mean ± S.E.M.) in control ($g\ m^{-2}$)	n	TW as % control(2)			
				Control	Low	Medium	High
6 Jan. 81	46	6.4(1)	21	100	78	93	74
				a	bc	ab	c
26 Mar. 81	125	46.7 ± 2.4	10	100	118	137	117
				a	b	c	b
12 May 81	47	301 ± 32	10	100	139	149	113
				a	b	b	a
16 June 81	35	338 ± 31	10	100	108	116	115
				-	-	-	-
11 Aug. 81	56	476 ± 68	10	100	105	99	115
				-	-	-	-
Total to:							
12 May 81	172	348 ± 32	10	100	136	148	113
				a	b	b	a
16 June 81	207	686 ± 50	10	100	122	132	114
				a	b	b	ab
11 Aug. 81	263	1162 ± 105	10	100	115	119	114
				-	-	-	-

(b)

Harvest date	Days growth	TW (mean ± S.E.M.) in control ($g\ m^{-2}$)	n	TW as % control(2)			
				Control	Low	Medium	High
16 Feb. 82	114	50.1(1)	21	100	129	85	94
				-	-	-	-
24 Mar. 82	150	88 ± 19	10	100	120	136	110
				-	-	-	-
19 May 82	56	336 ± 65	10	100	139	145	131
				a	b	b	b
9 July 82	51	457 ± 39	10	100	111	103	97
				-	-	-	-
Total to:							
19 May 82	206	425 ± 83	10	100	135	143	127
				a	b	b	b
9 July 82	257	882 ± 92	10	100	123	122	111
				-	-	-	-

(1) and (2) as Table 4.5 except results in Table A3.2.

more TW m^{-2} than the control and the yield in the medium treatment was significantly greater than in low or high. The percentage differences in treatment means in March 1982 were very similar to those in March 1981, but were not significant. At the May harvests in 1981 and 1982, low and medium treatments caused significant increases in TW m^{-2} of 40-50% and in 1982 the high treatment also caused a yield increase (of 31%). There were no treatment effects after the May harvests in either experiment (similar to S23).

The final cumulative TW m^{-2} of S24 was 1162 g m^{-2} after 263 days growth in 1981 compared with 882 g m^{-2} after 257 days growth in 1982. S24 outyielded S23 by about 30% in 1981 but yielded slightly less than S23 in 1982.

The TW of *L. multiflorum* was little affected by any of the treatments in either experiment (Table 4.7). The only significant effects were at the January 1981 harvest, where TW m^{-2} in the low and medium treatments were about 30% greater than in the control, and in 1981-82 the high treatment caused a 24% decrease in TW m^{-2} at the March harvest.

The cumulative TW m^{-2} of Italian was very similar by the final harvest in both years (1622 and 1644 g m^{-2}) and was considerably greater than the TW m^{-2} of either S23 or S24 (a reflection of its tendency to produce large amounts of stem in comparison with the latter two cultivars).

The number of plants m^{-2} and mean cumulative TW $plant^{-1}$ at the final harvest in each experiment are given in Table 4.8. There were no significant differences in either parameter for any of the cultivars. The number of plants m^{-2} was similar from one year to the next for each cultivar and the density of all cultivars was about 1000 plants m^{-2}. (This has the useful side-effect that g m^{-2} are roughly interpretable as mg $plant^{-1}$.) In the 1981-82 experiment the mean TW $plant^{-1}$ was calculated for each

Table 4.7 : TW of *L. multiflorum* grown in the Solardomes: (a) 1980-81, 1981-82.

(a)

Harvest date	Days growth	TW (mean ± S.E.M.) in control (g m ^{2})	n	TW as % control(2)			
				Control	Low	Medium	High
6 Jan. 81	46	6.1(1)	21	100 a	130 b	124 bc	105 ac
26 Mar. 81	125	134 ± 9	10	100 -	88 -	115 -	113 -
12 May 81	47	476 ± 27	10	100 -	109 -	94 -	106 -
16 June 81	35	498 ± 51	10	100 -	104 -	94 -	107 -
11 Aug. 81	56	514 ± 46	10	100 -	123 -	94 -	108 -
Total to:							
12 May 81	172	610 ± 25	10	100 -	104 -	98 -	108 -
16 June 81	207	1107 ± 68	10	100 -	104 -	97 -	107 -
11 Aug. 81	263	1622 ± 108	10	100 -	110 -	96 -	108 -

(b)

Harvest date	Days growth	TW (mean ± S.E.M.) in control (g m $^{-2}$)	n	TW as % control(2)			
				Control	Low	Medium	High
16 Feb. 82	114	57.2(1)	21	100 -	120 -	96 -	82 -
24 Mar. 82	150	217 ± 34	10	100 ab	111 a	87 bc	76 c
19 May 82	56	548 ± 64	10	100 -	108 -	107 -	94 -
9 July 82	51	878 ± 89	10	100 -	110 -	106 -	88 -
Total to:							
19 May 82	206	765 ± 98	10	100 -	109 -	101 -	89 -
9 July 82	257	1644 ± 132	10	100 -	109 -	104 -	89 -

(1) and (2) as Table 4.5 except results in Table A3.3.

Table 4.8 : Number of plants m^{-2} and mean TW $plant^{-1}$ at harvests on 11 August 1981 (a) and 9 July 1982 (b), stubble weights are included for the latter harvest.

	Parameter	Cultivar	Mean (± S.E.M.) in control	n	% of control$^{(1)}$			
					Control	Low	Medium	High
(a)	Plants m^{-2}	S23	1030 ± 31	10	100 -	106 -	113 -	98 -
		S24	1143 ± 29	10	100 -	103 -	108 -	104 -
		Italian	977 ± 51	10	100 -	97 -	100 -	101 -
	TW (mg $plant^{-1}$)	S23	873 ± 90	10	100 -	112 -	109 -	100 -
		S24	1014 ± 80	10	100 -	112 -	110 -	114 -
		Italian	1694 ± 135	10	100 -	111 -	95 -	106 -
(b)	Plants m^{-2}	S23	1165 ± 47	10	100 -	88 -	99 -	98 -
		S24	1130 ± 89	10	100 -	99 -	103 -	97 -
		Italian	940 ± 70	10	100 -	98 -	94 -	92 -
	TW (mg $plant^{-1}$)	S23	774 ± 24	10	100 -	126 -	108 -	104 -
		S24	791 ± 79	10	100 -	120 -	116 -	108 -
		Italian	1755 ± 74	10	100 -	109 -	113 -	92 -
	Stubble (g m^{-2})	S23	147 ± 13	10	100 a	85 ab	84 ab	72 b
		S24	130 ± 9	10	100 -	113 -	100 -	96 -
		Italian	173 ± 13	10	100 a	105 a	100 a	79 b

(1) percentages in each row are not significantly different when above the same letter ($p = 0.05$); '-' indicates no significant differences; exact results for all treatments are in Appendix 3, Table A3.4.

harvest: for all three cultivars the results were essentially the same as for TW m^{-2}, with the exception that, at the March 1982 harvest TWs $plant^{-1}$ of S24 were 30 and 37% greater than control in the low and medium treatments respectively.

Stubble weight m^{-2} was measured after the final harvest in 1982 (Table 4.8b). The stubble weight of S24 was not affected by any treatment but the high treatment decreased the stubble weight m^{-2} of S23 and Italian by over 20% in relation to the control. When the stubble weight was added to the cumulative TW at the final harvest to produce the total shoot yield to ground level there were found to be no effects of treatment in any cultivar.

Percent dead

Dead leaf material was separated from 'live leaf + stem' in 5 subplots per cultivar per treatment. The DWs m^{-2} for each cultivar in the control treatments are listed in Tables 4.9 (1980-81) and 4.10 (1981-82). The DW m^{-2} is also expressed as percent of TW m^{-2} (%D) and it is this parameter that is compared between treatments. It was only at the last two harvests in each experiment that there was enough dead material to separate from the rest.

Where there were significant treatment effects, %D was always increased in relation to control. At the June 1981 and May 1982 harvests there was only about 2% dead on all three cultivars in the control treatments, but by the following harvests %D increased to 9-20%. Over the experiments as a whole the %D of S23 was not affected by treatment, although there were some significant increases at individual harvests. %D of S24 was not affected in 1982 except at the May harvest, but in 1981 a significant increase in %D was caused by the high treatment over the season as a whole. The medium (in 1982) and high treatments (in 1981 and 1982) increased the

Table 4.9 : DW (g m^{-2}) in control treatment and %D of plants grown in Solardomes 20 November 1980-11 August 1981.

L. perenne cv. S23

Harvest date	Days growth	DW (mean ± S.E.M.) in control (g m^{-2})	%D in control⁽¹⁾	n	%D as % control⁽²⁾			
					Control	Low	Medium	High
16 June 81	35	8.5 ± 2.1	2.4	5	100 -	92 -	82 -	165 -
11 Aug. 81	56	30 ± 5	9.1	5	100 a	88 a	129 b	97 a
Total to:								
11 Aug. 81	263	39 ± 6	4.0	5	100 -	85 -	99 -	102 -
L. perenne cv. S24								
16 June 81	35	6.8 ± 1.2	2.0	5	100 -	116 -	119 -	154 -
11 Aug. 81	56	81 ± 15	15.9	5	100 a	110 a	117 a	152 b
Total to:								
11 Aug. 81	263	88 ± 11	6.9	5	100 a	92 a	94 a	145 b
L. multiflorum								
16 June 81	35	11.5 ± 2.1	2.3	5	100 -	88 -	135 -	118 -
11 Aug. 81	56	49 ± 2	8.7	5	100 ab	93 a	124 bc	134 c
Total to:								
11 Aug. 81	263	61 ± 1	3.6	5	100 ab	90 a	115 b	117 b

(1) back transformed after arcsine conversion

(2) percentages in each row are not significantly different when above the same letter ($p = 0.05$); '-' indicates no significant differences; exact results for % dead in all treatments are given in Appendix 3, Table A3.5.

Table 4.10 : DW (g m^{-2}) in control treatment and %D of plants grown in Solardomes 1 November 1981-9 July 1982.

L. perenne cv. S23

Harvest date	Days growth	DW (mean ± S.E.M.) in control (g m^{-2})	%D in control(1)	n	%D as % control(2)			
					Control	Low	Medium	High
19 May 82	56	6.5 ± 3.6	2.3	5	100 a	283 b	385 b	312 b
9 July 82	51	123 ± 8	19.2	5	100 a	119 a	98 a	152 b
Total to:								
9 July 82	257	129 ± 9	14.2	5	100 –	116 –	101 –	129 –

L. perenne cv. S24

19 May 82	56	10.1 ± 5.3	2.3	5	100 a	203 b	224 b	360 c
9 July 82	51	91 ± 6	21.9	5	100 –	98 –	116 –	128 –
Total to:								
9 July 82	257	101 ± 8	13.7	5	100 –	93 –	101 –	121 –

L. multiflorum

19 May 82	56	23.5 ± 6.6	3.5	5	100 –	97 –	101 –	112 –
9 July 82	51	117 ± 12	11.9	5	100 a	107 a	127 b	150 c
Total to:								
9 July 82	257	140 ± 12	7.8	5	100 a	104 a	126 b	146 c

(1) and (2) as Table 4.9 except results in Table A3.6.

%D of Italian at the final harvest but differences from control over the whole experiment were only seen in the medium and high treatments in 1982.

Spike number

The number of spikes in each subplot was counted whenever they were present. Results for the two years are presented in Tables 4.11 and 4.12. Italian flowered most prolifically in both years and was never affected by treatment. The number of spikes produced by S24 was not affected by treatment in 1981 or over the season as a whole in 1982, although a 40-50% increase was seen in the low and medium treatments at the May 1982 harvest. S24 produced about 2.5 times more spikes m^{-2} in 1982 than 1981. In 1981 S23 had produced 55% less spikes m^{-2} in the high treatment than in the control by the end of the experiment, but in 1982 there were no effects. The total number of spikes m^{-2} produced by S23 was similar in both years.

The large but non-significant percentage differences seen in S23 and S24 in 1981 are a reflection of very few spikes per subplot: there were about 1000 plants m^{-2} ($\equiv$ 40 plants per subplot) and from Table 4.11 it can be seen that in some cases there were on average less than 1 spike per 5 plants (< 8 spikes per subplot).

Roots

Roots were only sampled at the end of the 1982 experiment. Although sampling roots from a sward in the manner used in this experiment was not likely to have been accurate, large differences between treatments should have been apparent. Table 4.13 lists the RW m^{-2}, the cumulative TW m^{-2} to the final harvest for the subplots sampled for RW, and the TW/RW ratio. No cultivar showed a significant treatment effect on RW but all showed non-significant reductions which tended to increase with increasing SO_2 concentration. However, regression of RW against SO_2 concentration proved

Table 4.11 : Number of spikes m^{-2} of plants grown in Solardomes, 20 November 1980-11 August 1981.

L. perenne cv. S23

Harvest date	Days growth	No. spikes m^{-2} (mean ± S.E.M.) in control	n	No. spikes m^{-2} as % control(1)			
				Control	Low	Medium	High
16 June 81	207	665 ± 68	10	100 a	92 a	164 b	41 c
11 Aug. 81	56	362 ± 142	10	100 -	57 -	32 -	52 -
Total to:							
11 Aug. 81	263	1027 ± 181	10	100 ab	80 b	118 a	45 c

L. perenne cv. S24

16 June 81	207	763 ± 55	10	100 -	100 -	89 -	89 -
11 Aug. 81	56	182 ± 48	10	100 -	67 -	51 -	70 -
Total to:							
11 Aug. 81	263	945 ± 63	10	100 -	94 -	82 -	85 -

L. multiflorum

16 June 81	207	1180 ± 126	10	100 -	109 -	94 -	98 -
11 Aug. 81	56	1947 ± 126	10	100 -	113 -	98 -	100 -
Total to:							
11 Aug. 81	263	3127 ± 224	10	100 -	112 -	96 -	99 -

(1) percentages in each row are not significantly different when above the same letter ($p = 0.05$); '-' indicates no significant differences; exact results for all treatments are given in Appendix 3, Table A3.7.

Table 4.12 : Number of spikes m^{-2} of plants grown in Solardomes, 1 November 1981-9 July 1982.

L. perenne cv. S23

Harvest date	Days growth	No. spikes m^{-2} (mean ± S.E.M.) in control	n	No. spikes m^{-2} as % control$^{(1)}$			
				Control	Low	Medium	High
19 May 82	206	0	10	no spikes in any treatment			
9 July 82	51	875 ± 81	10	100 –	119 –	103 –	101 –

L. perenne cv. S24

Harvest date	Days growth	No. spikes m^{-2} (mean ± S.E.M.) in control	n	Control	Low	Medium	High
19 May 82	206	1530 ± 314	10	100 a	138 b	151 b	127 ab
9 July 82	51	875 ± 131	10	100 –	104 –	85 –	104 –
Total to:							
9 July 82	257	2405 ± 145	10	100 –	125 –	127 –	119 –

L. multiflorum

Harvest date	Days growth	No. spikes m^{-2} (mean ± S.E.M.) in control	n	Control	Low	Medium	High
19 May 82	206	672 ± 113	10	100 –	130 –	133 –	103 –
9 July 82	51	2055 ± 158	10	100 –	106 –	112 –	94 –
Total to:							
9 July 82	257	2727 ± 190	10	100 –	112 –	117 –	96 –

(1) as Table 4.11 except data in Table A3.8.

Table 4.13 : RW, cumulative TW and TW/RW at final harvest, July 1982.

L. perenne cv. S23

Parameter	n	Treatment			
		Control	Low	Medium	High
RW (g m^{-2})	5	225 ± 20(1) 100(2) -(3)	181 ± 31 80 -	200 ± 21 89 -	159 ± 37 71 -
TW to July(4) (g m^{-2})	5	1073 ± 99 100 -	1068 ± 161 99 -	1053 ± 106 98 -	1051 ± 129 98 -
TW/RW	5	4.82 ± 0.38 100 -	6.14 ± 0.60 128 -	5.40 ± 0.63 112 -	7.49 ± 1.36 155 -

L. perenne cv. S24

RW (g m^{-2})	5	169 ± 16 100 -	141 ± 22 83 -	128 ± 17 75 -	132 ± 20 78 -
TW to July (g m^{-2})	5	942 ± 203 100 -	1338 ± 124 142 -	1257 ± 87 133 -	1021 ± 90 108 -
TW/RW	5	6.06 ± 1.86 100 a	10.16 ± 1.59 168 b	10.74 ± 1.86 177 b	8.32 ± 1.21 137 ab

L. multiflorum

RW (g m^{-2})	5	205 ± 19 100 -	209 ± 30 102 -	162 ± 19 79 -	160 ± 22 79 -
TW to July (g m^{-2})	5	2006 ± 186 100 -	2094 ± 188 104 -	1904 ± 133 95 -	1658 ± 217 83 -
TW/RW	5	9.98 ± 0.85 100 -	10.49 ± 0.96 105 -	12.11 ± 0.89 121 -	12.54 ± 4.33 126 -

(1) mean ± S.E.M.

(2) mean as % of control

(3) means above the same letter are not significantly different ($p = 0.05$); '-' indicates no significant differences.

(4) The TWs are for the five subplots used for root sampling.

non-significant for each cultivar. The corresponding TW were usually very similar to, or greater than, control. The only significant treatment effects were that the low and medium treatments increased the TW/RW ratio of S24 by about 70%.

4.3.3 Sulphur and nitrogen content

In Figure 4.7 %S is plotted against SO_2 concentration and TW m^{-2}. It is clear that %S generally increased linearly with increasing SO_2 concentration and was not related to TW in each of the three cultivars when considered individually. The %S of S23 was slightly higher in March than in May and Italian had a lower %S content than S23 or S24. Total nitrogen content was neither related to NO_2 concentration (Fig. 4.8a) nor to TW m^{-2} when each cultivar was considered separately (Fig. 4.8b). It is interesting to note that when all three cultivars are considered, both S and N contents are negatively correlated with yield, although this is only significant for N ($r = 0.79$, $p < 0.01$).

4.4 Discussion

4.4.1 Pollutant concentrations

It was shown in Chapter 2 that in the UK mean concentrations of SO_2 were generally lower in summer than in winter, especially in urban areas (e.g. Figures 2.1 to 2.4). In these experiments, with the exception of a particularly high monthly mean in February, there were only minor differences between summer and winter SO_2 concentrations (Fig. 4.4). NO_2 concentrations in rural and some urban areas were higher in winter than summer, but were slightly higher in summer than in winter in central London (Section 2.3). In these experiments NO_2 concentrations fell by about 25% from winter to summer.

For most purposes SO_2 concentrations in the two experiments were

Figure 4.7 : Sulphur content of ryegrass plotted against (a) SO_2 concentration in the atmosphere and (b) yield (shoot dry weight, g m^{-2}).

—○—	S23	March harvest 1981
—●—	S23	May harvest 1981
--■--	S24	
—▲—	Italian	

Bars represent S.E.M.

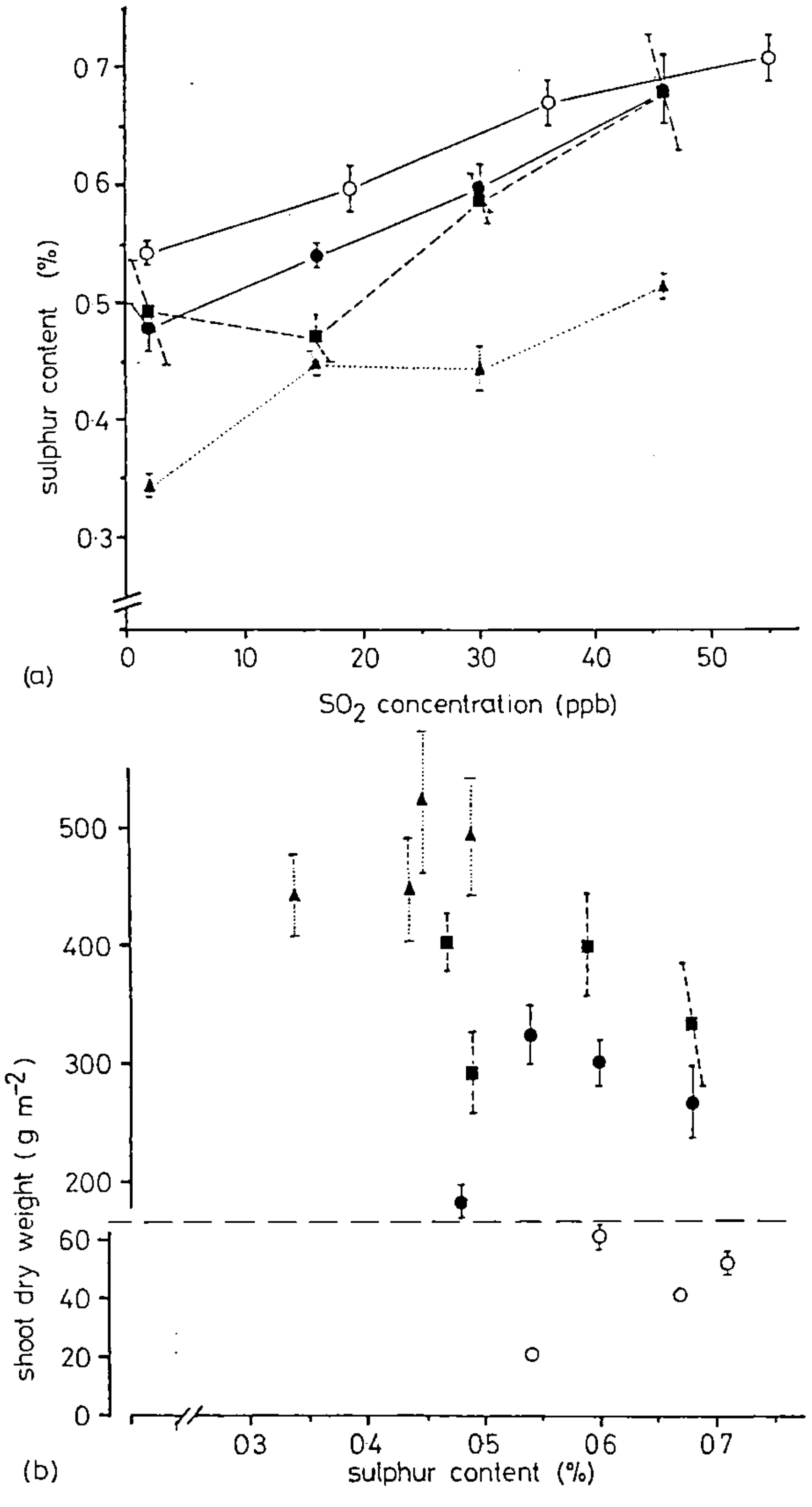

0 7
0 6
0 5
0 4
0·3
sulphur content (%)
0
10
20
30
40
50
(a)
SO2 concentration (ppb)
500
400
300
200
60
40
20
0
shoot dry weight (g m-2)
03
04
05
06
07
(b)
sulphur content (%)

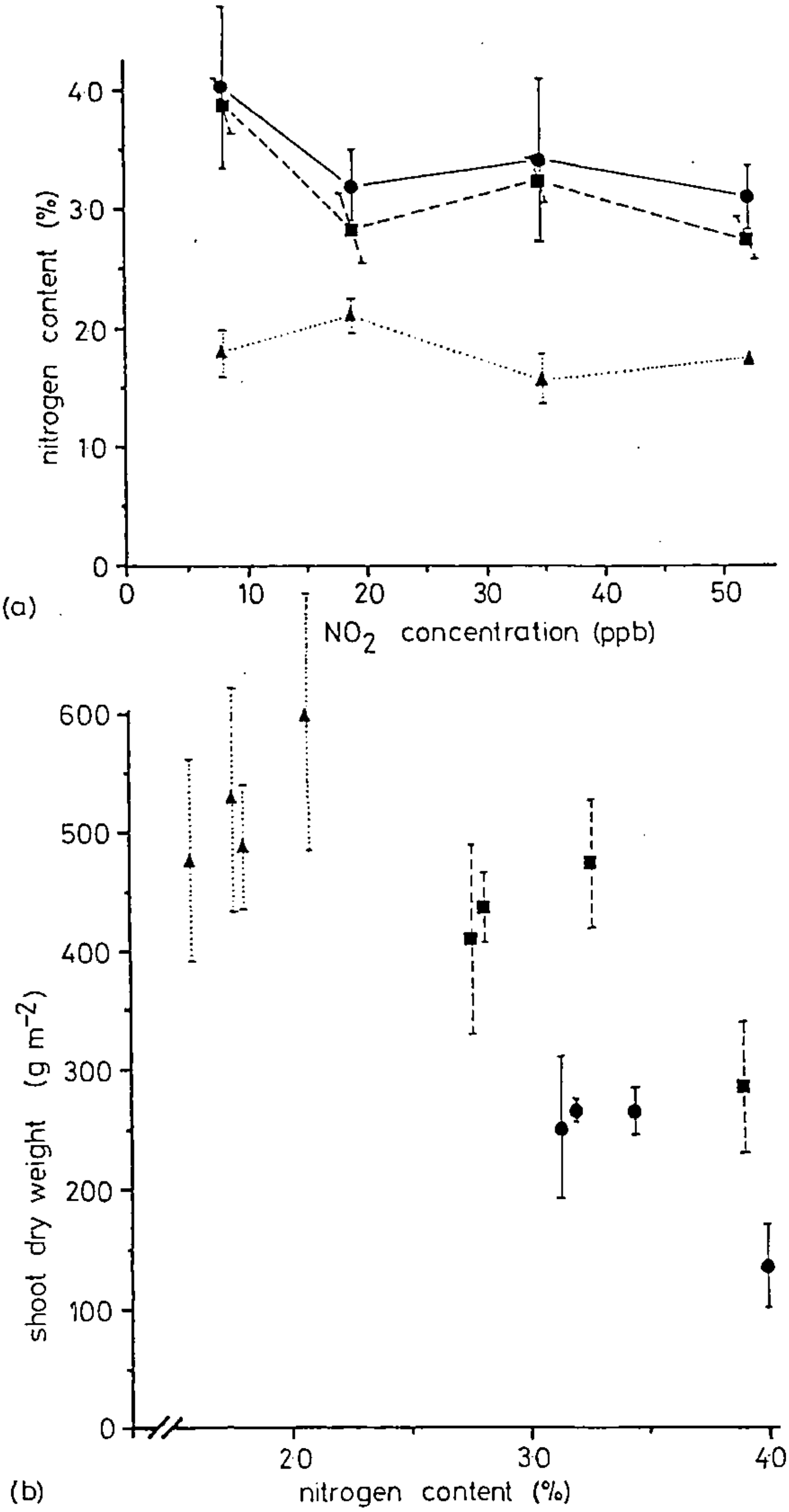
Figure 4.8 : Nitrogen content of ryegrass plotted against (a) NO_2 concentration in the atmosphere and (b) yield (shoot dry weight, g m^{-2}). All data from May harvest 1981.

—●— S23

--■-- S24

—▲— Italian

Bars represent S.E.M.


nitrogen content (%)
4·0
3·0
2·0
1·0
0
0
10
20
30
40
50
(a)
NO$_2$ concentration (ppb)
shoot dry weight (g m^{-2})
600
500
400
300
200
100
0
2·0
3·0
4·0
(b)
nitrogen content (%)

essentially equal in their respective treatments, and during the periods when NO_2 was supplied, the same generalisation applied. In addition, SO_2 and NO_2 concentrations were similar, with the exception of during May and June when SO_2 exceeded NO_2 by about 40%. The overall mean concentrations and cfd's of the medium treatment (approximately 35 ppb SO_2 plus 35 ppb NO_2) can be considered fairly representative of many urban areas in the UK, those of the low treatment were equivalent to fringe areas and those of the high treatment probably represented the highest SO_2 and NO_2 levels likely to be found in urban areas. Seasonal variations in mean concentrations were not so well reproduced

4.4.2 Effects of treatments on yield

Total shoot dry weight

At the start of the experiments it was expected that, at least in the high treatment, a large reduction in yield would be found. In Chapter 3, experiments (conducted at Lancaster University) were described which had shown large yield reductions in four grass species exposed to 68 ppb SO_2 + 68 ppb NO_2 for up to 140 days (Ashenden, 1979b; Ashenden & Williams, 1980). Subsequently, the same laboratory has provided much support for their earlier work and has reinforced the observation that these reductions persist for at least 5 months in overwinter fumigations (e.g. Whitmore & Freer-Smith, 1982). Therefore, it was surprising to find a general lack of evidence, even in the high treatment, for SO_2 + NO_2 causing a reduction of total shoot dry weight.

The small difference in mean pollutant concentrations used at Lancaster (60-68 ppb) and in the high treatment in the present experiments at CERL (~50 ppb) is most unlikely to be a major cause of the large difference in results. Discussion of reasons for the observed differences between previously published results and those obtained here is included in Chapter 7.

Before discussing the results further it is important to ensure that they had not been confounded by environmental differences between the domes, even though the treatments were moved from one dome to another from the first to the second experiment. In Table 4.14 the yields from the control experiment and the cumulative totals at the end of each major experiment are ranked for each cultivar and listed according to dome. Clearly there is no pattern indicating that one dome affected growth differently in comparison with the others, but on the contrary, a treatment effect becomes apparent: most maximum yields occur in the low and medium treatments in both years.

The mean cumulative shoot dry weights at the final harvests for all three cultivars are shown in Figure 4.9a. The tendency for maximum yields to occur in the low and medium treatments can be seen, but there is much variation in yield between cultivars and/or between experiments. In order to test the hypothesis that maximum yields occur in the presence of moderate levels of pollutants it was necessary to render the results comparable from one year to the next and between cultivars. To do this, for each cultivar and experiment, individual mean dry weights were divided by the overall mean weight for the respective cultivar and experiment. This makes the assumption that changes caused by treatments were not affected by differences in growth between the two experiments and that the treatments were the same in both experiments. The results of this transformation are shown in Figure 4.9b. The 'proportional weights' were regressed against SO_2 concentration and tested for non-linearity (Walpole & Myers, 1972, p. 295 et seq.). When the cultivars were tested individually only S24 showed a significant ($p < 0.001$) systematic variation, indicating departure from

Table 4.14 : Ranked yields of S23, S24 and Italian in the control experiment and at the end of each major experiment, listed according to dome. A rank of 1 = minimum and 4 = maximum yield for each cultivar/experiment.

		Cultivar	Dome			
			1	2	3	4
Control experiment:	ranked yields(1)	S24	1	2	4	3
1980-81:	treatment		Medium	Control	High	Low
	ranked yields(2)	S23	4	2	1	3
		S24	4	1	2	3
		Italian	1	2	3	4
1981-82:	treatment		Control	Medium	Low	High
	ranked yields(2)	S23	1	2	4	3
		S24	1	3	4	2
		Italian	2	3	4	1

(1) shoot dry weight plant^{-1}.

(2) cumulative total shoot dry weight m^{-2} at final harvest.

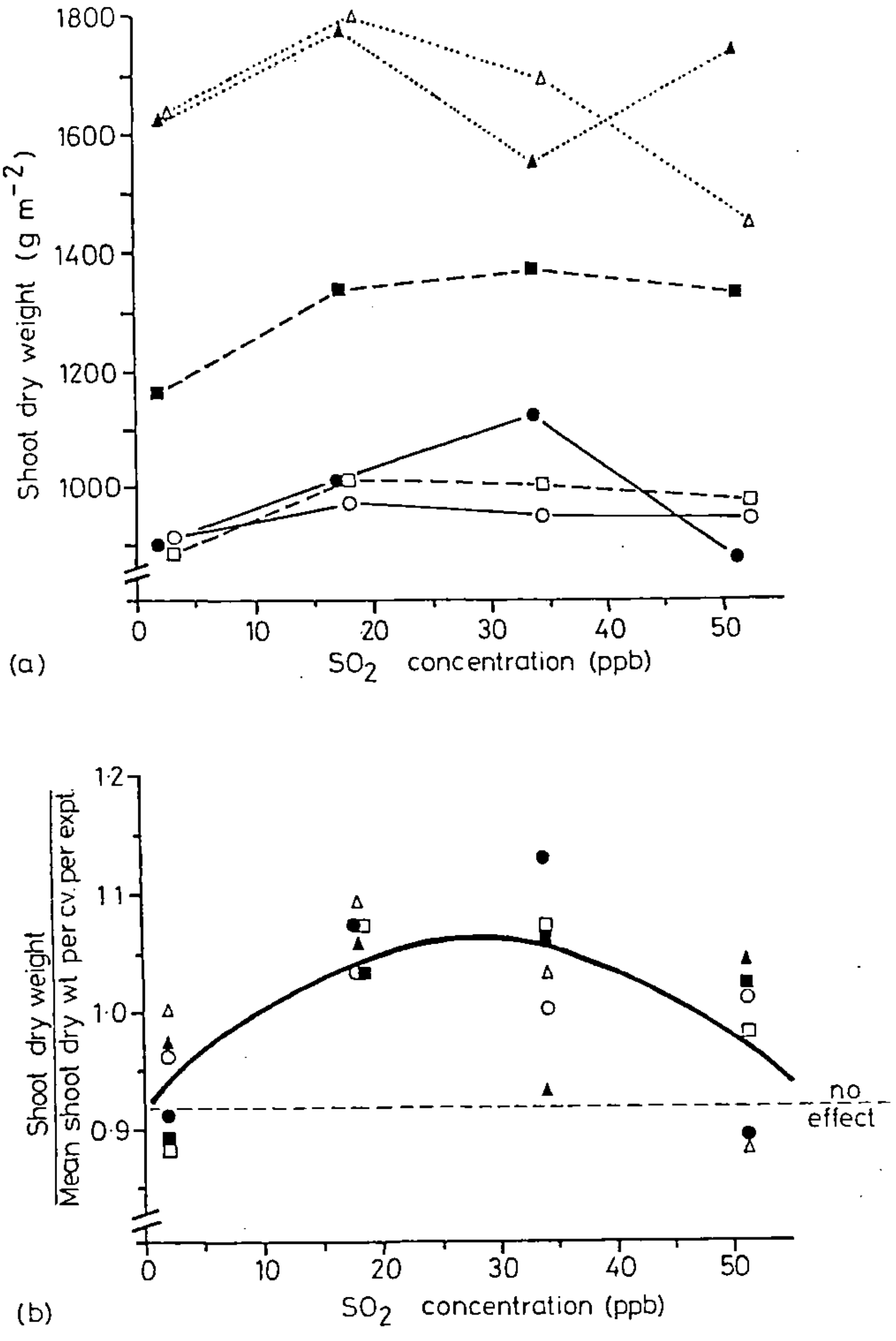


Figure 4.9 : Relationship between cumulative shoot dry weights and mean SO_2 concentration.

(a) Mean cumulative shoot dry weight (g m^{-2}) for each cultivar and treatment.

(b) Individual mean cumulative shoot dry weights divided by overall mean dry weight for the respective cultivar and experiment.

——— = regression line, $y = 92.3 + 0.957x - 0.0169x^2$, ($r = 0.68$).

●, S23; ■, S24; ▲, Italian (1980-81)
○, S23; □, S24; △, Italian (1981-82)

linearity. Combining the data from all the cultivars also showed a significant ($p < 0.005$) systematic variation.

A significant departure from linearity justifies the use of higher order terms in a regression analysis, and so the proportional weights of all cultivars were regressed against SO_2 and $(SO_2)^2$ (Fig. 4.9b). The correlation coefficient, r, and both the SO_2 and $(SO_2)^2$ terms were all significant at $p < 0.001$. Thus, the apparent maximum yields at low and medium pollutant concentrations may be considered to be real. Nevertheless, it must be remembered that, for each individual cultivar per experiment there were no significant effects by the final harvest and much of the increased yields were due to the late winter and spring harvests (Tables 4.5-4.7).

No biological significance for the use of SO_2 and $(SO_2)^2$ terms is claimed. In addition NO_2 is assumed to be present at a similar concentration to SO_2, therefore the results are not comparable to those from fumigations with SO_2 alone; indeed, the SO_2 concentration may be considered as an index of pollution rather than an exact measure of SO_2 alone.

The use of all three cultivars in a single regression analysis may not be justified in view of the results obtained using the individual cultivars. This depends on whether there was a true difference between the cultivars (a two-way analysis of variance on the 'proportional weights' showed no significant species x treatment interaction), or whether the lack of significance was simply due to only 2 replicates for individual cultivars, compared with 6 'replicates' if all the cultivars were assumed similar.

In the Solardomes, the maximum proportional increases in yield due to SO_2 + NO_2 (and therefore maximum increases in relative growth rate) were found at the late winter and spring harvests. This cannot be attributed to an alleviation of sulphur-deficiency, since even in the control treatment the S content of the shoots was well above the level of 0.2% that has been suggested as the critical deficiency level (Jones, Cowling & Lockyer, 1972). In addition, for each cultivar, S content was not related to yield (Fig. 4.7). In the only other reported experiment where grass was fumigated with SO_2 + NO_2 overwinter and through the following summer (Whitmore & Freer-Smith, 1982; see Fig. 3.1a) it is interesting to note that the relative growth rate of plants in SO_2 + NO_2 also must have been greater than that of the control plants in spring and early summer. (The SO_2 + NO_2 treated plants were ~20% of the weight of control plants in March, but were nearly equal in size by June.)

Percent dead

Essentially no dead material was found after winter growth. Most previous studies using *L. perenne* have found some dead material on the control plants, which was usually increased by fumigations with SO_2 (Table 3.5). Davies (1980b) has also noted that the %D was consistently greater on plants of *Phleum pratense* exposed to SO_2 + NO_2 for only 56 days. Only in two fumigation experiments has the senescence of *L. perenne* swards been measured: 21 ppb SO_2 had no significant effect on %D after 56 and 85 days (Cowling & Lockyer, 1978), but Bell *et al.* (1979) found that 16 ppb SO_2 increased the dead leaf dry weight by 140% after a 173 day overwinter exposure.

During the spring and summer growth the effects of the pollutant treatments on %D varied from the first to the second experiment. In 1981 there were few effects other than small increases in the %D in the high treatment; at the May 1982 harvest there were large increases in the %D of S23 and S24 in all treatments with added pollutants, but Italian was not affected until July. The only relevant published information on *L. multi-*

florum is that from Ashenden & Williams (1980): in their study the proportion of dead leaves plus stubble, after a 140 day overwinter exposure, increased from 46% in the control to 63% in 68 ppb SO_2 + NO_2. Many species other than *L. perenne* or *L. multiflorum* have been shown to produce an increased %D after exposure to in excess of 60 ppb SO_2 (see Table 3.5).

There is not enough published information to know whether the lack of overwinter effects seen in the Solardomes was due to lower pollutant concentrations, or the use of different species/cultivars or experimental conditions (swards, fluctuating pollutant concentrations, growing plants directly in the ground). However, in most cases, the increases in %D due to pollutants over summer were a small proportion of the total shoot material and were probably of little importance from the point of view of crop quality.

Number of spikes

There is only one published account of the effects of SO_2 or SO_2 + NO_2 on the number of spikes produced by a grass species (Whitmore & Freer-Smith, 1982). In their experiment, 68 ppb SO_2, with or without 68 ppb NO_2, reduced the number of flowering heads of *Poa pratensis* to less than half that of the controls. In the Solardomes, the only effect over each experiment as a whole was a 55% reduction in the number of spikes produced by S23 in 1981. However, as this effect was found only in the one case, no conclusion can be safely drawn.

Root dry weight

In Chapter 3 it was noted that, for many grass species, SO_2 has been shown to reduce the dry weight of roots by a greater proportion than that of the shoots. Although there were no significant treatment effects on root weights in the Solardomes, there was a tendency for a reduction to occur with increasing pollutant concentration. All the evidence for a greater effect of SO_2 on the roots than the shoots of *L. perenne*, listed in Table 3.5, used mean SO_2 concentrations in excess of 70 ppb. This may partly account for the lack of significant effects found in the Solardomes, where only 18-52 ppb SO_2 (plus a similar concentration of NO_2) were used.

Following a similar procedure to that used above for the shoot dry weights, the individual mean root weights were divided by their respective overall cultivar means to provide 'proportional weights' (Fig. 4.10). A linear regression using the combined data from all three cultivars was highly significant ($p < 0.001$, $r = 0.85$), indicating an increased reduction of root dry weight with increased SO_2 concentration. Similar comments to those made above for shoots apply to the validity of this exercise.

4.4.3 Sulphur and nitrogen content

The minimum content of sulphur required for maximum growth by *L. perenne* has been suggested to be 0.2% (Jones, Cowling & Lockyer, 1972). Even in the control treatment *L. perenne* averaged about 0.5% sulphur, reaching 0.7% in the high treatment. The S content increased linearly with increasing SO_2 concentration (Fig. 4.7), similar to results reported by Cowling & Koziol (1978); in addition, S content was not related to yield within each cultivar (Fig. 4.8), again similar to results from other studies (Cowling & Koziol, 1978; Cowling, Jones & Lockyer, 1978; Cowling & Lockyer, 1976). It is possible that high concentrations of S in the shoots are toxic, but both Cowling & Lockyer (1976) and Colvill *et al.* (1983) have reported concentrations in excess of 0.7% without apparent injury.

It is known that atmospheric NO_2 can be absorbed by plants and utilised in the production of amino-acids (Yoneyama & Sasakawa, 1979) or 'high molecules' (Matsumaru, Yoneyama, Totsuka & Shiratori, 1979). There-

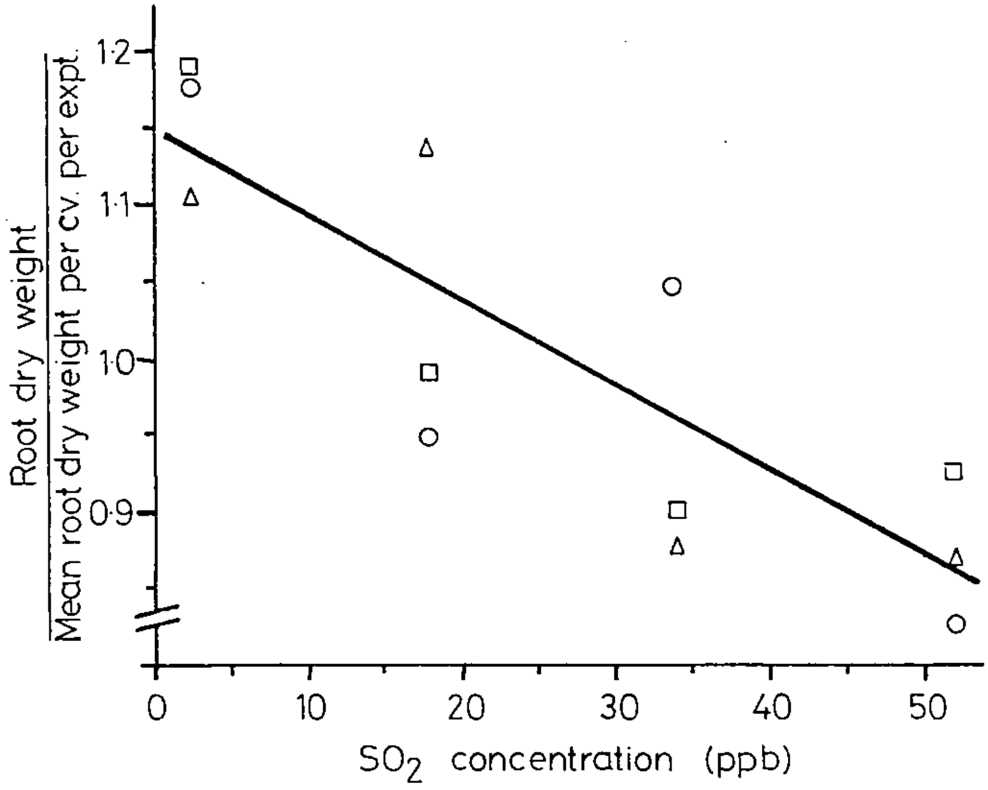


Figure 4.10 : Relationship between SO_2 concentration and root weights (expressed as a proportion of overall mean dry weights for the respective cultivar and experiment).

—— = regression line; y = 1.15 - 0.0056x, r = 0.85

○ = S23

□ = S24

△ = Italian

fore, in theory at least, NO_2 may act as a fertiliser. Valentine & Charles (1979) reported that several authors have found that increased N-fertiliser application generally resulted in increased yields but did not affect the nitrogen content of several varieties of perennial ryegrass. Thus, if NO_2 was acting as a fertiliser, one would expect an increased yield, rather than an increased N content, with increasing NO_2 concentrations. In the Solardomes, the yield was not proportional to the NO_2 concentration (Tables 4.5-4.7) and the N content was not affected by treatment (Fig. 4.8a). Since N is a major nutrient (3-4% dry weight is normal for ryegrass, Valentine & Charles, 1978; Cowling & Bristow, 1979) the proportion of total N that could be absorbed from the atmosphere is probably negligable. In contrast, the S content is about 10% that of N and may be affected by pollutant uptake.

4.5 Conclusions

Under the conditions of these experiments, levels of SO_2 + NO_2 typical of a heavily polluted urban environment (high treatment) were shown not to affect the cumulative shoot dry weights of *L. perenne* cvs S23 and S24 and *L. multiflorum* cv. RvP after long-term fumigations. There was evidence that lower levels of SO_2 + NO_2, such as may be found in normal urban or urban fringe environments, slightly increased shoot dry weight but that this was probably largely due to effects in the late winter and spring on S23 and S24. Root dry weights may decrease in proportion to increases in pollutant concentration. At levels of SO_2 and NO_2 encountered in normal urban and urban fringe areas, flowering and senescence (except %D on Italian in 1982) were not significantly affected over each experiment as a whole: significant effects were found only when the mean concentrations were in excess of about 50 ppb of both SO_2 and NO_2.

CHAPTER 5

FUMIGATION EXPERIMENTS, II

EFFECTS OF SO_2, NO_2 AND NO APPLIED SINGLY AND IN COMBINATION

5.1 Introduction

In the Introduction to Chapter 4 it was mentioned that, due to the uncertainties involved in extrapolating results obtained from fumigation experiments using essentially constant levels of pollutants to a field situation, use of more realistic pollutant regimes may be advisable. As a step towards a more accurate simulation of ambient pollution conditions, in the experiments reported in this Chapter the pollutants were fluctuated on an hourly basis, rather than on a daily basis as in the Solardomes. Also in contrast to the Solardome experiments, pollutants were supplied both singly and in mixtures, in order to estimate the relative contributions of individual pollutants and the magnitude of any interactive effects.

Pollutant concentrations were fluctuated to give typical cumulative frequency distributions with long-term means of about 30 ppb SO_2 and 25 ppb NO_2, slightly less than in the medium (= 'urban') treatment in the Solardomes. In addition to simulating cfd's, the experimental design incorporated diurnal patterns, peak durations and correlation of hourly mean pollutant concentrations (see Section 2.4, Fig. 2.15).

Although an attempt was made to simulate SO_2, NO_2 and (in one experiment) NO concentrations typical of a polluted environment, the comments on the problems associated with chamber experiments made in the Introduction to Chapter 4, are also relevant here. It must be re-emphasised that, apart from the pollutants specifically monitored, many environmental conditions within the chambers were not the same as in an urban environment, and therefore care must be taken when comparing results from the following experiments with effects likely to be encountered in the field.

Two major experiments were carried out, one from the end of January until August 1981, the other from November 1981 until June 1982. Both experiments involved SO_2 and NO_2 and the first also included NO, but due to problems with maintaining a controlled supply its use was not continued in the second experiment. In between these experiments, from August to October 1981, plants were grown in each chamber, without added pollutants, to test for differences in growth caused by possible minor environmental differences between chambers.

5.2 Materials and Methods

The six chambers used in these experiments were sited at Imperial College, Silwood Park, Ascot. They had been previously used for fumigation experiments with SO_2 alone (e.g. Farrar, Relton & Rutter, 1977; Bell, Rutter & Relton, 1979; Garsed, Mueller & Rutter, 1982) and were already fitted with equipment capable of fluctuating SO_2 concentrations but required modification to accommodate NO_2 and NO.

5.2.1 Chamber design and position

The six chambers and fans were arranged as shown in Figure 5.1a. Air was blown through charcoal filters, along 11 cm diameter ducts into the side of each chamber and up towards the roof (Fig. 5.1b) to give approximately even flow throughout each chamber. Air flow was sufficient for ~1.8 air-changes per minute (checked regularly in each chamber during both experiments) and was allowed out of the chambers via three 6 cm diameter holes near the base of one wall (Fig. 5.1b).

Each chamber measured 1.5 x 1.5 x 1.0 m high, and was raised 0.8 m from ground level (Fig. 5.1b). The walls and roof were constructed from clear 'Perspex'. Doors in two opposite walls of each chamber allowed

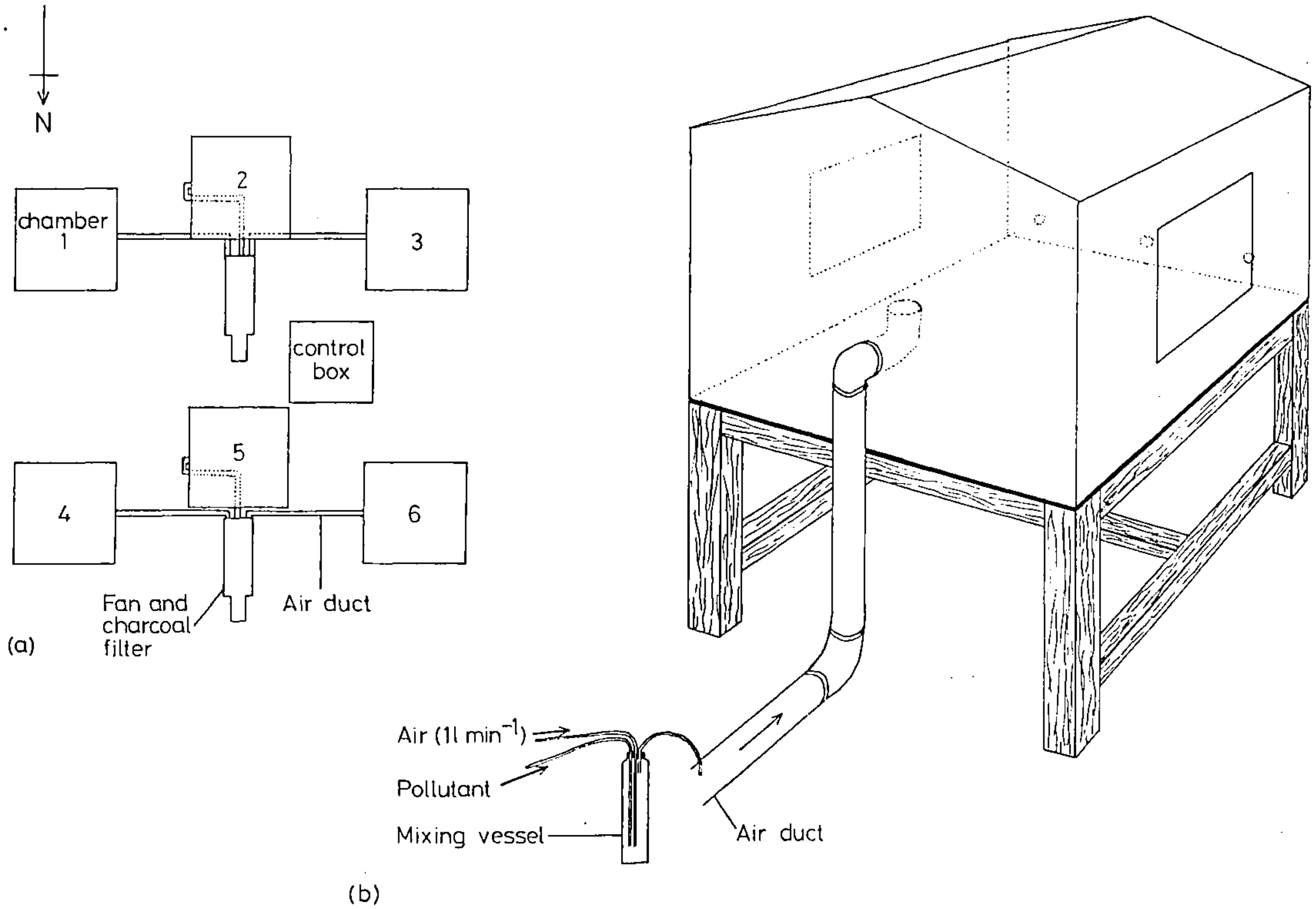


Figure 5.1 : Schematic diagram of Silwood chambers. (a) Arrangement of chambers, fans and control box. (b) A single chamber.

access. The wooden base of each chamber was lined with polythene sheet and covered with a 4 cm layer of coarse sand.

A wooden 'control box', 1.3 x 1.3 x 1.0 m high, was positioned close to the chambers (Fig. 5.1a) to house the gas supply, sample and monitoring systems.

5.2.2 Pollutant supply

A diagram of the pollutant supply system is given in Figure 5.2a. The method of controlling the concentrations of each pollutant was similar, so only a single example is illustrated in detail in the Figure. All the pollutants were supplied by the British Oxygen Company Ltd., diluted to 1% in nitrogen. Pressure from the NO_2 and NO cylinders was controlled with stainless steel regulators (BOC Spectrol series) and from the SO_2 cylinder with a brass (oxygen-nitrogen) regulator. A 0.25 inch diameter PTFE tube from each regulator was divided into two or three lines, each with a stainless steel on-off solenoid valve. After each of these 'supply valves' there was a 5 cm length of 0.2 mm glass capillary tubing, a flow-meter and 'flostat' (gas flow controller, G.A. Platon Ltd.,) (Fig. 5.2a). From each flostat, a 0.25 inch diameter PTFE tube led to a mixing vessel adjacent to a main air duct supplying the appropriate chamber (see below and Fig. 5.1b).

Controlling the flow of pollutants to produce fluctuating concentrations was achieved in two ways, (a) the flostats were set to give a flow of ~150 cm^3 min^{-1} when the supply valves were open and (b) the supply valves were opened from 1 to 45 seconds on a 45-second cycle. The lengths of time for which each valve remained open were controlled by a microprocessor (designed and built by Dr. P.W. Mueller) which could be programmed with different values for each valve for each hour of the day. Thus, pollutant flow was intermittent unless the supply valves were continually open.

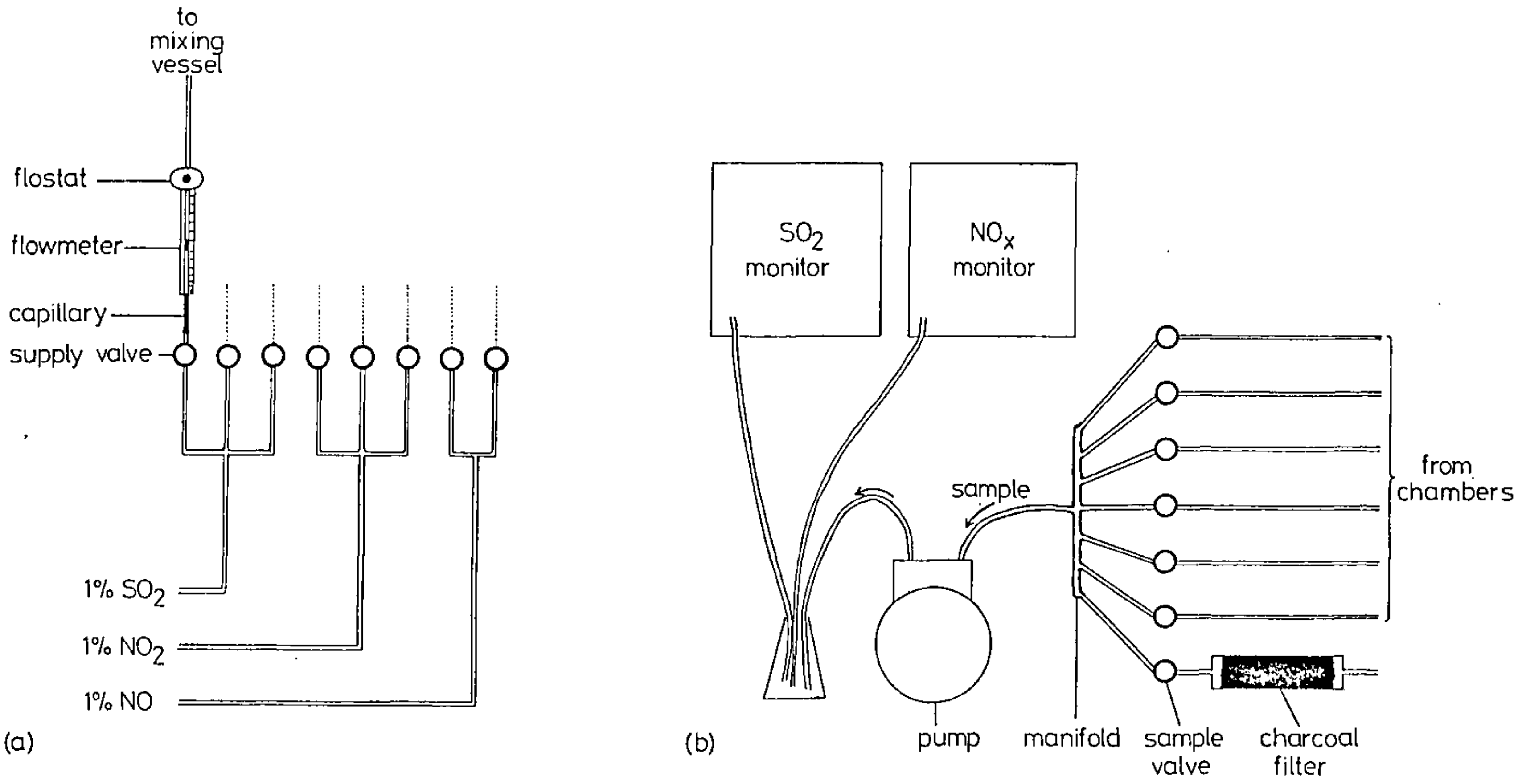


Figure 5.2 : Pollutant supply and sample systems for Silwood chambers.

(a) Supply system: only one example drawn in detail, the others were similar.

(b) Sample system.

For further details see text.

Each time a valve opened there was a surge of pollutant through the relevant flowmeter/flostat, but this was minimised by the capillary tubing which limited the maximum flow rate more effectively than the flostats (although the latter worked well with constant pressure and flow stabilised in < 2 seconds). When the pollutants were injected directly into the ducts the 45-second cycle was readily detected on the SO_2 monitor (which had a maximum lag time of 10 seconds). In order to 'smooth out' the flow of pollutants, each supply line led from the flostat into a 2-litre polythene mixing vessel, into which ambient air was pumped at ~1 litre min^{-1}, before entering the main ducts (Fig. 5.1b). Since the valves operated on a 45-second cycle, and the flow rate through the mixing vessel was about one air change every 2 minutes, the 45-second fluctuations in SO_2 (and presumably NO_x) were reduced to an amount that was not detectable on the SO_2 monitor.

It was not possible to control the concentration of any pollutant below about 15 ppb, and therefore when the experimental design required the concentration of a particular pollutant to be less than 15 ppb the relevant supply valves were closed, giving no additions of pollutant.

5.2.3 Choice of pollutant concentrations

Initially it had been hoped to conduct one experiment using urban levels of SO_2 and NO_x and, in a second experiment, use lower levels typical of polluted agricultural areas. However, in view of the results obtained from the first experiment, the designed concentrations were kept the same during the respective calendar months of each experiment. Data supplied by the GLC (see Chapter 2) were used as a base for designing the fluctuating levels. One month's data on hourly mean concentrations of SO_2, NO_2 and NO were slightly modified to provide an 'average' month that fitted the desired characteristics (cfd's, diurnal patterns, correlation of concentrations and peak durations). Monthly means for 1978 and 1979 were also supplied by the GLC, Scientific Branch (pers. comm.), and these were used as a basis for varying the seasonal mean concentrations. To achieve different concentrations from one month to the next, each hourly mean value for the 'average' month was multiplied by a suitable factor for each of SO_2, NO_2 and NO. Thus, the 'pattern' of pollution was similar for each pollutant during each month of the fumigation periods, although the concentrations varied.

This approach to the experimental design was used because only three months' detailed data were available. Therefore, it was not possible to base the fumigation regime on one year's data (as in the Solardomes). However, since in neither method were pollutant concentrations related to weather, the difference in principle was small.

Various combinations of single pollutants and mixtures were used, which included replicate treatments in 1981-82 (Table 5.1). To allow comparison of single pollutants with mixtures, it was clearly necessary to keep the SO_2 (or NO_2 or NO) concentrations the same in all the chambers with added SO_2 (or NO_2 or NO).

5.2.4 Pollutant monitoring

Preliminary tests showed that there was no significant spatial variation in pollutant concentration within a chamber. A 0.25 inch diameter PTFE sample line was therefore placed in the centre of each chamber; each line led into the control box and joined a common glass manifold (Fig. 5.2b). In addition, one other line was attached to the manifold to provide charcoal-filtered ambient air. Just prior to the manifold, on each line there was a solenoid valve which could be controlled by the microprocessor such that only one valve was open at any one time. A PTFE-coated diaphragm pump was connected to the manifold and drew air

Table 5.1 : List of treatments used in the Silwood chambers for the two major experiments.

30 January- 4 August 1981	15 November 1981- 30 June 1982
control (filtered air)	control (A)
+ NO_2	control (B)
+ SO_2	+ NO_2
+ SO_2 + NO_2	+ SO_2
+ NO	+ SO_2 + NO_2 (A)
+ SO_2 + NO_2 + NO	+ SO_2 + NO_2 (B)

(~10 l min^{-1}) from each treatment in turn for 7.5 minutes, followed by 15 minutes through the charcoal-filtered air to provide a check on clean air in addition to the control treatment(s). Thus, each treatment was sampled once an hour.

The gas monitors, also situated in the control box, subsampled from a small container attached to a short length of PTFE tube leading from the outlet of the pump (Fig. 5.2b). A Meloy SA285 flame photometric total sulphur analyser was used in both experiments. From 25 March-4 August 1981 a Monitor Labs model 8440 NO_x analyser was used to monitor NO and NO_2 concentrations. Throughout the 1981-82 experiment a Beckman model 952 NO_x analyser was used to monitor NO_2 concentrations. NO was not monitored in 1981-82

Between the start of the first experiment (29 January) and 25 March 1981 NO_2 was fluctuated on a daily basis and monitored as daily means using bubblers containing a triethanolamine solution, modified as recommended by Mulik, Fuerst, Guyer, Meeker & Sawaki (1974). NO was not monitored during this period, although some was added during February using the flowmeters to estimate concentrations.

Outputs from the gas monitors were connected to chart recorders. Hourly concentrations of each pollutant in each treatment were transferred to computer files and analysed to produce means, cfd's, diurnal patterns, correlations and peak durations over various periods specified in the Results (Section 5.3.2).

Tests on the efficiency of the sample system were carried out by varying the design of the system and also concurrently using hydrogen peroxide bubblers for SO_2 (National Survey method, Anon., 1966). Results showed that losses of pollutants by adsorption to the sample lines, valves and pump were negligible. At low concentrations (< 10 ppb) the accuracy of the monitors (± 2 ppb for SO_2 and ± 2-5 ppb for NO_2 and NO) resulted in potentially large proportional errors but these were considered unimportant because their absolute size was small. Checks on the calibration of the monitors were performed occasionally using an SO_2 calibrator (Meloy Labs, model CS 10-2X) and a cylinder containing 240 ppb NO_2 (BOC Spectrol). All readings from the monitors were noted and treated as exact.

5.2.5 Species, planting and harvesting

In all the experiments, plants were grown in pots containing a fertilised peat-sand mixture (a modified University of California D1 mix, 3 peat:1 sand; to each 100 l were added 15 g KNO_3, 15 g K_2SO_4, 60 g superphosphate, 148 g magnesian limestone, 118 g $CaCO_3$ and 18 g fritted trace elements, Bell *et al.*, 1979). Plants were grown either individually in 7.5 cm square pots or as swards in 15 cm square pots.

Control experiment

To test for environmental differences between the chambers, individual plants of *Lolium perenne* cv. S24 were grown in the chambers when they were all receiving filtered air without added pollutants.

A few seeds of *L. perenne* were planted in each of 108 pots (18 per chamber) on 10 August 1981 and placed in the chambers on the same day. Germination occurred on 14 August and plants were thinned to 1 per pot on 27 August. The pots were left undisturbed until 11 October, when they were harvested. Tiller numbers were counted and total shoot dry weights determined.

1980-81

Seeds of *L. perenne* cv. S24 and *Phleum pratense* cv. Odenwalder were sown as swards on 17 November 1980 (108 pots per species; 0.05 g *L. perenne* seed or 0.03 g *P. pratense* seed per pot). The pots were placed outside and germination of both species began on 8 December 1980. Eighteen pots of each species were placed adjacent to each other in each chamber on 29 January 1981 when the plants were 52 days old. Fumigation began the following day. The swards were thinned to 20 plants per pot ($\equiv 950\ m^{-2}$) on 17 February (*L. perenne*) or 4 March (*P. pratense*), the removed plants were dried and a maximum of 50 per treatment were weighed individually (shoots only).

Three major harvests were carried out. Each species required 2 or 3 days per harvest and mid-harvest dates are listed in Table 5.2. At each harvest, the numbers of plants and tillers per pot were counted; the shoots were cut to 4 cm and, for 10 pots per treatment, 'dead leaves' were separated from the 'live leaves plus stem'. The numbers of spikes per pot were counted when present. After the final harvest the remaining 'stubble' was cut at soil level. Shoot material was dried at 80°C for at least three days before weighing.

A standard 15:15:15 NPK granular fertiliser was applied at a rate of 60 kg N ha^{-1} after the May and June harvests (Table 5.2).

1981-82

Seeds of *L. perenne* cv. S24 and *P. pratense* cv. Odenwalder were sown as swards on 23 October 1981 (at the same rates as in the previous year). At the same time, *L. perenne* cv. S24 was sown to produce individual plants. Germination of both species had occurred by 9 November and pots were placed in the chambers on 15 November 1981 (Table 5.3). Fumigation began the following day, when the plants were only 7 days old. The plants were thinned to 1 or 20 plant(s) per pot in February 1982 (Table 5.3); removed plants were dried and weighed as in 1981.

Seeds of *Dactylis glomerata* cv. S26 were sown as swards (108 pots, 0.03 g seed per pot) on 7 December 1981 and kept in a cool glasshouse until

Table 5.2 : Summary of major events in the Silwood chambers, with dates, age of plants and duration of fumigation, 1980-81.

Event	*Lolium perenne*			*Phleum pratense*		
	Date	Age of plants (days)	Length of fumigation (days)	Date	Age of plants (days)	Length of fumigation (days)
Sow seed	17 November 1980	0	0	17 November 1980	0	0
Germination	8 December 1980	1	0	8 December 1980	1	0
Pots into chambers	29 January 1981	52	0	29 January 1981	52	0
Thin to 20 plants/pot	17 February 1981	71	19	4 March 1981	86	34
Harvest	4 May 1981	147	95	7 May 1981	150	98
Apply fertiliser	14 May 1981	157	105	14 May 1981	157	105
Harvest	9 June 1981	183	131	8 June 1981	182	130
Apply fertiliser	13 June 1981	187	135	13 June 1981	187	135
Harvest	4 August 1981	239	187	1 August 1981	235	183

Table 5.3 : Summary of major events in the Silwood chambers, with dates, age of plants and duration of fumigation, 1981-82.

Event	*Lolium perenne* (individual plants and swards)			*Phleum pratense*			*Dactylis glomerata*		
	Date	Age of plants (days)	Length of fumigation (days)	Date	Age of plants (days)	Length of fumigation (days)	Date	Age of plants (days)	Length of fumigation (days)
Sow seed	23 October 1981	0	0	23 October 1981	0	0	7 December 1981	0	0
Germination	9 November 1981	1	0	9 November 1981	0	0	30 December 1981	1	0
Pots into chambers	15 November 1981	7	0	15 November 1981	7	0	31 January 1982	33	0
Thin to 20 (or 1) plants/pot	22 February 1982	106	100	19 February 1982	103	97	28 January 1982	30	0
Harvest	19 April 1982	162	156	22 April 1982	165	159	11 May 1982	133	103
Apply fertiliser	27 April 1982	170	164	27 April 1982	170	164	14 May 1982	136	106
Harvest	9 June 1982	213	207	17 June 1982	221	215	30 June 1982	183	153

placed in the chambers on 31 January 1982. Germination occurred on 30 December and plants were thinned to 20 per pot on 28 January 1982.

Two major harvests were carried out on all species and mid-harvest dates are listed in Table 5.3. Harvests were conducted similarly to those in 1981, except that after the final harvest root samples were taken from *L. perenne*: from each treatment, the roots from 10 pots containing individual plants were washed in a sieve under running water; two 3.75 cm diameter cores to the base of the pot were taken from each of 5 pots per treatment of the *L. perenne* swards. The two cores from each pot were combined and washed. Roots outside the pots were not included.

Standard 15:15:15 NPK granular fertiliser was applied at 60 kg N ha^{-1} after the first harvest. An equivalent amount of granular fertiliser could not be used for the individual plants because the required quantity was too small. Instead, a liquid fertiliser was used containing 5.2:5.2:6 NPK and applied at 40 kg N ha^{-1} (Bio Plant Food, Pan Britannica Industries, Ltd.).

The abbreviations used in the text are the same as for the Solardomes:

DW = dead leaf dry weight (above 4 cm)
TW = total shoot dry weight (above 4 cm)
RW = root dry weight
%D = % dead material, (DW/TW) x 100.

5.2.6 Maintenance

In these experiments the plants were grown in pots and could therefore be moved both within and between chambers. In order to minimise the possibility of environmental conditions in individual chambers modifying the effects of the pollution treatments, pots were moved from one chamber to another about once every four weeks. At the same time the pollutant supply lines were re-connected to the appropriate ducts to keep the plants continuously in their respective treatments. The 18 pots within each species/treatment were randomised once a fortnight to reduce positional effects within each chamber.

Watering was carried out from above as necessary to keep the soil moist. The sand on the base of each chamber also acted as a reservoir for sub-irrigation.

Plants were sprayed with Benlate against powdery mildew as required. Infection was never severe and occurred on only one occasion per experiment.

5.2.7 Analysis of results and statistics

Results from all swards were treated similarly in both years. Essentially similar information was calculated for the individual plants of *L. perenne* except that results were only expressed as plant^{-1} or tiller^{-1}, not m^{-2}.

The plants removed during thinning were tested for differences between treatments using anovar with least significant differences (when all sample sizes were equal) or with a modified F-test on each possible pair of treatments (when the sample sizes were unequal) (Walpole & Myers, 1972). To make the results comparable with later harvests and the Solardome experiments, they were converted to a m^{-2} basis assuming 20 plants per pot or, in one case, using plant density at the first major harvest (see Results, Section 5.3.3). Significant differences in weight m^{-2} between treatments were assumed to be the same as those for weight plant^{-1} (except for swards of *L. perenne* in 1982, see Results).

Data were analysed in a similar manner to those from the Solardomes. Results were obtained for individual harvests and as 'totals to date'. Average plant and tiller weights were calculated for each pot and are referred to as weight plant^{-1} or tiller^{-1} even though they are means (see

Section 4.2.9). Percentage data were arcsine transformed before analysis and the means were backtransformed to percent for convenience. All results were compared between treatments using one-way anovar with LSDs for $p = 0.05$. In the second major experiment, when some treatments were duplicated, the results from comparable treatments were often dissimilar and therefore they were always considered as different treatments for the purposes of statistical analysis, rather than as replicates of the same treatments.

To test for an interaction between the effects of SO_2 and NO_2, two-way anovar was used, with presence or absence of SO_2 and NO_2 as the factors.

5.3 Results

5.3.1 Control experiment

Individual plants of *L. perenne* cv. S24 were grown in each of the chambers for 58 days over summer. There were no differences in dry weight plant^{-1} or tiller^{-1} (Table 5.4), although the ratios of the smallest to largest mean weights were 1:1.23 for plants and 1:1.17 for tillers. However, the number of tillers plant^{-1} differed between chambers and the smallest to largest ratio was 1:1.45. There were no apparent reasons for the differences and no obvious positional effect (the relative locations of each chamber are shown in Fig. 5.1a).

5.3.2 Pollutant concentrations

Means

Monthly mean concentrations of each pollutant, for treatments with and without added pollutants, are illustrated in Figure 5.3. Means for the periods up to each harvest and between major harvests are listed in Tables 5.5 (1981) and 5.6 (1982). In 1982, for the purposes of analysing

Table 5.4 : Results from the control experiment in the Silwood chambers.

Chamber	Mean total shoot dry wt (g)$^{(1)}$	Mean number of tillers plant$^{-1\,(2)}$	Mean weight per tiller (g)
1	0.81 ± 0.06	21.2 ± 1.5c	0.040 ± 0.003
2	0.80 ± 0.06	18.0 ± 0.8b	0.044 ± 0.003
3	0.73 ± 0.04	17.1 ± 1.2ab	0.044 ± 0.002
4	0.66 ± 0.06	14.6 ± 1.1a	0.047 ± 0.003
5	0.80 ± 0.04	17.7 ± 1.0ab	0.046 ± 0.002
6	0.70 ± 0.05	16.3 ± 1.0ab	0.043 ± 0.002

(1) ± S.E.M.

(2) means followed by the same letter are not significantly different at $p = 0.05$.

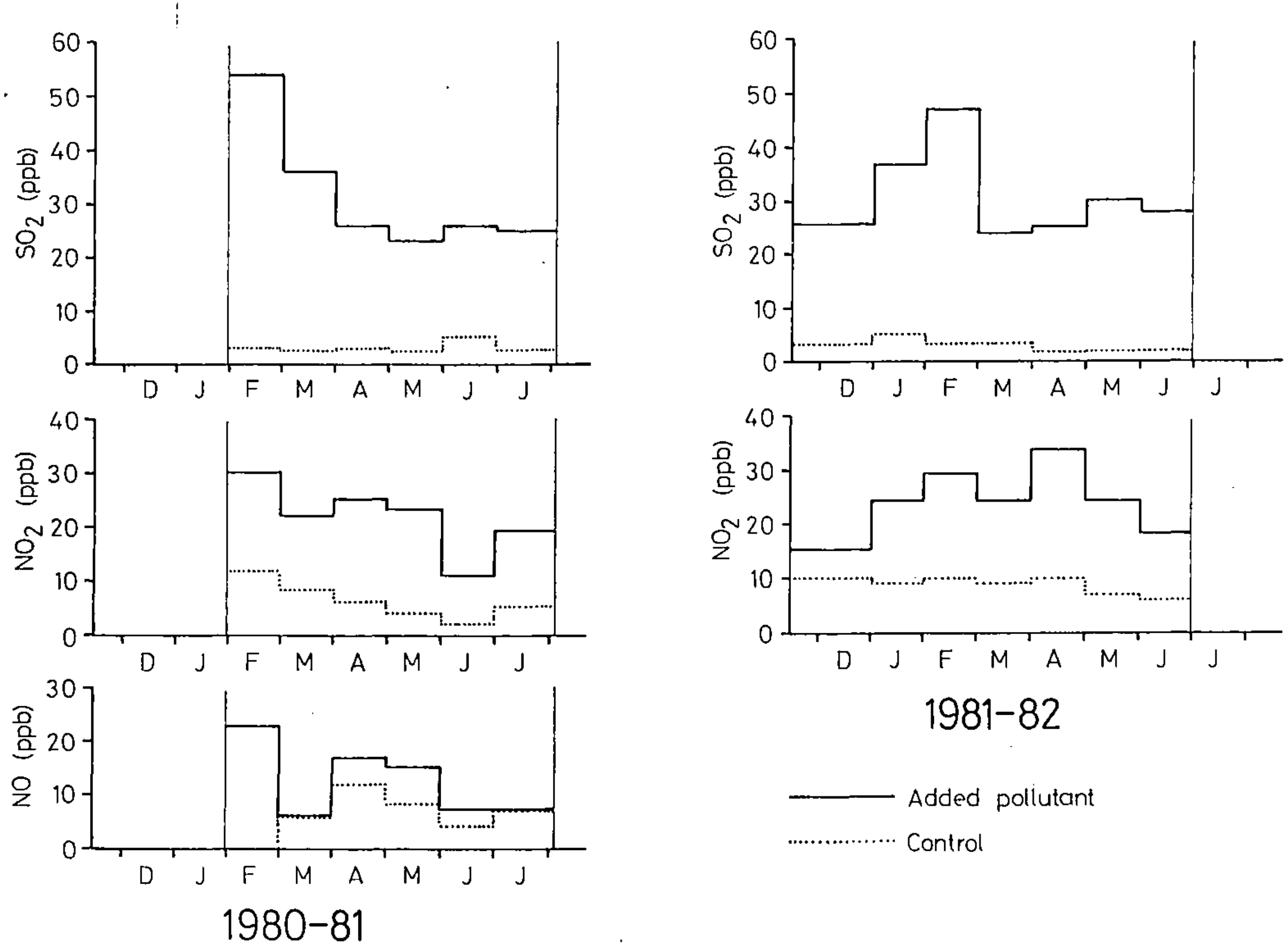


Figure 5.3 : Monthly mean SO_2, NO_2 and NO concentrations in treatments with and without added pollutants in the Silwood chambers.

Table 5.5 : Mean concentrations (ppb) of pollutants in each treatment for the periods up to each harvest and between consecutive major harvests, from 30 January-4 August 1981.

Pollutant	Treatment	30:1:81 to 19:2:81	30:1:81 to 4:3:81	30:1:81 to 6:5:81	7:5:81 to 8:6:81	9:6:81 to 4:8:81	30:1:81 to 8:6:81	30:1:81 to 4:8:81
SO_2	control	2.9	3.1	3.2	2.7	3.9	3.1	3.3
	+ NO_2	2.7	2.9	3.1	2.6	3.5	3.0	3.2
	+ SO_2	48.9	50.9	38.4	24.0	25.6	34.5	31.7
	+ SO_2 + NO_2	50.2	51.2	38.9	25.0	24.8	35.2	31.9
	+ NO	2.8	3.0	3.2	2.7	3.6	3.0	3.2
	+ SO_2 + NO_2 + NO	51.6	52.7	40.0	23.6	24.3	34.8	31.5
NO_2	control	10.2	10.5	7.9	3.4	3.6	6.7	5.2
	+ NO_2	27.0	26.7	24.7	19.3	15.8	23.2	21.0
	+ SO_2	8.7	9.0	13.6	3.2	4.6	11.0	5.7
	+ SO_2 + NO_2	31.7	31.2	25.6	19.5	15.5	24.2	19.8
	+ NO	14.1	13.1	9.2	3.5	3.3	7.7	6.3
	+ SO_2 + NO_2 + NO	39.7	34.4	28.0	20.2	15.6	26.0	22.8
NO(1)	control	0	0	6.3	7.5	4.6	6.6	6.0
	+ NO_2	0	0	6.1	8.2	6.4	6.6	6.6
	+ SO_2	0	0	7.7	6.1	4.4	7.4	5.3
	+ SO_2 + NO_2	0	0	5.4	6.5	6.6	5.6	5.9
	+ NO	25.0	23.0	15.2	14.6	4.9	15.0	11.6
	+ SO_2 + NO_2 + NO	25.0	23.0	15.8	13.9	7.0	15.3	12.6
NO_x	control	10.2	10.5	14.2	10.7	8.3	13.4	11.9
	+ NO_2	27.0	26.7	30.8	26.4	22.2	29.6	27.4
	+ SO_2	8.7	9.0	20.9	9.1	8.9	18.2	11.1
	+ SO_2 + NO_2	31.7	31.2	31.1	25.4	22.1	29.8	26.3
	+ NO	39.7	37.5	24.4	18.0	8.1	22.8	17.9
	+ SO_2 + NO_2 + NO	62.9	60.5	43.7	33.4	22.6	41.1	34.8

(1) There were no data for 'background' NO concentrations until 25 March. From the start until 25 March only additions of NO were estimated (see text). Therefore mean NO concentrations over periods that include dates until 25 March were underestimates of actual concentrations.

Table 5.6 : Mean concentrations of SO_2 and NO_2 in each treatment for the periods up to each harvest and between consecutive major harvest, 15 November 1981-30 June 1982.

Pollutant	Treatment	Periods to harvests of *L. perenne* and *P. pratense*				Periods to harvests of *D. glomerata*		
		15:11:81 to 20:2:82	15:11:81 to 20:4:82	21:4:82 to 9:6:82	15:11:81 to 9:6:82	31:1:82 to 11:5:82	12:5:82 to 30:6:82	31:1:82 to 30:6:82
SO_2	control (A)	3.4	3.1	1.6	2.7	2.3	1.7	2.1
	control (B)	3.3	3.1	1.6	2.7	2.3	1.8	2.2
	+ NO_2	3.3	3.1	1.7	2.7	2.4	1.8	2.2
	+ SO_2	35.3	32.1	30.0	31.6	32.1	28.3	30.9
	+ SO_2 + NO_2 (A)	35.5	31.4	29.3	30.9	31.0	28.1	30.1
	+ SO_2 + NO_2 (B)	36.4	33.1	30.0	32.4	33.5	27.8	31.6
NO_2	control (A)	8.9	9.6	7.7	9.1	9.5	6.7	8.6
	control (B)	9.4	9.7	7.6	9.2	9.1	7.4	8.6
	+ NO_2	21.6	24.2	25.4	24.5	27.9	21.1	25.7
	+ SO_2	9.8	9.9	7.5	9.2	9.1	6.8	8.3
	+ SO_2 + NO_2 (A)	21.2	25.6	26.3	25.8	31.1	19.9	27.4
	+ SO_2 + NO_2 (B)	22.2	24.1	23.8	24.0	27.6	19.3	24.9

pollutant conditions, *L. perenne* and *P. pratense* were assumed to be harvested on similar dates, but *D. glomerata* was treated separately. Inspection of Tables 5.5 and 5.6 shows that, in the majority of cases, the mean concentrations of a given pollutant over a given period were similar in treatments to which that pollutant was added. Exceptions to this were the NO_2 concentrations at the start of the first experiment (Table 5.5), but after the first major harvest, in May 1981, the relevant mean concentrations were similar. Any differences in effect caused by the minor differences in pollutant concentrations between comparable treatments could not be determined in this type of experiment.

In both experiments monthly mean SO_2 concentrations were highest (~50 ppb) in February and about 25 ppb during spring and summer (Fig. 5.3). From November 1981 until January 1982 the mean SO_2 concentrations were 26-37 ppb, lower than the intended levels of 40-50 ppb due to downtime in the cold weather during December and January. With the exception of March, SO_2 concentrations in comparable months were similar in the two experiments. Mean SO_2 concentrations for the duration of each experiment were both about 31 ppb in the '+SO_2' treatments, compared with ~3 ppb in the treatments without added SO_2.

NO_2 concentrations in 1981 decreased slightly from February until July, with the exception of a very low mean concentration in June (Fig. 5.3). At the start of the 1981-82 experiment, mean NO_2 concentrations in the '+NO_2' treatments were only 6 ppb above the background of 10 ppb. However, from January to June 1982 the NO_2 levels in the '+NO_2' treatments were considerably greater than background NO_2, monthly means varying from 19 to 34 ppb but with no seasonal trend. Overall mean NO_2 concentrations in 1981 were ~21 ppb but ~26 ppb in 1981-82.

Due to difficulties in maintaining a controlled supply of NO, the mean concentrations in the '+NO' treatments were only slightly above the background levels. NO was not supplied during March and July.

Cumulative frequency distributions

Cumulative frequency distributions for each treatment were calculated for each of the time periods used to produce Tables 5.5 and 5.6. As expected, comparable cfd's were very similar in all cases. Cfd's for the duration of each experiment are illustrated in Figures 5.4 and 5.5. In 1981 the SO_2 and NO_2 cfd's in the SO_2 + NO_2 + NO treatment were approximately linear over the upper 70% of their distributions (Fig. 5.4). The lower 30% deviate from linearity for two reasons, (a) downtime due to mechanical failure and, (b) the inability to control concentrations below 15 ppb. Similar SO_2 and NO_2 cfd's were found in the 1981-82 experiments (Fig. 5.5). The cfd for NO (Fig. 5.4) shows that for the ~40% of hours it was supplied, a reasonably linear cfd was achieved (but not greatly above that in the control chamber).

Direct comparison of these results with Figures 2.13 and 2.14, illustrating hourly mean cfd's for SO_2, NO_2 and NO at several UK sites, is difficult as cfd's vary with mean concentration (although the slopes for a given pollutant remain similar). Comparison between given percentiles is only possible when the means are approximately equal, but the slopes of the linear portions of the cfd's of respective pollutants in these experiments and at UK sites were clearly not dissimilar.

Diurnal patterns

Mean diurnal patterns were calculated for each pollutant and treatment for the periods up to and between each major harvest, but a detailed analysis was performed only over the whole of each experiment for the SO_2 + NO_2 (+ NO) treatments. As a consequence of using a similar monthly

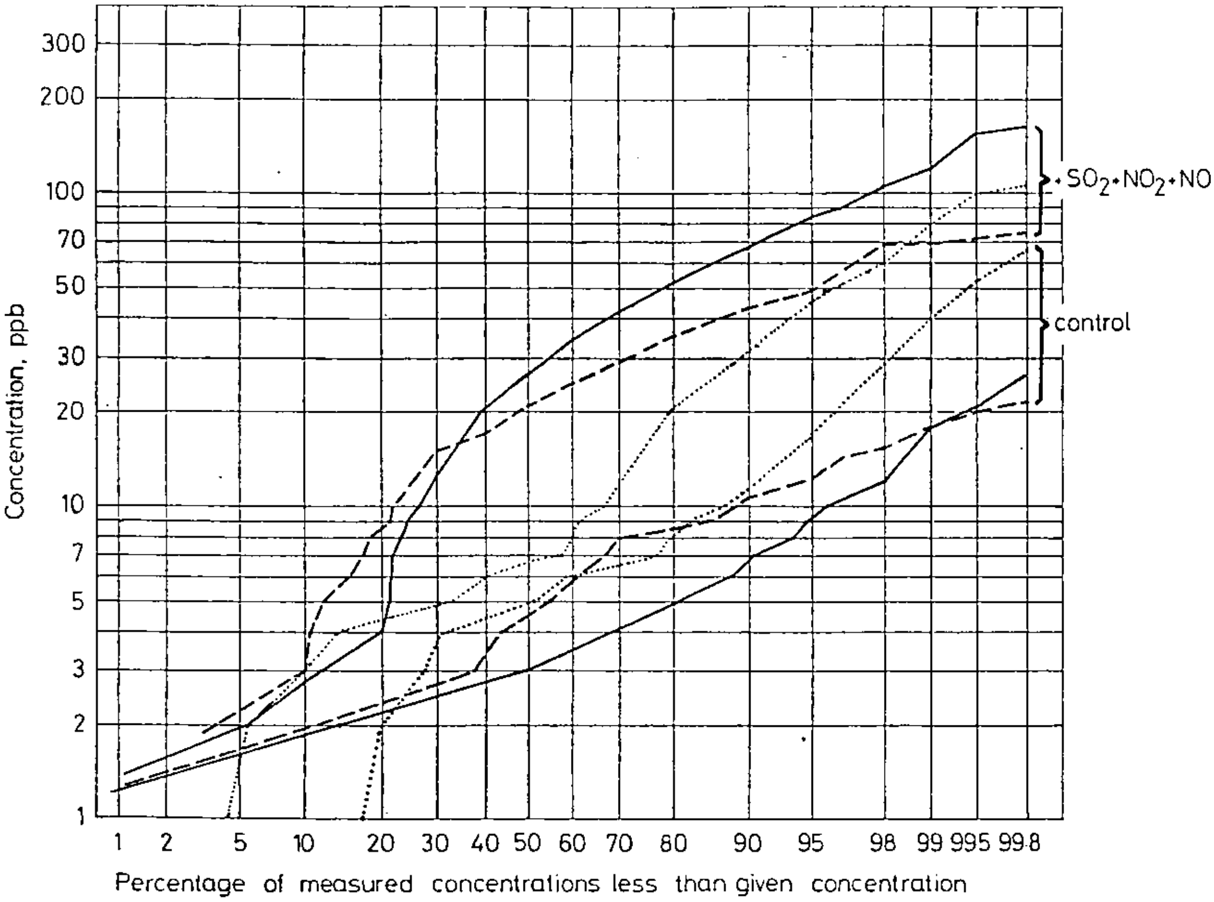


Figure 5.4 : Cumulative frequency distributions of hourly mean SO_2, NO_2 and NO concentrations in the control and SO_2 + NO_2 + NO treatment in the Silwood chambers, 30 January-4 August 1981.

—— SO_2

– – NO_2

········ NO

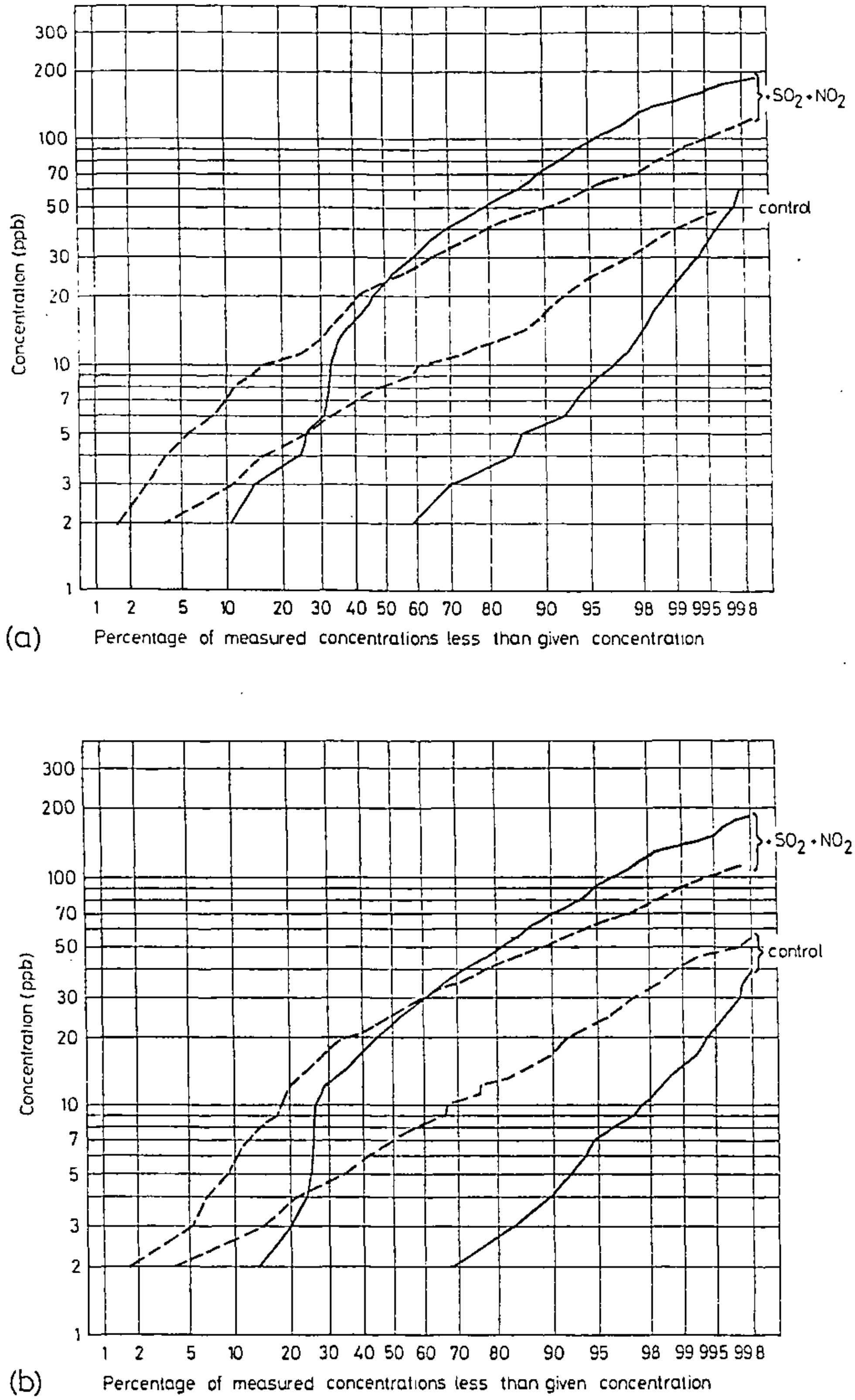


Figure 5.5 : Cumulative frequency distributions of hourly mean SO_2 and NO_2 concentrations in the control and SO_2 + NO_2 treatments in the Silwood chambers.

(a) 15 November 1981-9 June 1982 (growth period for *L. perenne* and *P. pratense*)

(b) 31 January-30 June 1982 (growth period for *D. glomerata*)

—— SO_2, – – NO_2.

pattern (Section 5.2.3), diurnal patterns for the shorter periods were essentially similar to those for the whole of their respective experiments and are not described here. The detailed analyses are illustrated in Figures 5.6 to 5.9.

SO_2 showed the most marked diurnal patterns: in both experiments minimum mean concentrations (~25 ppb) occurred from midnight to 0600 hours; maximum mean concentrations were 35-40 ppb and occurred from 0700-1200 hours. This pattern was similar to that found in central London (Fig. 2.18) although in the experiments the mean concentrations were lower.

In 1981 NO_2 showed very little diurnal patterns except for slightly higher mean concentrations from ~1800-0100 hours than during the rest of the day (Fig. 5.6), similar to the pattern in central London (Fig. 2.18). The situation in 1982 was similar except that the difference between 1800-0100 hours and the rest of the day was greater (Figs. 5.8 and 5.9).

There were no marked diurnal patterns in NO or NO_x concentrations, in contrast to the situation in central London (Fig. 2.19) and at other UK sites (Fig. 2.16).

For each pollutant the percentage of time above a given concentration at each hour of the day was, as expected, closely related to the mean diurnal pattern.

Correlation of hourly mean concentrations

The degrees of correlation of SO_2 with NO_2 and NO for 1981 are shown in Figure 5.10 and of SO_2 with NO_2 for 1981-82 in Figure 5.11. In all cases it is evident that there was a wide variation in the concentration of one pollutant at any given concentration of the other, but nevertheless, some correlation was present. All three SO_2:NO_2 diagrams show two main features: firstly, NO_2 was often > 10 ppb at very low SO_2 (< 5 ppb) concentrations (in contrast to the situation in London, Fig. 2.15);

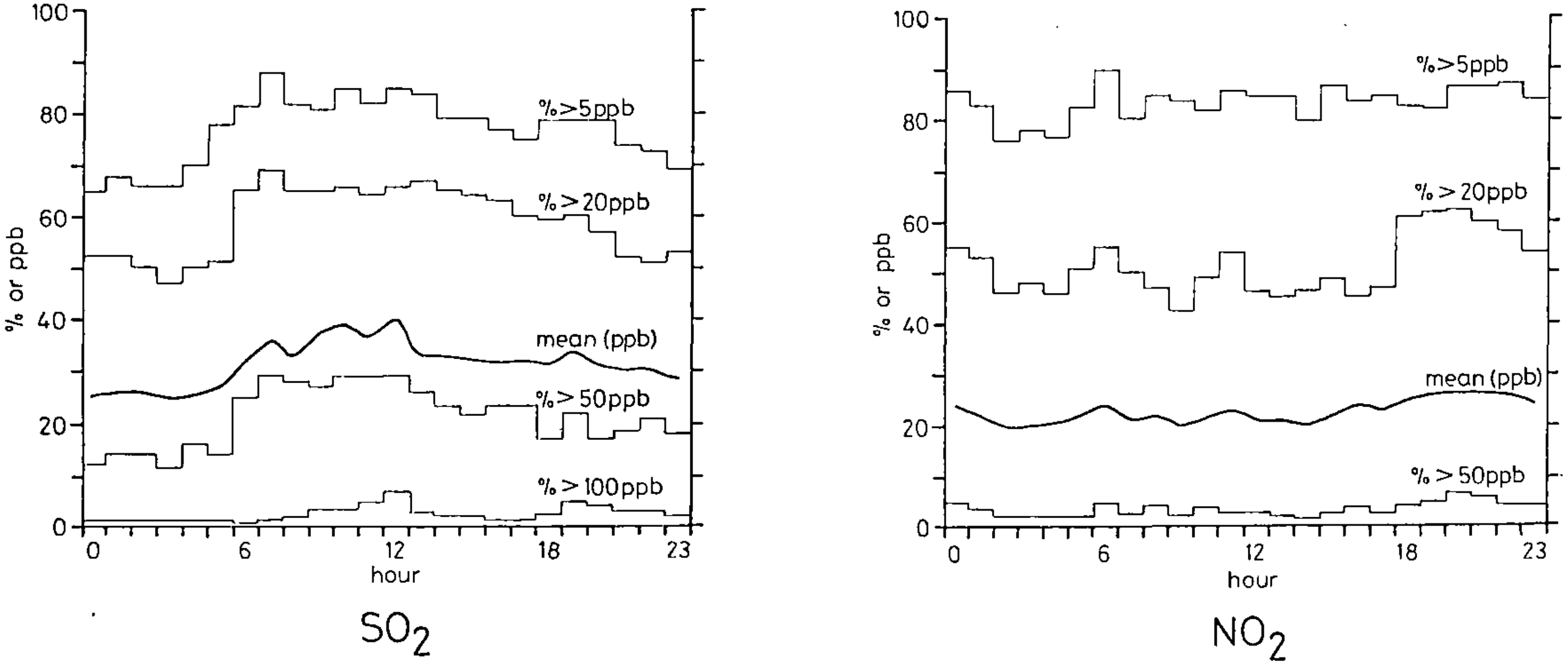


Figure 5.6 : Mean diurnal patterns of SO_2 and NO_2 in the SO_2 + NO_2 + NO treatment in the Silwood chambers, 30 January-4 August 1981.

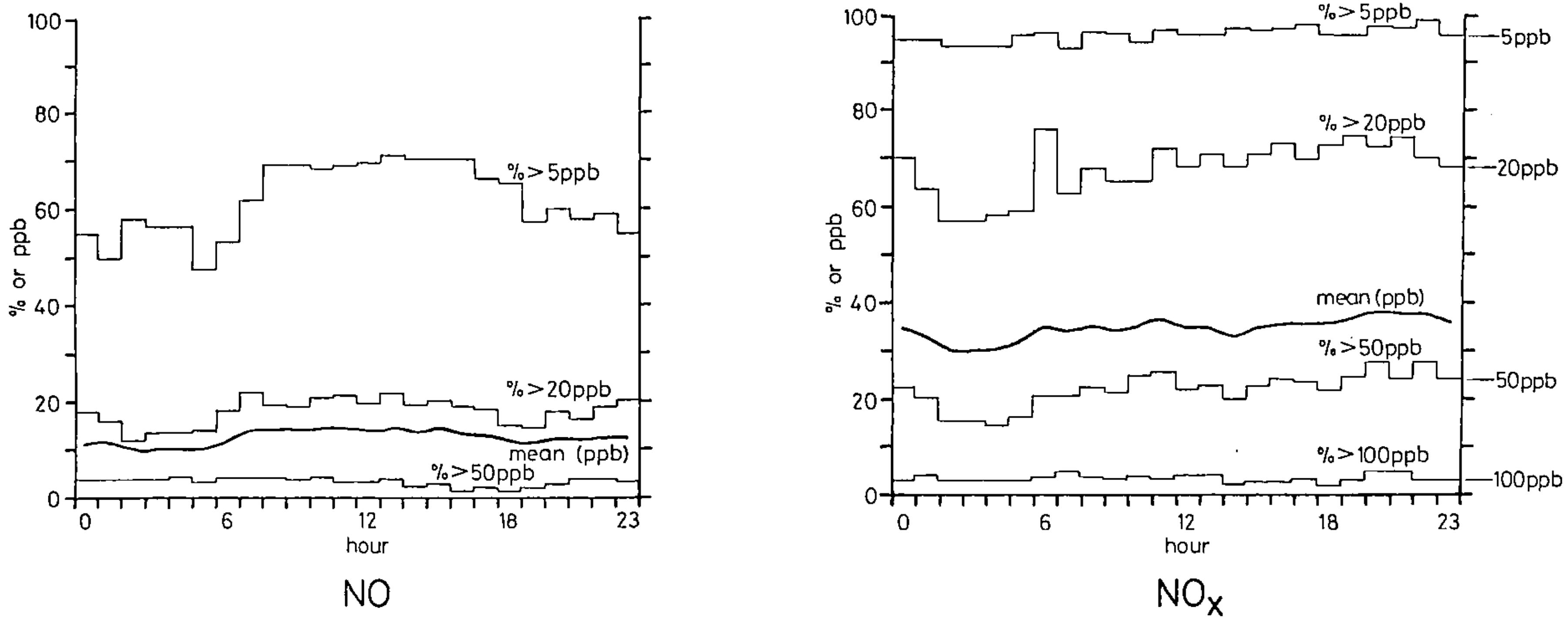


Figure 5.7 : Mean diurnal patterns of NO and NO$_x$ in the SO$_2$ + NO$_2$ + NO treatment in the Silwood chambers, 30 January-4 August 1981.

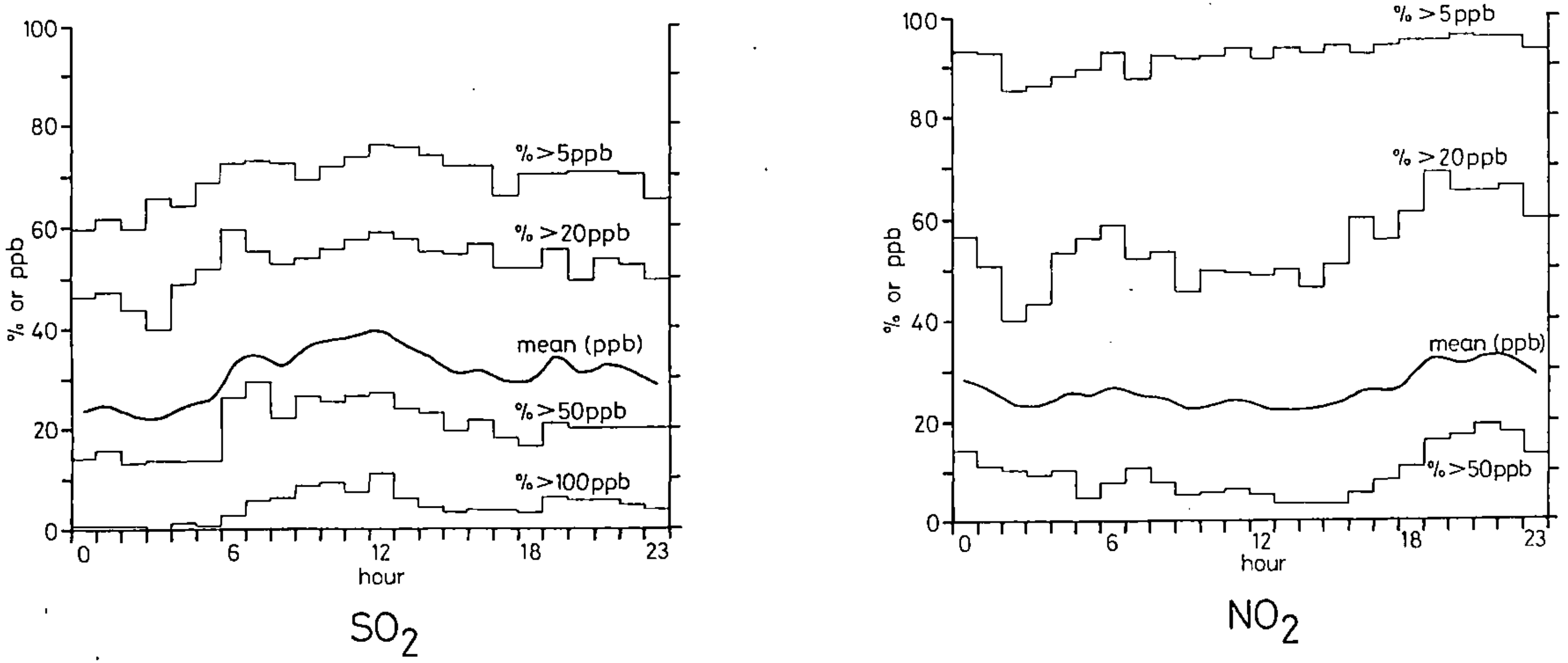


Figure 5.8 : Mean diurnal patterns of SO_2 and NO_2 in the SO_2 + NO_2 treatments in the Silwood chambers, 25 November 1981-9 June 1982 (growth period for *L. perenne* and *P. pratense*).

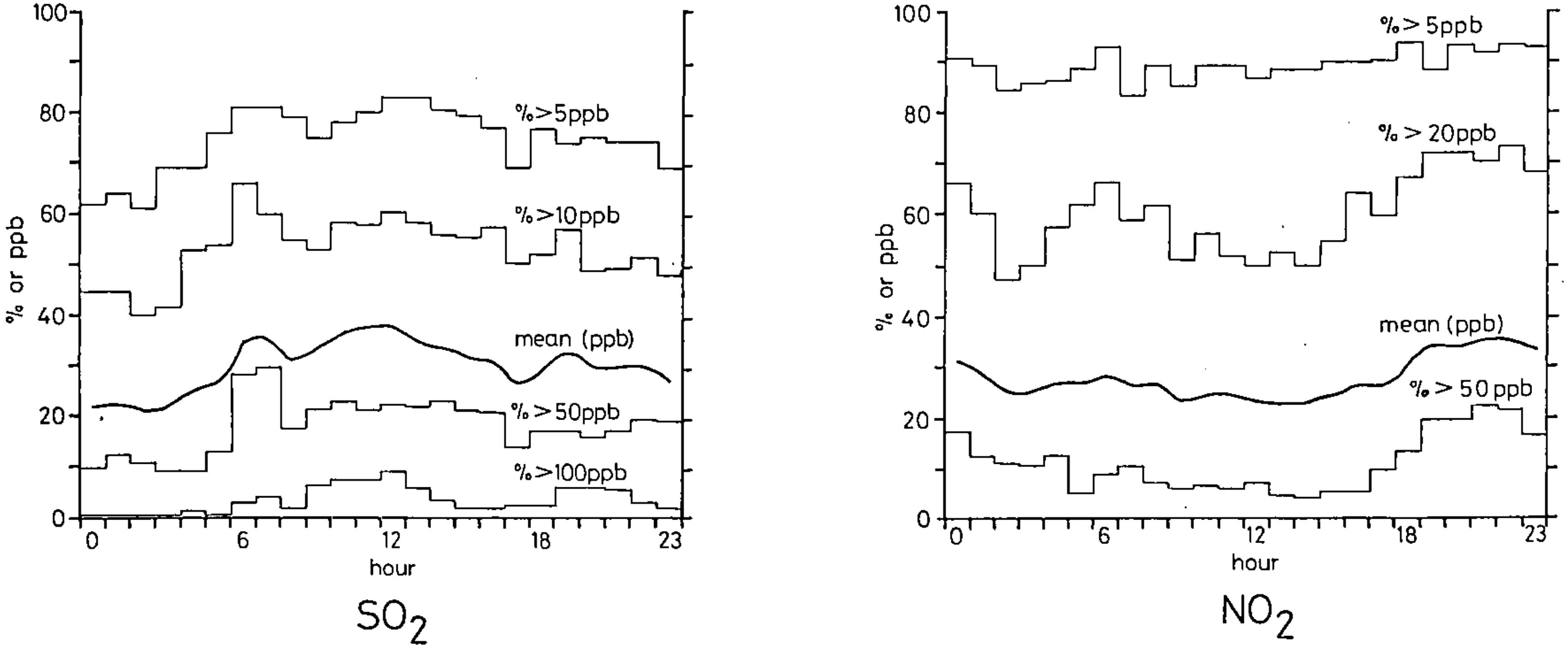


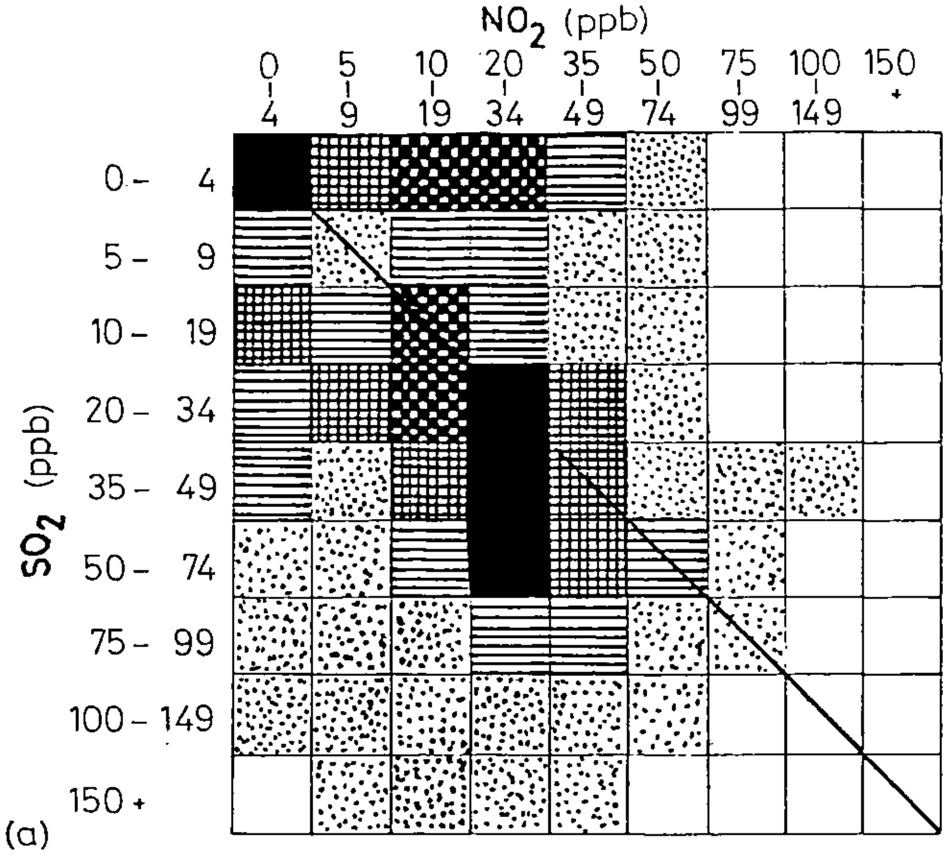
Figure 5.9 : Mean diurnal patterns of SO_2 and NO_2 in the SO_2 + NO_2 treatments in the Silwood chambers, 31 January-30 June 1982 (growth period for *D. glomerata*).

Figure 5.10 : Correlation of hourly mean concentrations, (a) of SO_2 with NO_2 and (b) of SO_2 with NO, in the SO_2 + NO_2 + NO treatment in the Silwood chambers, 30 January-4 August 1981.

The diagonal lines represent 1:1 correlation.

Individual squares represent the percentage of total hours in each combination of concentrations.

	%
□	0
░	0 < - ≤ 1
▤	1 < - ≤ 2
▦	2 < - ≤ 4
▓	4 < - ≤ 6
■	6 <


NO2 (ppb)
0-4
5-9
10-19
20-34
35-49
50-74
75-99
100-149
150+
SO2 (ppb)
0- 4
5- 9
10- 19
20- 34
35- 49
50- 74
75- 99
100-149
150+
(a)

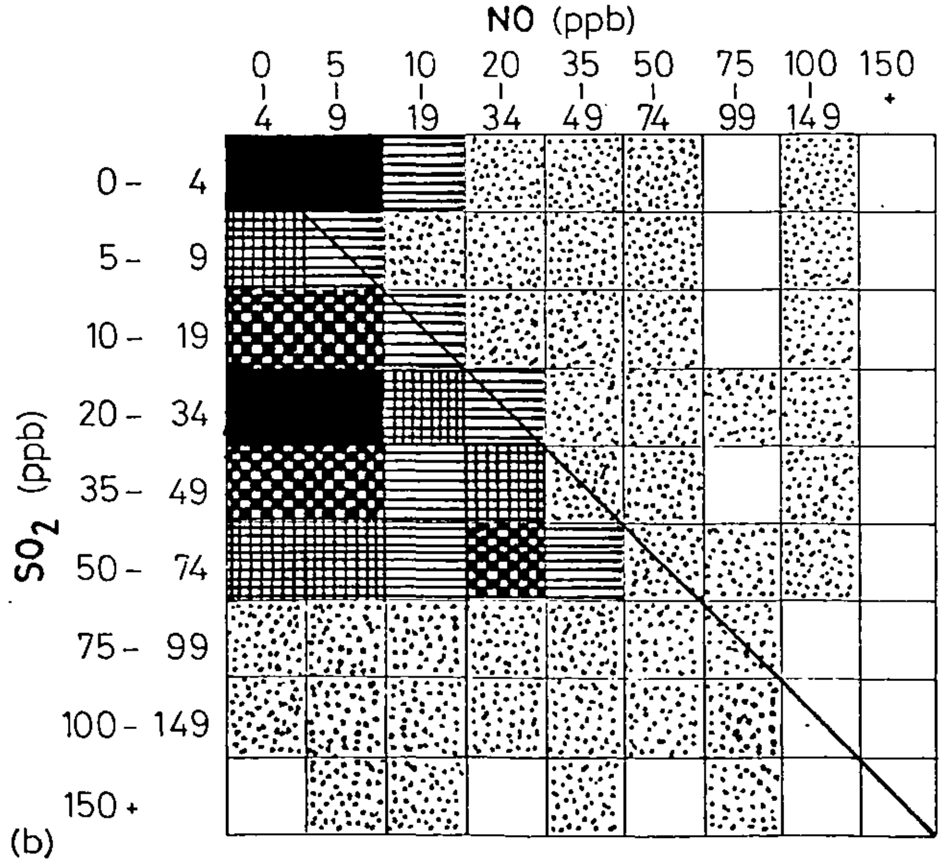
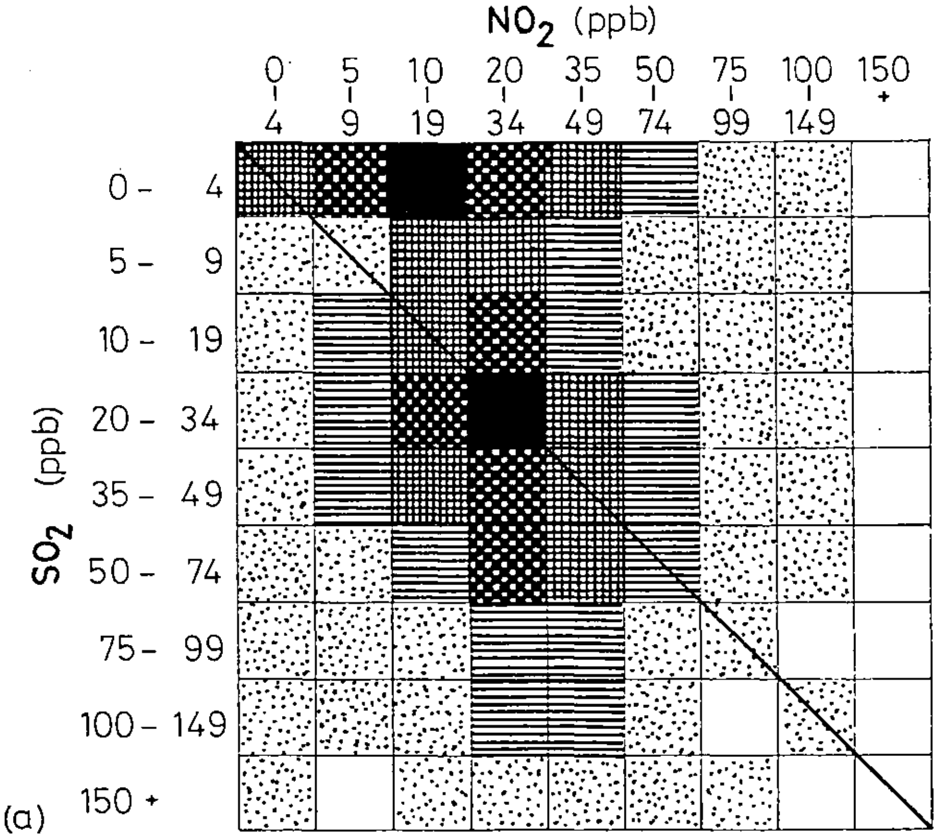
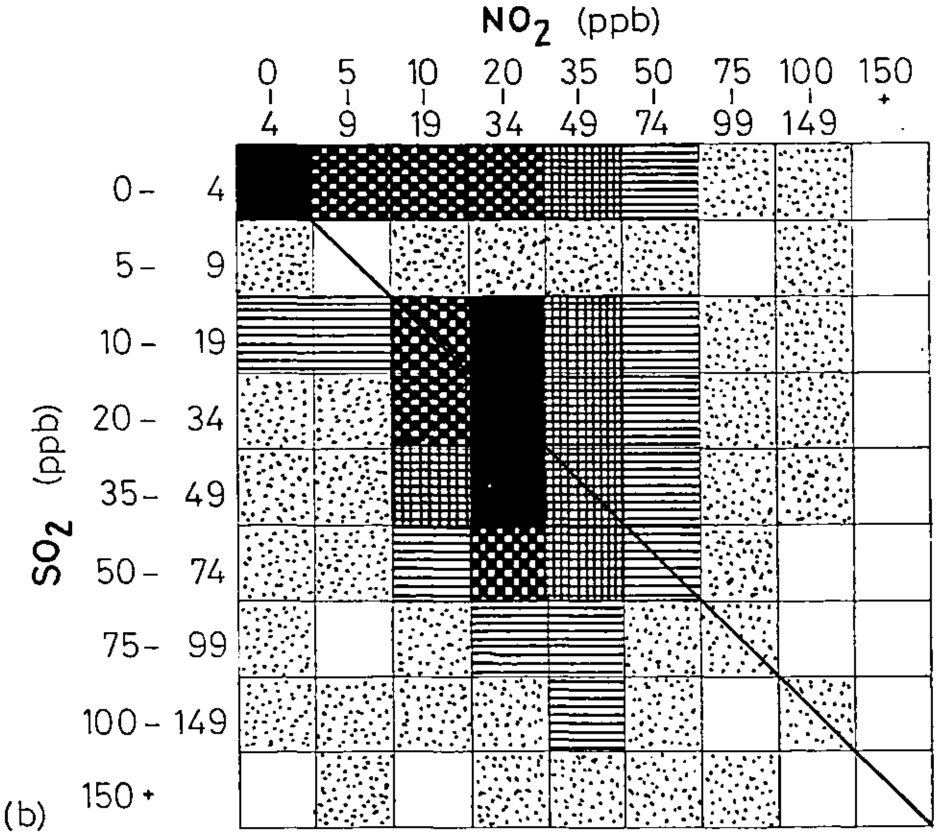

NO (ppb)
0-4
5-9
10-19
20-34
35-49
50-74
75-99
100-149
150+
SO2 (ppb)
0- 4
5- 9
10- 19
20- 34
35- 49
50- 74
75- 99
100-149
150+
(b)

Figure 5.11 : Correlation of hourly mean concentrations of SO_2 with NO_2 in the SO_2 + NO_2 treatments in the Silwood chambers, (a) 25 November 1981-9 June 1982 (growth period for *L. perenne* and *P. pratense*), (b) 31 January-30 June 1982 (growth period for *D. glomerata*).

Key as for Figure 5.10.


NO$_2$ (ppb)
0-4
5-9
10-19
20-34
35-49
50-74
75-99
100-149
150+
SO$_2$ (ppb)
0 - 4
5 - 9
10 - 19
20 - 34
35 - 49
50 - 74
75 - 99
100 - 149
150+
(a)


NO$_2$ (ppb)
0-4
5-9
10-19
20-34
35-49
50-74
75-99
100-149
150+
SO$_2$ (ppb)
0 - 4
5 - 9
10 - 19
20 - 34
35 - 49
50 - 74
75 - 99
100 - 149
150+
(b)

secondly, when NO_2 was 20-34 ppb, SO_2 was frequently 20-74 ppb (similar to the situation in London). In general, however, the correlation of SO_2 with NO_2 was not as well defined as in the London data. The correlation of SO_2 with NO (Fig. 5.10b) shows that NO was less than 20 ppb most of the time (see also Fig. 5.4) and was not strongly related to SO_2 concentration, although when NO was > 10 ppb there was a slight positive correlation with SO_2. This was in contrast to the design of the pollutant regime which was intended to produce results similar to those for central London (Fig. 2.15).

Peak duration

The durations of peaks of SO_2, NO_2, NO and NO_x in 1981 are illustrated in Figures 5.12 and 5.13, and of SO_2 and NO_2 in 1981-82 in Figures 5.14 and 5.15. In most cases the peak durations at each base level were approximately log-normally distributed, as found in central London and elsewhere (Section 2.7). Direct comparison with the data from central London (Figs. 2.20 and 2.21) is not possible because the experiments used lower mean concentrations than those of the London data, and peak durations are presumably related to mean concentration.

Comparison between the two experiments showed an acceptable degree of similarity for SO_2. For example, in 1981 at base levels of 20, 50, 75 and 100 ppb, 90% of peaks were shorter than 16, 10, 8 and 5 hours respectively (Fig. 5.12); comparable figures for 1981-82 were 15, 7, 5 and 5 hours (Fig. 5.15). At base levels of 20 and 50 ppb, NO_2 peak durations were distributed similarly in both experiments. However, whereas in 1981 NO_2 rarely exceeded 75 ppb for more than 2 hours, in 1981-82 peaks of NO_2 in excess of 75 ppb occasionally lasted for more than 4 hours and some peaks of short duration occurred above 100 ppb.

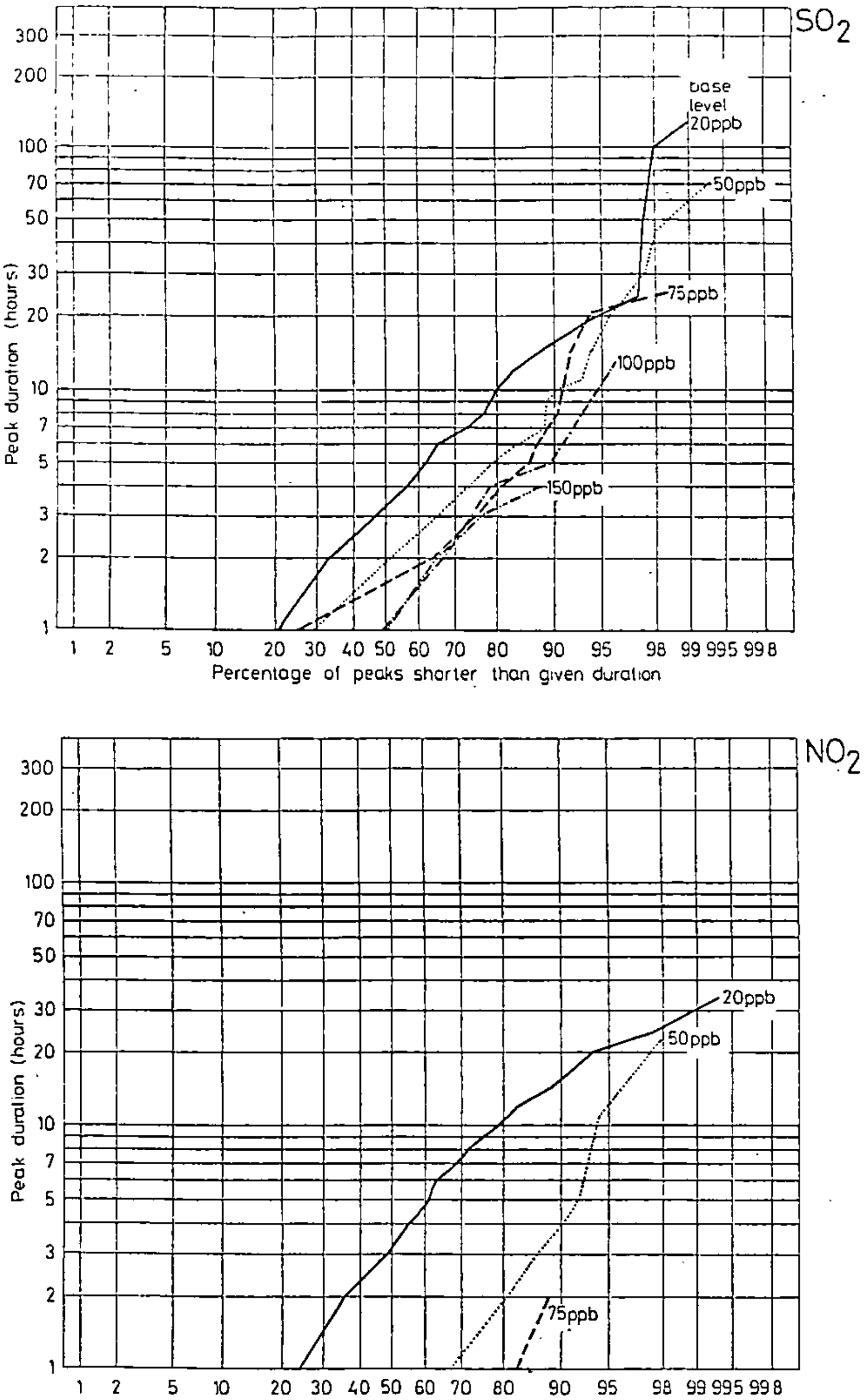
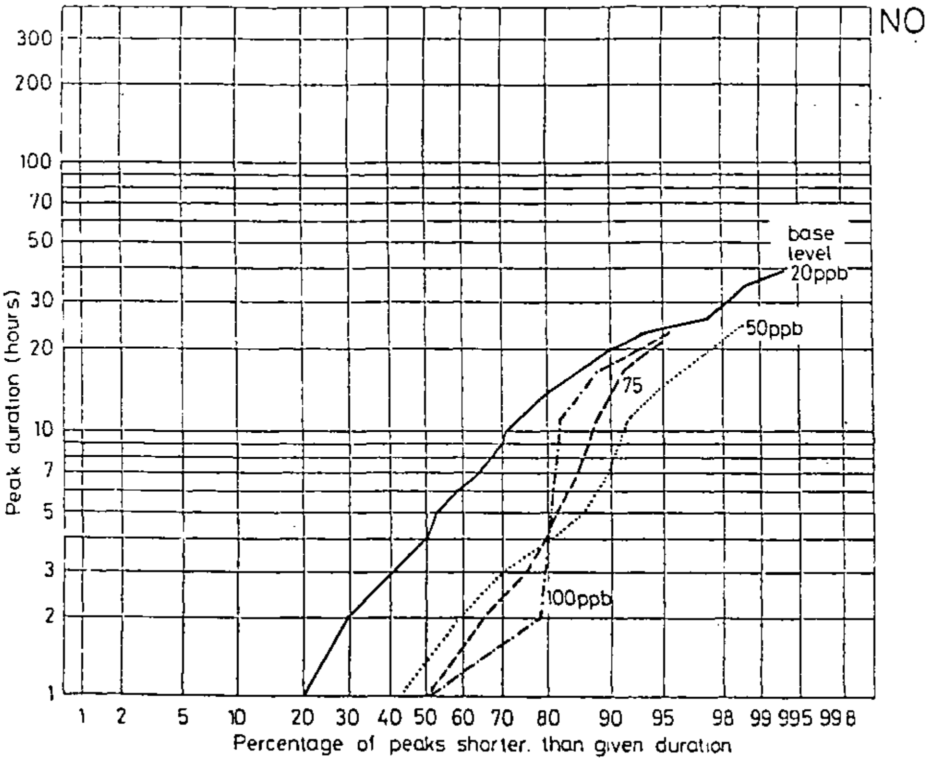


Figure 5.12 : Cumulative frequency distributions for peak durations of SO_2 and NO_2 above various base levels in the SO_2 + NO_2 + NO treatment in the Silwood chambers, 30 January-4 August 1981.



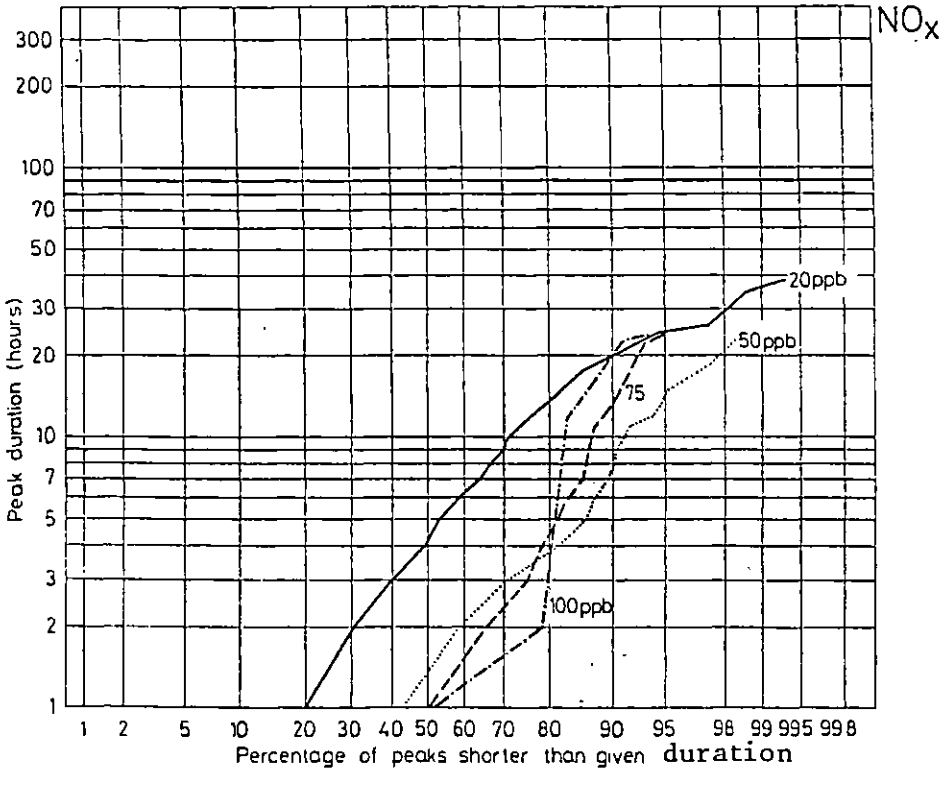


Figure 5.13 : Cumulative frequency distributions of peak durations of NO and NO_x above various base levels in the $SO_2 + NO_2 + NO$ treatment in the Silwood chambers, 30 January-4 August 1981.

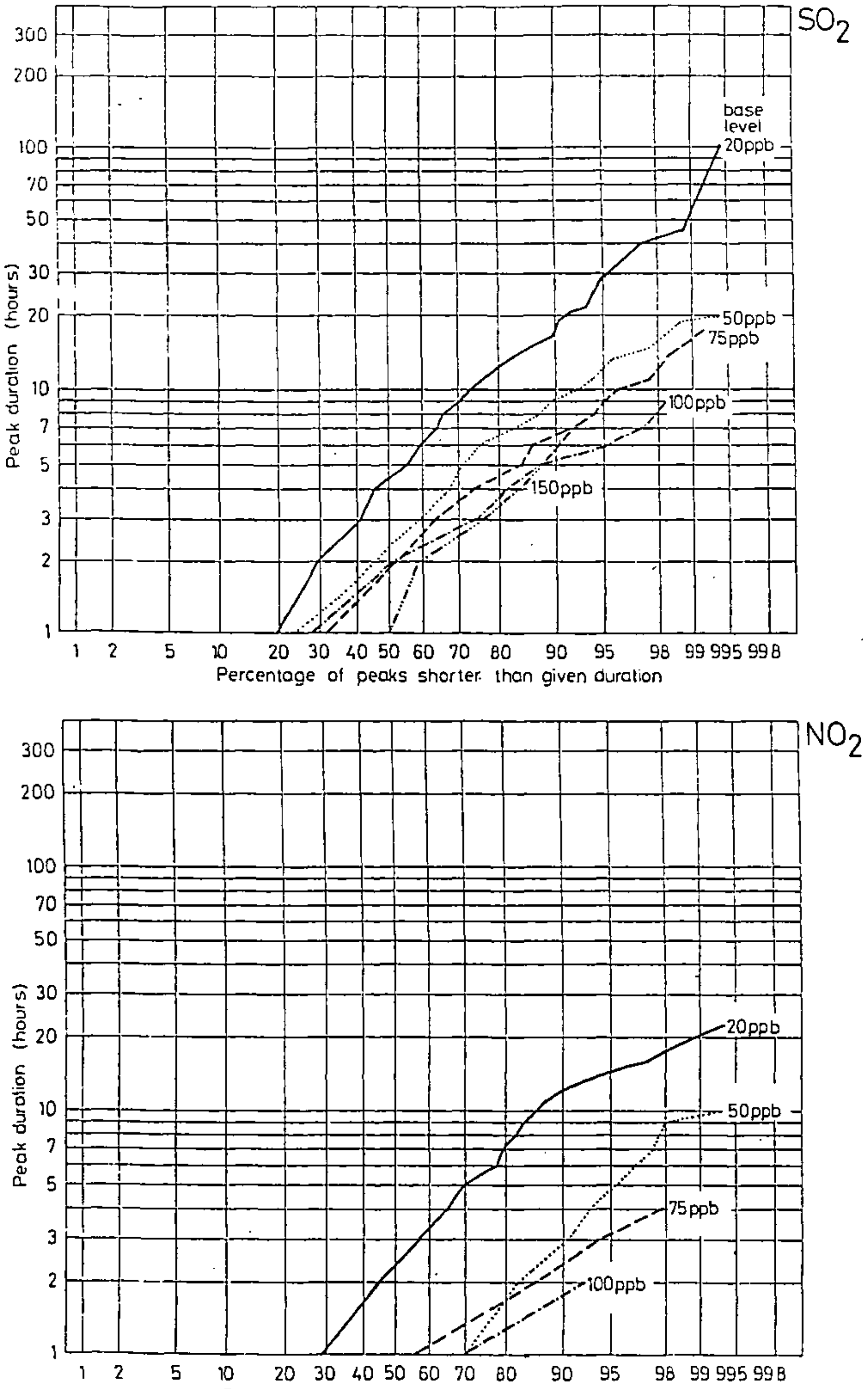


Figure 5.14 : Cumulative frequency distributions for peak durations of SO_2 and NO_2 above various base levels in the SO_2 + NO_2 treatments in the Silwood chambers, 29 November 1981-9 June 1982 (growth period for *L. perenne* and *P. pratense*).

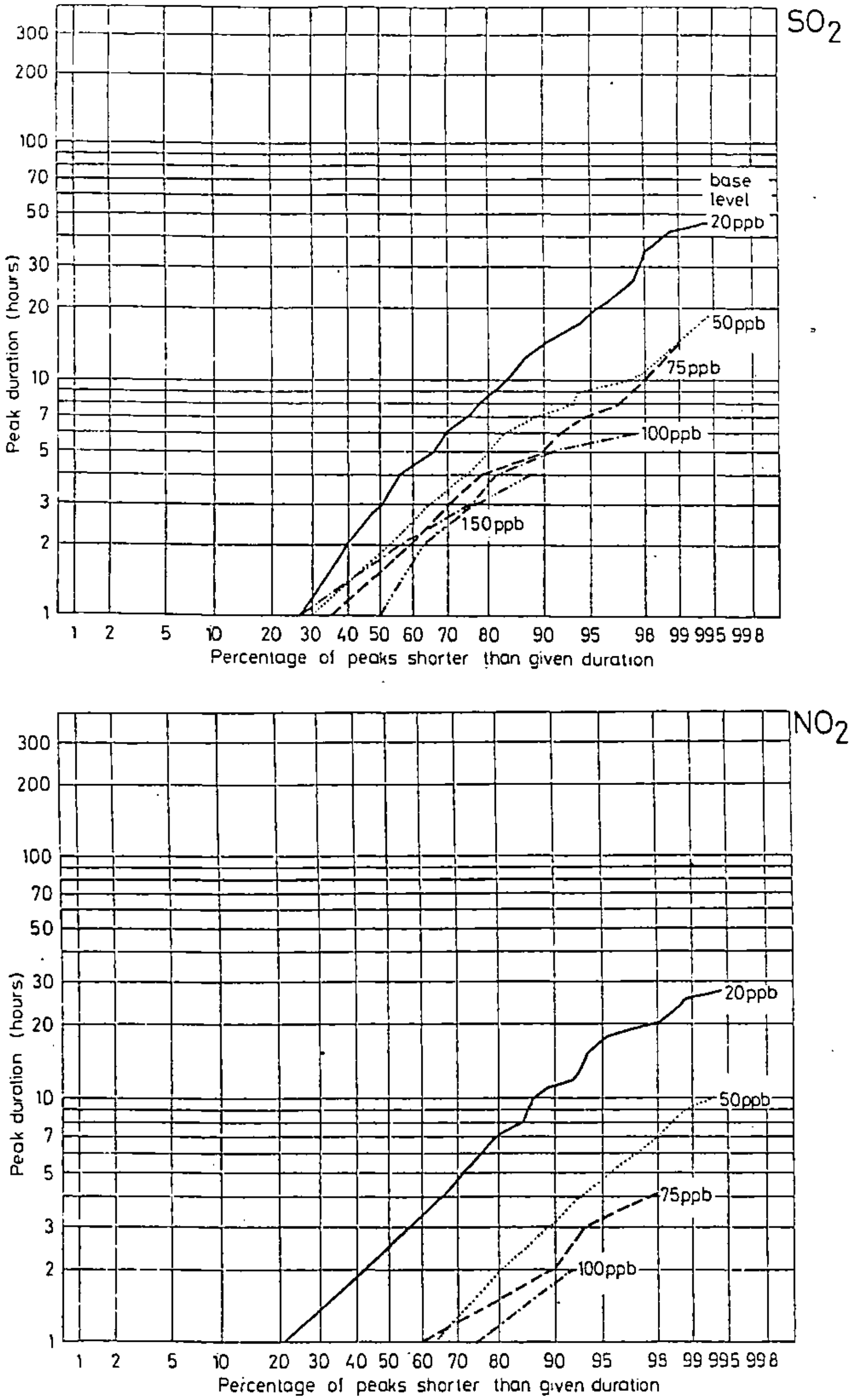


Figure 5.15 : Cumulative frequency distributions for peak durations of SO_2 and NO_2 above various base levels in the SO_2 + NO_2 treatments in the Silwood chambers, 31 January-30 June 1982 (growth period for *D. glomerata*).

5.3.3 Effects of treatment on yield

In late December 1981, about 6 weeks after the start of the second major experiment, it was noticed that a large number of *L. perenne* plants had died in the three chambers supplied by one of the fans (chambers 4, 5 and 6). The plants in all 3 chambers seemed similarly affected and there was no apparent relationship with pollutant concentrations (chambers 4 to 6 were receiving SO_2 + NO_2, filtered air and SO_2, respectively). In mid-December 1981 there was a week of very cold weather (minimum recorded temperature of -17^oC). At the start of that week the inlet to one fan (supplying chambers 1 to 3) became partially blocked by ice, whereas the inlet to the other fan remained fully open. Thus chambers 4 to 6 received a normal air flow whilst 1 to 3 received a severely reduced flow, and therefore high pollutant concentrations. The high pollutant concentrations (over one night only) appear to have had little effect, but the moving and very cold air may have been the cause of the severe injury observed on many *L. perenne* plants. Although the damage was not noticed until about 10 days after the event was presumed to have occurred, the fans and pollutants had been turned off for the remainder of the severe weather, preventing more extensive damage.

As a consequence, when the *L. perenne* plants were thinned to ~20 per pot in mid-February, it was found that there were often only 15-18 plants in many of the pots that were in chambers 4-6 in mid-December. Also the remaining plants appeared small in comparison with those in the other three treatments. In this section, the treatments presumed to have been affected by wind are indicated by an '*' on the tables of results. Although only injury to *L. perenne* was noticed, *P. pratense* may also have been affected, but *D. glomerata* was not placed in the chambers until January and therefore escaped injury.

The results are presented in a similar manner to those from the Solardomes, with most means expressed as % of control (in 1981) or of the mean of the control treatments (in 1982), although all means are given in Appendix 4.

Total shoot dry weight

The TWs m^{-2} of *L. perenne* swards for 1981 and 1982 are given in Tables 5.7 and 5.8 respectively. With one exception, by the final harvest, cumulative TWs in treatments with added pollutants were not significantly different from their respective controls. In February 1981, after 19 days fumigation with ~50 ppb SO_2 and/or ~30 ppb NO_2 (Table 5.5), the TW m^{-2} of swards in all the treatments which included SO_2 were 25-32% less than those in the control, NO_2 or NO treatments (Table 5.7). At the February 1982 harvest, after 100 days growth with ~35 ppb SO_2 and/or 22 ppb NO_2 (Table 5.6) the results were complicated by the wind-induced damage discussed above. Table 5.8 shows that the TWs m^{-2} (estimated as mean TW $plant^{-1}$ in February x plant density in April) were less in the wind-damaged treatments than in the others, but a statistical analysis of the weights per plant showed that only those from the NO_2 treatment were significantly different from control. At the May 1981 harvest, after fumigation with mean SO_2, NO_2 and NO concentrations of ~40, ~26 and ~15 ppb respectively, all TWs except those from the SO_2 treatment were reduced in comparison with control. In June and August 1981 there were no significant differences from control but the cumulative TW m^{-2} in the NO_2 treatment was significantly less than control at the final harvest (overall mean concentrations were about 32 ppb SO_2, 20 ppb NO_2 and 12 ppb NO). In 1982 there were significant increases in TW m^{-2} at the April harvest in the SO_2, NO_2 and one of the SO_2 + NO_2 treatments, but there were no differences from controls at the June harvest or in the cumulative total TW m^{-2} (overall

Table 5.7 : TW m^{-2} of *L. perenne* swards in Silwood chambers, 1981.

Harvest date	TW (mean ± S.E.M.)		n	TW m^{-2} as % of control(2)					
	Days growth(1)	In control (g m^{-2})		Control	NO_2	SO_2	SO_2+NO_2	NO	SO_2+NO_2+NO
17 Feb. 81	19	5.75(3)	50	100 a	85 ab	75 bc	75 bc	91 ab	68 c
4 May 81	95	132.0 ± 5.1	18	100 a	61 c	91 a	72 bc	76 b	73 bc
9 June 81	36	287 ± 11	18	100 –	103 –	101 –	103 –	95 –	93 –
4 Aug. 81	56	338 ± 8	18	100 ab	93 a	102 b	107 b	105 b	102 b
Total to:									
9 June 81	131	419 ± 13	18	100 a	90 bc	98 ab	93 abc	89 bc	87 c
4 Aug. 81	187	757 ± 16	18	100 a	91 b	100 a	99 a	96 ab	94 ab

(1) 52 days old when experiment began.

(2) percentages in each row are not significantly different when above the same (p = 0.05); '–' indicates no significant differences; exact results for all treatments are in Appendix 4, Table A4.1.

(3) estimated from individual plant weights.

Table 5.8 : TW m^{-2} of *L. perenne* swards in Silwood chambers, 1982.

Harvest date	Days growth$^{(1)}$	TW (mean ± S.E.M.) in controls (g m^{-2})		n	TW m^{-2} as % of mean controls$^{(2)}$					
					Controls				SO_2 + NO_2	
		A	B		A	B*	NO_2	SO_2*	A	B*
22 Feb. 82	100	13.4$^{(3)}$	8.9$^{(3)}$	6-50	121	79	176	95	140	80
							statistics not available			
19 Apr. 82	156	169 ± 6	179 ± 6	18	97	103	125	116	131	90
					a	a	bc	b	c	a
9 June 82	51	492 ± 12	526 ± 12	18	97	103	96	104	101	97
					–	–	–	–	–	–
Total to:										
9 June 82	207	661 ± 15	704 ± 16	18	97	103	103	107	109	95
					ab	bc	bc	c	c	a

* wind damaged treatments (see text for explanation).

(1) 7 days old when experiment began.

(2) and (3) as Table 5.7.

mean concentrations of 31 ppb SO_2 and 25 ppb NO_2). The two SO_2 + NO_2 treatments differed significantly, presumably due to wind-damage in the SO_2 + NO_2 (B) treatment (Table 5.8) (also see below).

The cumulative TWs m^{-2} of *L. perenne* swards over the two experiments were similar, at ~700 g m^{-2} after 200 days.

The individual plants of *L. perenne* were affected less than the swards by both wind and pollution treatments (Table 5.9). The TW $plant^{-1}$ was increased by NO_2 (22 ppb) at the February harvest but there were no effects of any pollutant at subsequent harvests or over the season as a whole.

Tables 5.10 and 5.11 give the TWs m^{-2} for *P. pratense* in 1981 and 1982 respectively. By the end of the experiments, after exposure to mean concentrations of ~32 ppb SO_2 and/or 20-25 ppb NO_2 and/or 12 ppb NO, there were no differences in TW m^{-2} from control. In 1981 there were no effects at the March harvest, but in May a mean NO concentration of 15 ppb apparently reduced TW m^{-2} by 32% and both SO_2 (40 ppb) and SO_2 + NO_2 + NO (40, 26 and 15 ppb) increased TW m^{-2} by ~20% (Table 5.10). NO_2 increased TW m^{-2} at the June 1981 harvest but decreased it at the August harvest; other treatments were not significantly different from control. In February 1982 NO_2 increased TW m^{-2}, but TW was reduced in the two wind-damaged treatments which included SO_2 but not in the wind-damaged control treatment, suggesting a possible wind x pollution interaction. At the April and June 1982 harvests the variation between the controls was large (~20%) and all TWs m^{-2} were similar to one or other of the controls (Table 5.11). It may be noted that wind-damage was not directly responsible for the difference between the controls since the greater overall yield occurred in the wind-damaged control (Table 5.11). By the end of each experiment the cumulative TWs for *P. pratense* in the control treatments were about

Table 5.9 : TW $plant^{-1}$ of individual plants of *L. perenne* in Silwood chambers.

Harvest date	Days growth(1)	TW (mean ± S.E.M.) in controls (mg $plant^{-1}$)		n	TW as % of mean controls(2)					
					Controls				SO_2 + NO_2	
		A	B		A	B*	NO_2	SO_2*	A	B*
22 Feb. 82	100	9.72 ± 0.83	not available	9-30	100 a	n.a.	163 b	83 a	113 a	99 a
19 Apr. 82	156	229 ± 29	230 ± 34	18	100 –	100 –	114 –	103 –	85 –	121 –
9 June 82	51	2174 ± 78	2217 ± 107	18	99 –	101 –	100 –	93 –	105 –	102 –
Total to:										
9 June 82	207	2403 ± 90	2447 ± 132	18	99 –	101 –	101 –	94 –	104 –	104 –

*, (1) and (2) as Table 5.8, except results in Table A4.2.

Table 5.10 : TW m^{-2} of *P. pratense* in Silwood chambers, 1981.

Harvest date	Days growth(1)	TW (mean ± S.E.M.) in control (g m^{-2})	n	TW m^{-2} as % of control(2)					
				Control	NO_2	SO_2	SO_2 + NO_2	NO	SO_2 + NO_2 + NO
4 Mar. 81	34	3.02(3)	50	100 –	108 –	102 –	108 –	125 –	123 –
7 May 81	98	77.3 ± 3.1	18	100 a	102 a	120 bc	109 ab	68 d	125 c
8 June 81	32	323 ± 10	18	100 ac	113 b	104 ab	94 c	96 ac	93 c
1 Aug. 81	54	516 ± 16	18	100 ac	89 b	102 ac	97 ab	100 ac	108 c
Total to:									
8 June 81	130	400 ± 11	18	100 ac	111 d	107 cd	97 ab	91 b	99 abc
1 Aug. 81	184	916 ± 20	18	100 –	99 –	104 –	97 –	96 –	104 –

(1), (2) and (3) as Table 5.7, except results in Table A4.3.

Table 5.11 : TW m^{-2} of *P. pratense* in Silwood chambers, 1982.

Harvest date	Days growth(1)	TW (mean ± S.E.M.) in controls (g m^{-2})		n	TW m^{-2} as % of mean controls(2)					
					Controls				SO_2 + NO_2	
		A	B		A	B*	NO_2	SO_2*	A	B*
19 Feb. 82	97	7.81(3)	7.60(3)	50	102 a	98 a	126 b	59 c	94 a	65 c
22 Apr. 82	159	138 ± 4	162 ± 6	18	92 a	108 b	118 b	112 b	110 b	93 a
17 June 82	56	755 ± 18	954 ± 18	18	88 a	112 c	112 c	103 b	112 c	103 b
Total to:										
17 June 82	215	892 ± 18	1116 ± 23	18	89 a	111 c	113 c	105 b	112 c	101 b

*, (1), (2) and (3) as Table 5.8, except results in Table A4.3.

900 g m^{-2}.

D. glomerata was grown in 1982 over a similar period to *L. perenne* and *P. pratense* in 1981. In contrast to the latter two species there was no evidence that the TW of *D. glomerata* was reduced by pollutants at any of the harvests, indeed there were some significant pollutant-induced increases at the first major harvest and over the season as a whole (Table 5.12). The plants were thinned to 20 per pot before they were put into the chambers, so, not surprisingly, there were no differences at the January harvest. At the May harvest, after 103 days growth in ~32 ppb SO_2 and/or ~28 ppb NO_2, all pollutants increased the TW m^{-2} although only those plants in the SO_2 + NO_2 treatments were significantly greater than both controls. The increases in the SO_2 + NO_2 treatments were not significant in June but the cumulative TW of one SO_2 + NO_2 treatment was significantly greater than controls at the end of the experiment (mean concentrations of ~31 ppb SO_2 and/or ~26 ppb SO_2).

As with *P. pratense* in 1982, the TWs of the *D. glomerata* controls differed significantly, but only by ~8%. Control (B) produced a greater yield than control (A) for all species (not significant with *L. perenne*) which strongly suggests there were environmental differences between chambers that affected growth during the 4 week periods that the plants remained in each chamber, and ones to which *P. pratense* was most responsive and *L. perenne* the least.

The number of plants m^{-2} of all species in both years are listed in Table 5.13. With the exception of *L. perenne* in 1982 there were no differences in density between treatments (as expected since the swards were thinned to ~20 plants per pot after the seedlings had become established). The mean TWs $plant^{-1}$ were calculated for all the harvests listed in Tables 5.7, 5.8 and 5.10-5.12. With the exception of *L. perenne* in 1982,

Table 5.12 : TW m^{-2} of *D. glomerata* in Silwood chambers.

Harvest date	Days growth(1)	TW (mean ± S.E.M.) in controls (g m^{-2})		n	TW m^{-2} as % of mean controls(2)					
					Controls				SO_2 + NO_2	
		A	B		A	B	NO_2	SO_2	A	B
28 Jan. 82	0	2.54(3)	2.68(3)	50	97 –	103 –	96 –	103 –	83 –	99 –
11 May 82	103	111 ± 7	120 ± 7	18	96 a	104 ab	118 bc	120 bc	131 cd	139 d
30 June 82	50	449 ± 14	489 ± 15	18	96 a	104 bc	100 ab	96 a	105 bc	111 c
Total to: 30 June 82	153	560 ± 17	609 ± 17	18	96 a	104 bc	104 bc	101 ab	110 cd	116 d

(1) 33 days old when experiment began.

(2) and (3) as Table 5.7 except results in Table A4.4.

Table 5.13 : Number of plants m^{-2} and stubble dry weight of all species at the final harvests in (a) 1981 and (b) 1982. Also included are the cumulative TWs $plant^{-1}$ of *L. perenne* at the final harvest in 1982.

(a) 1981	Species	Treatment					
		Control	NO_2	SO_2	$SO_2 + NO_2$	NO	$SO_2 + NO_2 + NO$
Number of plants m^{-2}	*L. perenne*	949 ± 7(1) 100(2) -(3)	949 ± 5 100 -	951 ± 6 100 -	946 ± 4 100 -	943 ± 4 99 -	946 ± 4 100 -
	P. pratense	938 ± 13 100 -	933 ± 13 99 -	943 ± 4 101 -	949 ± 3 101 -	951 ± 0 101 -	946 ± 4 101 -
Stubble dry weight ($g\ m^{-2}$)	*L. perenne*	226 ± 6 100 ab	210 ± 8 93 bc	232 ± 8 103 a	226 ± 7 100 ab	230 ± 6 102 a	202 ± 7 90 c
	P. pratense	200 ± 5 100 ab	215 ± 7 108 a	192 ± 6 96 bc	178 ± 6 89 cd	197 ± 5 98 b	174 ± 6 87 d

(b) 1982	Species	Treatment					
		Controls				$SO_2 + NO_2$	
		A	B*	NO_2	SO_2*	A	B*
Number of plants m^{-2}	*L. perenne* (swards)	922 ± 17 108 c	785 ± 27 92 ab	956 ± 7 112 c	753 ± 38 88 a	943 ± 10 111 c	827 ± 25 97 b
	P. pratense	930 ± 9 100 -	935 ± 8 100 -	951 ± 8 102 -	941 ± 7 101 -	943 ± 6 101 -	926 ± 11 99 -
	D. glomerata	927 ± 8 100 -	933 ± 7 100 -	938 ± 6 101 -	925 ± 11 99 -	933 ± 7 100 -	933 ± 8 100 -
Stubble dry weight ($g\ m^{-2}$)	*L. perenne* (swards)	166 ± 4 99 a	168 ± 5 101 ab	193 ± 7 116 c	170 ± 6 102 ab	183 ± 7 110 bc	158 ± 6 95 a
	P. pratense	186 ± 5 95 cd	205 ± 6 105 b	228 ± 5 117 a	196 ± 5 100 bc	178 ± 5 91 d	176 ± 5 90 d
	D. glomerata	348 ± 11 102 b	336 ± 11 98 b	349 ± 9 102 b	307 ± 7 90 a	304 ± 8 89 a	338 ± 7 99 b
Stubble dry weight ($mg\ plant^{-1}$)	*L. perenne* (individual plants)	654 ± 35 104 -	607 ± 29 96 -	691 ± 26 110 -	625 ± 39 99 -	722 ± 30 115 -	669 ± 28 106 -
TW ($mg\ plant^{-1}$)	*L. perenne* (swards)	721 ± 23 88 a	917 ± 38 112 b	736 ± 23 90 a	1014 ± 58 124 c	790 ± 20 97 a	794 ± 24 97 a

* wind damaged treatments

(1) mean ± S.E.M.

(2) mean as % of control

(3) means above the same letter are not significantly different at $p = 0.05$; '-' indicates no significant differences.

when the results were expressed as percent of control they were within ± 2% of the results for TW m^{-2} and did not significantly alter the overall interpretation of the effects. From Table 5.13 it is clear that in 1982 the number of *L. perenne* plants m^{-2} was less in the wind-damaged treatments than the others. By the final harvest the control (B) and SO_2 plants yielded more than the control (A) plants (Table 5.13), compensating for their reduced density (see Table 5.8). In contrast, plants in the SO_2 + NO_2 treatments produced the same cumulative TW (Table 5.13) indicating there had been no overall increase in growth $plant^{-1}$ as a result of a decrease in density, explaining the differences in TW m^{-2} seen in Table 5.8. However, as TWs m^{-2} were not significantly different at the June harvest, compensation was probably beginning to occur in the summer.

After the final harvest, the remaining stubble was harvested. In 1981 the stubble from *L. perenne* and *P. pratense* in the SO_2 + NO_2 + NO treatment was less than in the control (Table 5.13). In 1982 the stubble weight of *L. perenne* and *P. pratense* swards were increased by ~16% in the NO_2 treatment, but that of *D. glomerata* was reduced by ~10% in the SO_2 and SO_2 + NO_2 (A) treatments. There were no other significant differences from control(s). The stubble weights of individual plants of *L. perenne* were not affected by treatment.

Adding the stubble weight to the cumulative TW for the respective experiments/species did not significantly change the treatment effects.

Originally it had been intended to ascribe treatment-induced changes in weight to changes in tiller number and/or weight, but with a few exceptions, due to the general lack of treatment-effects, tiller numbers and mean tiller weights were of little interest. Tiller numbers and TW $tiller^{-1}$ for each major harvest are listed in Appendix 4, Tables A4.5 to A4.10.

The relatively large decreases in TW m^{-2} of *L. perenne* in some treatments at the May 1981 harvest (Table 5.7) were largely due to decreases in TW $tiller^{-1}$ (Table A4.5), but the smaller changes in TW m^{-2} of swards of both *L. perenne* and *P. pratense* (Tables 5.7, 5.8, 5.10 and 5.11) were caused by changes in tiller number and/or weight (Tables A4.5, A4.6, A4.8 and A4.9). In some cases there were decreases in TW $tiller^{-1}$ and corresponding increases in numbers of tillers $plant^{-1}$ (or vice versa) to give no net effect on TW m^{-2}.

Increases in the TW m^{-2} of *D. glomerata* (Table 5.12) were largely due to increases in TW $tiller^{-1}$ and not in number of tillers $plant^{-1}$ (Table A4.10).

Percent dead

The %D of *L. perenne* swards at each harvest are given in Tables 5.14 and 5.15 for 1981 and 1982 respectively. In 1981, all pollution treatments increased %D at all harvests. There was no consistent difference in effects caused by individual pollutants, but the mixtures increased %D by a greater amount than single pollutants at the first two harvests, although at the final harvest the largest %D was in the SO_2 treatment. Over the season as a whole, SO_2 alone or SO_2 + NO_2 (+ NO) caused similar increases in %D (from ~8% in control to 14% in the presence of SO_2). In 1982 the swards of *L. perenne* showed no overall effect on %D, although at the April harvest NO_2 and SO_2 + NO_2 increased %D compared with at least one of the controls. At the June harvest there was a large proportional difference in the %D on the two controls (6.98 and 3.79%, Table A4.11), and control (A) exhibited a higher proportion of dead material than any other treatment (Table 5.15).

The %D on individual plants of *L. perenne* were very small at both harvests (Table 5.16). Only SO_2 alone increased %D compared with the

Table 5.14 : DW in control treatment and %D of *L. perenne* swards in Silwood chambers, 1981.

Harvest date	Days growth(1)	n	DW (mean ± S.E.M.) in control (g m^{-2})	%D					
				Control	NO_2	SO_2	$SO_2 + NO_2$	NO	$SO_2 + NO_2 + NO$
4 May 81	95	10	7.6 ± 0.8	5.9(2) 100(3) a(4)	8.0 134 b	11.1 187 c	13.9 235 d	10.0 168 c	13.2 221 d
9 June 81	36	10	0	0 a	0.32 bc	0.66 c	1.14 d	0.26 b	1.29 d
4 Aug. 81	56	10	54.1 ± 3.1	16.0 100 a	23.5 147 bc	26.2 164 c	21.1 131 b	20.6 129 b	22.3 139 b
Total to:									
9 June 81	131	10	7.6 ± 0.8	1.88 100 a	2.12 112 a	3.75 199 c	4.48 238 d	2.95 157 b	4.38 232 cd
4 Aug. 81	187	10	61.7 ± 3.1	8.4 100 a	12.1 144 bc	14.5 173 d	12.9 153 bcd	11.8 140 b	13.6 162 cd

(1) 52 days old when experiment began.

(2) mean.

(3) mean as % of control.

(4) means in each row are not significantly different when above the same letter (p = 0.05).

<u>Table 5.15</u> : DW in control treatments and %D of *L. perenne* swards in Silwood chambers, 1982.

Harvest date	Days growth(1)	DW (mean ± S.E.M.) in controls (g m^{-2})		%D in controls		n	%D as % of mean controls(2)					
							Controls				SO_2 + NO_2	
		A	B	A	B		A	B*	NO_2	SO_2*	A	B*
19 Apr. 82	156	7.2 ± 0.9	6.1 ± 0.8	3.98	3.33	10	109 ab	91 a	146 c	94 a	166 c	140 bc
9 June 82	51	34.3 ± 1.9	20.3 ± 2.0	6.98	3.79	10	130 c	70 a	88 b	115 c	120 c	120 c
<u>Total to:</u>												
9 June 82	207	41.5 ± 1.8	26.5 ± 2.5	6.23	3.70	10	126 cd	74 a	100 b	110 bc	129 d	124 cd

* wind damaged treatments.

(1) 7 days old when experiments began.

(2) percentages in each row are not significantly different when above the same letter (p = 0.05), exact results for %D are in Appendix 4, Table A4.11a.

Table 5.16 : DW in control treatments and %D of individual plants of *L. perenne* in Silwood chambers.

Harvest date	Days growth$^{(1)}$	DW (mean ± S.E.M.) in controls (mg plant^{-1})		%D in controls		n	%D as % of mean controls$^{(2)}$					
							Controls				SO_2 + NO_2	
		A	B	A	B		A	B*	NO_2	SO_2*	A	B*
19 Apr. 82	154	2.6 ± 1.0	2.5 ± 0.8	0.45	0.35	18	112 -	88 -	187 -	81 -	382 -	202 -
9 June 82	51	67.2 ± 13.6	18.9 ± 16.7	2.65	0.71	18	158 ac	42 b	65 ab	330 d	122 ac	203 c
Total to:												
9 June 82	207	69.8 ± 13.7	21.5 ± 3.9	1.95	0.63	18	151 c	49 a	72 ab	308 d	120 bc	196 c

* wind damaged treatments.

(1) 7 days old when experiment began.

(2) percentages in each row are not significantly different when above the same letter (p = 0.05); '-' indicates no significant differences, exact results for %D are in Appendix 4, Table A4.11b.

controls, but only from < 2% to ~4% over the whole experiment (Table A4.11).

The %D of *P. pratense* responded differently to pollutants in comparison with *L. perenne* (Tables 5.17 and 5.18). At the May 1981 harvest NO_2 had no effect on %D but it was more than doubled by SO_2, and SO_2 + NO_2 increased it to ~400% of control (a significantly greater than additive effect, $p < 0.001$). In June 1981 the control, NO_2 and NO treatments produced no dead material but SO_2 caused 0.67 %D and the mixtures ~1.6 %D. In August the highest %D (~10%) was in the control treatment; NO_2 almost prevented senescence (73% less than control) and the other pollutant treatments reduced %D by 20-30%. SO_2 + NO_2 + NO increased %D by 22%, NO decreased it by 26% and NO_2 decreased it by 68%, SO_2 and SO_2 + NO_2 had no effect.

In 1982 at the first harvest there was a similar pattern to the previous year: NO_2 had no effect, SO_2 increased %D sixfold but the mixtures increased %D to over 9 times that of the controls (again a significant interaction, $p < 0.001$). The percentage increases were greater than in 1981 but the percentage dead in the mixtures in 1982 was ~22% (Appendix 4, Table A4.11), very similar to the 21 %D in 1981 (Table 5.17). By the June harvest in 1982 the effects were much smaller with only SO_2 and SO_2 + NO_2 (B) significantly greater than control. In both experiments a total of about 6 %D was produced in the control treatments over the whole period.

SO_2 and SO_2 + NO_2 caused broadly similar increases in %D of *D. glomerata*, which by the end of the experiment amounted to about twice that in the controls (about 15 and 7% respectively) (Table 5.19).

The wind-induced damage early in the experiment did not obviously affect the proportion of dead material produced by any species.

Spike number

The numbers of spikes produced by both the swards and the individual plants of *L. perenne* are given in Table 5.20. In 1981 the numbers of

Table 5.17 : DW in control treatments and %D of *P. pratense* swards in Silwood chambers, 1981.

Harvest date	Days growth(1)	n	DW (mean ± S.E.M.) in control (g m^{-2})	%D					
				Control	NO_2	SO_2	SO_2 + NO_2	NO	SO_2 + NO_2 + NO
7 May 81	98	10	4.4 ± 0.6	5.0(2) 100(3) a(4)	5.6 114 a	11.7 235 c	20.9 413 d	7.1 142 b	20.9 421 d
8 June 81	32	10	0	0 a	0 a	0.67 b	1.40 c	0 a	1.84 c
1 Aug. 81	54	10	49.0 ± 3.3	9.82 100 a	2.68 27 c	7.33 75 b	7.87 80 b	6.72 68 b	8.08 82 b
Total to:									
8 June 81	130	10	4.4 ± 0.6	1.13 100 a	1.13 100 a	3.05 269 b	5.88 518 c	1.11 98 a	6.47 571 c
1 Aug. 81	184	10	53.4 ± 3.0	6.08 100 ad	1.95 32 c	5.49 90 a	6.98 115 de	4.47 74 b	7.44 122 e

(1) - (4) as Table 5.14.

Table 5.18 : DW in control treatments and %D of *P. pratense* swards in Silwood chambers, 1982.

Harvest date	Days growth$^{(1)}$	DW (mean ± S.E.M.) in controls g m^{-2}		%D in controls		n	%D as % of mean controls$^{(2)}$					
							Controls				SO_2 + NO_2	
		A	B	A	B		A	B*	NO_2	SO_2*	A	B*
22 Apr. 82	159	3.0 ± 0.4	4.4 ± 0.5	2.19	2.50	10	93 a	107 a	100 a	598 b	911 c	941 c
17 June 82	56	58.5 ± 5.5	68.2 ± 5.2	7.62	6.97	10	104 ab	96 a	99 ab	132 c	119 bc	186 d
Total to:												
17 June 82	215	61.5 ± 5.5	72.6 ± 5.5	6.82	6.30	10	104 a	96 a	99 a	158 b	162 b	224 c

* wind damaged treatments.

(1), (2) as Table 5.15, except results in Table A4.11c.

Table 5.19 : DW in control treatment and %D of *D. glomerata* swards in Silwood chambers.

Harvest date	Days growth(1)	DW (mean ± S.E.M.) in controls (g m^{-2})		%D in controls		n	%D as % of mean controls(2)					
							Controls				SO_2 + NO_2	
		A	B	A	B		A	B*	NO_2	SO_2*	A	B*
11 May 82	103	7.4 ± 0.8	14.6 ± 1.7	7.01	11.5	10	76 a	124 b	90 a	301 d	225 c	272 d
30 June 82	50	35.8 ± 4.7	26.5 ± 4.4	7.61	4.97	10	121 b	79 a	126 b	191 c	180 c	179 c
Total to:												
30 June 82	153	43.1 ± 4.4	41.1 ± 4.5	7.60	6.44	10	108 ab	92 a	115 b	225 d	192 c	207 cd

* wind damaged treatments.

(1) 33 days old when experiment began.

(2) means in each row are not significantly different when above the same letter (p = 0.05); exact results for %D are in Appendix 4, Table A4.11d.

spikes were reduced by 25-40% in all pollution treatments with no obvious difference between pollutants. The large percentage increases seen in August were not significant due to the large variability of a very small proportion of flowering plants (n.b. there were approximately 950 plants m^{-2}, Table 5.13). In 1982 there were over three times as many spikes produced and pollutants had less of an effect with only those plants in the NO_2 and SO_2 + NO_2 (B) treatments producing fewer spikes than the control plants. The numbers of spikes on individual plants of *L. perenne* were not affected by treatment.

P. pratense produced fewer spikes than *L. perenne* in both years (Table 5.21). At the June 1981 harvest NO reduced their number but SO_2 alone increased it, and the latter effect remained over the season as a whole. In 1982 there were nearly 10 times as many spikes produced in comparison with 1981 and there were no significant differences from controls.

D. glomerata did not flower during the experiment.

Roots

Root samples from the *L. perenne* swards and individual plants were taken after the 1982 experiment (Table 5.22). There were no apparent effects of treatment on RW or TW/RW. Although the samples were small, particularly from the swards, the maximum differences from mean controls were -13% to + 19% for RW and -11 to + 21% for TW/RW, suggesting an effect not detected due to variability within the samples would not be large.

5.4 Discussion

5.4.1 Pollutant concentrations

From the point of view of pollutant concentrations, the objective of these experiments was to simulate, as far as possible, urban levels of SO_2,

Table 5.20 : Number of spikes on *L. perenne* in Silwood chambers: (a) swards 1981, (b) swards 1982, (c) individual plants.

(a)

Harvest date	Days growth$^{(1)}$	No. spikes m^{-2} (mean ± S.E.M.) in control	n	No. spikes m^{-2} as % control$^{(3)}$					
				Control	NO_2	SO_2	SO_2 + NO_2	NO	SO_2 + NO_2 + NO
9 June 81	131	721 ± 62	18	100 a	54 b	73 b	72 b	58 b	57 b
4 Aug. 81	56	24 ± 12	18	100 -	178 -	176 -	200 -	289 -	200 -
Total to:									
4 Aug. 81	187	745 ± 61	18	100 a	58 c	76 b	76 b	65 bc	63 bc

(b)

Harvest date	Days growth$^{(2)}$	No. spikes m^{-2} (mean ± S.E.M.) in control		n	No. spikes m^{-2} as % control					
					Controls				SO_2 + NO_2	
		A	B		A	B*	NO_2	SO_2*	A	B*
9 June 82	207	2441 ± 86	2307 ± 73	18	103 a	97 ab	80 c	97 ab	90 bc	85 c

(c)

Harvest date	Days growth$^{(2)}$	No. spikes plant^{-1} (mean ± S.E.M.) in control		n	No. spikes plant^{-1} as % control					
					Controls				SO_2 + NO_2	
		A	B		A	B*	NO_2	SO_2*	A	B*
9 June 82	207	8.1 ± 0.5	8.1 ± 0.7	18	100 -	100 -	104 -	93 -	94 -	91 -

* wind damaged treatments

(1) 52 days old when experiment began

(2) 7 days old when experiment began

(3) means in each row are not significantly different when above the same letter ($p = 0.05$), exact results for all treatments are in Appendix 4, Table A4.12.

Table 5.21 : Number of spikes m^{-2} of *P. pratense* in Silwood chambers: (a) 1981, (b) 1982.

(a)

Harvest date	Days growth$^{(1)}$	No. spikes m^{-2} (mean ± S.E.M.) in control	n	No. spikes m^{-2} as % control$^{(3)}$					
				Control	No$_2$	SO$_2$	SO$_2$ + NO$_2$	NO	SO$_2$ + NO$_2$ + NO
8 June 81	130	82 ± 18	18	100 ab	142 b	261 c	152 b	48 a	152 b
1 Aug. 81	54	7.9 ± 4.3	18	100 –	201 –	33 –	134 –	100 –	100 –
Total to:									
1 Aug. 81	184	90 ± 18	18	100 ab	147 b	241 c	150 b	53 a	147 b

(b)

Harvest date	Days growth$^{(2)}$	No. spikes m^{-2} (mean ± S.E.M.) in control		n	No. spikes m^{-2} as % control					
					Controls				SO$_2$ + NO$_2$	
		A	B		A	B*	NO$_2$	SO$_2$*	A	B*
17 June 82	215	772 ± 18	824 ± 15	18	97 ab	103 bc	105 c	96 a	98 abc	96 a

* wind damaged treatments

(1) - (3) as Table 5.20, except results in Table A4.13.

Table 5.22 : RW, cumulative TW and TW/RW at final harvest of *L. perenne*, 1982: (a) swards, (b) individual plants.

	Parameter	Mean (± S.E.M.) in control chambers		n	Parameters expressed as % of mean controls(1)					
					Controls				SO_2 + NO_2	
		A	B		A	B*	NO_2	SO_2*	A	B*
(a)	RW (g m^{-2})	287 ± 35	255 ± 34	5	106	94	115	87	119	115
	TW to June(2) (g m^{-2})	851 ± 34	846 ± 47	5	100	100	108	109	109	97
	TW/RW	3.03 ± 0.39	3.37 ± 0.26	5	95	105	93	121	91	92
(b)	RW (mg $plant^{-1}$)	1227 ± 68	1122 ± 93	10	104	96	117	98	102	111
	TW to June(2) (mg $plant^{-1}$)	2842 ± 119	2982 ± 181	10	101	99	106	99	99	108
	TW/RW	2.56 ± 0.18	2.73 ± 0.14	10	97	103	89	99	98	96

* wind damaged treatments

(1) means in each row are not significantly different ($p = 0.05$), exact results for all treatments are in Appendix 4, Table A4.14.

(2) The TW's are for the pots used for root-sampling.

NO_2 and/or NO by varying levels from one hour to the next. Mean concentrations of SO_2 and NO_2 were about 10 ppb too low from November 1981 to January 1982, but otherwise were close to the desired levels in both experiments. However, this resulted in the decreases in SO_2 and NO_2 concentrations from winter to summer in 1981-82 being less marked than at typical UK urban sites (see Sections 2.1.1 and 2.3). Over the upper 70% of their concentration ranges cumulative frequency distributions of SO_2 and NO_2 were similar to those at UK sites. Diurnal patterns of SO_2 were satisfactorily simulated in both experiments, as were those of NO_2 in 1981; in 1982 the mean NO_2 concentrations were too high at night. In both experiments the correlations of hourly mean concentrations of SO_2 and NO_2 showed that up to 50 ppb NO_2 was often present when SO_2 was less than 5 ppb, in contrast to the situation in London. In addition, the correlations were less clearly defined in the experiments than in London. Peak durations appear to have been similar to those in London and were similar in each experiment. The concentrations of NO were generally too low and showed no diurnal pattern.

In general, it is reasonable to claim that the fluctuating hourly mean SO_2 and NO_2 concentrations were, for the majority of the time, representative of a UK urban or urban fringe environment. Perhaps the most important exceptions to this were the relatively low SO_2 and NO_2 concentrations from November 1981 to January 1982. NO was not well simulated. Also, for most purposes, comparable pollution treatments may be considered to have been similar in their respective calendar months in the first and second experiments. The differences between comparable treatments noted in Section 5.3 may have caused different effects, but the lack of sensitivity in the experimental design does not allow worthwhile speculation on the subject. The timing of the experiments, one beginning in November, the other at the end of January may also have affected the results.

5.4.2 Control experiment

There were no significant differences between total shoot weights in each chamber in the control experiment, although there was a 23% non-significant difference between the minimum and maximum mean weights (Table 5.4). However there was a significant 45% difference between the minimum and maximum mean number of tillers plant^{-1}. Fewer tillers were partially compensated for by larger mean tiller weights (Table 5.4). This suggested there were environmental differences between the chambers which affected tiller number by a greater proportion than total shoot weight.

5.4.3 Effects of treatment on yield

Total shoot dry weight

At the end of each experiment the cumulative TWs of polluted plants were significantly different from their respective controls in only one case: the TW of *D. glomerata* in one of the SO_2 + NO_2 treatments was increased by 16% compared with mean controls. Before discussing pollutant effects further, it is important to note the large differences between the TWs of *P. pratense* in the two control treatments in 1982 (Table 5.11). It is reasonable to assume that, because there were no additions of pollutants to the control treatments, any differences in TW must be due to environmental conditions other than degree of pollution. (In contrast, the occurrence of differences between the means of the replicate SO_2 + NO_2 treatments could have been due to small differences in the pollutant treatments.) Therefore perhaps all differences in TW of less than about 20% should be viewed with caution, but most differences in TW attributed to pollution were of this magnitude or smaller. *D. glomerata* showed smaller

(8%) differences in TWs between the controls and the TWs of *L. perenne* were not significantly different (Tables 5.12 and 5.8), indicating that these species were less affected than *P. pratense* by the environmental conditions concerned. It is evident that moving the pots from one chamber to another every 4 weeks did not effectively counteract inter-chamber variation.

In these experiments the pollutant-induced changes in TW were usually relatively small, also there were few consistent 'patterns' in these effects. This was probably at least partly due to the low mean pollutant concentrations, but effects caused by pollutants may have been masked by effects caused by differences between the chambers themselves. Nevertheless, there were some interesting trends in the results which may be attributed to pollutants with some certainty.

It has been recently shown that 60 ppb NO_2 caused a significant increase in the total plant weight of *Poa pratensis* at the start of an overwinter fumigation (Whitmore & Freer-Smith, 1982), although much other work with similar NO_2 concentrations has shown no effect or a reduction in TW (Section 3.2.3). In the present experiments NO_2 had various effects: for example, in 1981 a mean concentration of 22 ppb NO_2 reduced the TW of *L. perenne* but had no overall effect on *P. pratense*; in 1982 about 25 ppb NO_2 increased the TW of *L. perenne* and *P. pratense* at the winter (thinning) harvests (significant in all cases on a plant^{-1} basis) and the increase was still present in both species, and also in *D. glomerata*, at the spring harvests (although it was not always significant compared with the controls).

With one exception, at the spring harvest in both experiments 30-40 ppb SO_2 alone produced increases in the TWs of all swards (although it was not always significant). The exception was *L. perenne* in 1981 which showed a small, non-significant, decrease in the presence of SO_2 at the spring harvest. In Section 3.2.1 it was noted that published data suggested that below ~35 ppb SO_2 may cause an increase in the yield of *L. perenne* swards. The results from the Silwood experiments clearly provided further evidence for this, although it must be remembered that the stimulations were all lost by the end of each experiment. No analyses of sulphur content of the shoots were undertaken, so the possibility that the increased yield in the SO_2 treatments were caused by correction of sulphur deficiency cannot be eliminated. However, an increase in yield in the presence of SO_2 + NO_2 occurred in the Solardomes but there was no relationship between yield and sulphur content of the foliage (Section 4.3.3), proving that correction of sulphur-deficiency is not <u>necessarily</u> a prerequisite for yield increases in the presence of SO_2.

In Chapter 3 the effects of ~60 ppb SO_2 + NO_2 on yield were discussed. From available data it was shown that the mixture of pollutants often caused severe yield reductions. In the Silwood chambers about 30 ppb SO_2 + 25 ppb NO_2 (+ 12 ppb NO) had no consistant effect(s) on TW. For example, yields of *L. perenne* and *P. pratense* showed statistically significant increases and decreases at the spring harvests, but there were only decreases or no effects at the winter (thinning) harvests. With the exception of *D. glomerata* there were no significant effects of mixtures of pollutants at the summer harvests in 1981 or 1982.

The presence of SO_2 counteracted the beneficial effect of NO_2 (when present), and vice versa, but otherwise there was no evidence for an interaction of SO_2 with NO_2; only in *D. glomerata* was there a clear example of SO_2 and NO_2 showing an additive effect (May harvest, Table 5.12). Much of the literature on the effects of SO_2 and NO_2 on grass growth has also found no evidence for interaction after long-term fumigations, although additive effects were common (Chapter 3). The lack of additive effects in the present study was not surprising in view of the small effects of single pollutants.

There were two inconsistencies within the results which are worth mentioning separately: the large reductions in the yield of *L. perenne* caused by ~25 ppb NO_2 and of *L. perenne* and *P. pratense* caused by ~15 ppb NO in May 1981 (Tables 5.7 and 5.10). Previous work, discussed in Chapter 3, suggests that the growth of grass is reduced less by NO_2 than SO_2; in addition it is currently thought that NO has less effect than NO_2 at a given atmospheric concentration (Mansfield & Freer-Smith, 1981). Therefore these results are not typical, and indeed may be largely due to 'chamber effects' rather than to pollution, and should be treated as unusual.

One other point of interest was the decreases in TW at the February 1982 harvest of *P. pratense*, which occurred only in the wind-damaged treatments receiving SO_2 (+ NO_2) (Table 5.11). Davison & Bailey (1982) fumigated *L. perenne* cv. S23 with 94 ppb SO_2 for three weeks prior to exposing them to temperatures between -2 and -12°C. Reducing the temperature decreased the survival and yields of fumigated plants to a significantly greater extent than those of non-fumigated plants. Baker, Unsworth & Greenwood (1982) exposed field-grown wheat plants (*Triticum aestivum* cv. Bounty) to 115 ppb SO_2 or ambient air. After a period of snow and very cold weather (mean minimum daily temperature of -9.2°C) plants exposed to SO_2 were found to be visibly injured whereas plants in ambient air appeared healthy. The authors concluded that the cold-hardiness of the wheat had been reduced by SO_2, rather than the sensitivity to SO_2 increased by the cold. In the present experiments, all the treatments of *P. pratense* were subjected to the same very low temperatures but it was only those receiving both moving air and SO_2 that showed a decreased yield. Whether the SO_2 increased sensitivity to cold wind or vice versa cannot be decided from the available evidence, but the two reports mentioned above both suggest the former is more likely.

In contrast, as mentioned above, the number of plants of *L. perenne* presumed to have been killed by the action of the cold wind was not affected by pollution treatment. In addition, the surviving plants were not affected by the presence of SO_2.

The effects of pollutants on the TW of swards grown in the Silwood chambers were similar to those from the Solardomes (Chapter 4) insofar as mixtures of pollutants did not reduce growth after long-term experiments. The mean concentrations of SO_2 and NO_2 in the Silwood chambers were intermediate between those in the low and medium treatments in the Solardomes. *L. perenne* cv. S24 grown in the latter showed some evidence for a mid-winter decrease in TW, but an increase of 20-30% compared to control became apparent in the spring. In comparison, in the Silwood chambers there was no spring-time increase in TW of *L. perenne* in the presence of SO_2 + NO_2.

Previous studies have shown that reductions in TW caused by SO_2 were usually caused by a reduction both in tiller number and weight (see Table 3.5). The present experiments also showed that both parameters were involved in changes in overall yield, although larger changes in TW were generally caused by changes in tiller weight rather than tiller number. It is also worth remembering that in the control experiment (see above) the number and size of tillers was variable for a given overall mean shoot weight.

Fumigating two or more species simultaneously enables their relative sensitivities to pollutants to be compared, but there have been few experiments of this type reported in the literature for SO_2 and/or NO_2. Ashenden (1979b) and Ashenden & Williams (1980) found that the shoot weights of *D. glomerata* cv. S37, *Phleum pratense* cv. Eskimo, and *Poa pratensis* cv. Monopoly were all similarly reduced by SO_2 or (to a greater extent) by SO_2 + NO_2, whereas *L. multiflorum* cv. Milano was less affected (see Tables 3.7-3.10). Ayazloo & Bell (1981) fumigated natural populations of four grass species with SO_2 alone and found that *L. perenne* was least sensitive to SO_2, *D. glomerata* and *Festuca rubra* were of intermediate sensitivity and *Holcus lanatus* was the most sensitive. In the present experiments, *L. perenne* may be classed as most sensitive to SO_2 and/or NO_2 since it showed some yield reductions, *D. glomerata* benefitted from SO_2 + NO_2 and *P. pratense* was intermediate. The differences in relative sensitivities between experiments may have been a result of variation in sensitivity between cultivars or experimental conditions (see Chapter 7 for further discussion).

Percent dead

In the control treatments the proportion of dead leaves varied between harvests, species and experiments. In general, the greatest effects of pollutants were found at the spring harvests, with less marked or no effects later in the summer. This was in contrast to the swards in the Solardomes which produced essentially no dead material overwinter.

The cumulative effects of treatments on %D over each experiment varied from a large reduction in the NO_2 treatment of *P. pratense* in 1981 (Table 5.17) through no effect of any treatment compared to controls (*L. perenne* swards in 1982, Table 5.15) to 50-100% increases in the presence of SO_2 (*L. perenne* in 1981, Table 5.14; *P. pratense* and *D. glomerata* in 1982, Tables 5.18 and 5.19). In general, NO_2 had less effect than SO_2 but mixtures had a similar or greater effect than SO_2 alone.

Most grass species studied have been shown to produce a greater proportion of dead leaves when exposed to SO_2 alone (Table 3.5), consistent with many of the results reported here. It is interesting to note that the individual plants of *L. perenne* produced a much smaller proportion of dead leaves than the swards and only SO_2 alone significantly increased the %D compared to the controls.

At the spring harvests in both years and at the June 1981 harvest SO_2 + NO_2 had a greater than additive effect on the %D of *P. pratense* (Tables 5.17 and 5.18). Similarly, Davies (1980b) found that SO_2 + NO_2 increased the %D of *P. pratense* whereas individual pollutants had little effect (Section 3.2.3).

Spike number

The results in Table 5.20 suggest that NO_2 may have reduced the spike number on *L. perenne* swards more than either SO_2 or SO_2 + NO_2, but not always significantly so. In contrast, Whitmore & Freer-Smith (1982) found the spike number on *Poa pratensis* was not affected by NO_2 but was reduced by half in the presence of SO_2 and SO_2 + NO_2. For comparison, in the Solardomes the number of spikes on *L. perenne* cv. S24 was increased by 40-50% in the low and medium treatments in May 1982, although there was no effect over the season as a whole (Table 4.12).

The flowering of *P. pratense* was not significantly reduced by pollutants and in 1981 SO_2 alone more than doubled the number of spikes produced.

The failure of *D. glomerata* to produce spikes was probably explained by failure to meet its induction requirements. At the seedling stage, *D. glomerata* does not respond to induction treatments (cold, short daylength): only when the plants are several weeks old may induction take place (Calder, 1963, 1966). *D. glomerata* did not germinate until 30 December and thus may have remained in the seedling stage throughout the period of short days and low temperatures needed for induction.

Roots

Previous studies have often shown a greater reduction in root than shoot weight (Table 3.5) but results from the Solardomes for individual cultivars suggested there was no effect at the concentrations used (up to 50 ppb SO_2 and NO_2). Nevertheless, combining the data from all three cultivars used in the Solardomes produced a significant effect (Fig. 4.10) which indicated a 15% reduction in RW at 31 ppb SO_2 plus NO_2. However, in the Silwood chambers there was no evidence for a detrimental effect of pollutants either on RW or TW/RW (Table 5.22).

5.5 Conclusions

The concentrations of SO_2 and NO_2, but not NO, used in these experiments were representative of urban or urban fringe areas. After long-term fumigations, single pollutants or mixtures caused few effects on the total shoot dry weight of *L. perenne* cv. S24, *P. pratense* cv. Odenwalder or *D. glomerata* cv. S26. The roots of *L. perenne* were also unaffected by treatment. Thus, under the conditions of these experiments, SO_2 and NO_2 seem unlikely to cause yield reductions in these grass species at the edge of (or even within) urban areas in the UK. However, it is possible that other factors are important in a field situation. For example, some filtration experiments (discussed in Section 3.3) have shown that filtering air in urban areas significantly improved the yield of *L. perenne*, suggesting that urban air was detrimental to the growth of grass. The differences between the results from fumigating with SO_2 + NO_2 and from filtration experiments are discussed in detail in Chapter 7.

The proportions of dead leaves were often increased in the presence of SO_2, but by the end of the experiments the increase was usually less than 7% of the total shoot weight (e.g. 7% dead in controls, 14% dead in SO_2 + NO_2). Flowering of *L. perenne* was reduced in one experiment.

Whether either of these pollutant-induced changes would have affected crop quality significantly is not known.

CHAPTER 6

FILTRATION EXPERIMENTS

6.1 Introduction

Experiments using chambers receiving filtered and unfiltered air have the advantage over controlled fumigation experiments that, in the unfiltered chamber, pollutant concentrations will be similar to ambient and will vary according to the weather. In contrast, the most sophisticated controlled fumigation experiments using SO_2 and/or NO_2 have, as yet, made no attempt to fluctuate concentrations in response to changes in the weather. Pollutant concentrations in the filtered chambers will depend upon chamber design and filter efficiency. As with fumigation experiments carried out within chambers, the other environmental conditions will differ from ambient as described in the Introduction to Chapter 4.

In the experiment reported below, chambers ventilated with filtered and unfiltered air were placed in an area with moderate levels of SO_2 and NO_x pollution for two successive winters. This area receives air pollution at concentrations comparable to those in the more polluted agricultural areas of the UK.

6.2 Materials and Methods

The chambers used in these experiments were designed by Dr. M.R. Ashmore for use as open-top chambers to investigate the effects of ozone on crops.

6.2.1 Chamber design and position

Four chambers were set up at CERL, Leatherhead, Surrey (National Grid Reference TQ 157576). Each chamber was cylindrical and built on an aluminium frame 1.55 m in diameter and 1.52 m high. The framework was covered with clear polythene sheet around the sides, a portion being removable to allow access. The chambers were originally designed for use in summer, but in winter, when the air is frequently turbulent, an open-top design is not suitable due to incursions of ambient air into the filtered chambers. In order to prevent these incursions, the top was covered with clear polythene sheet pierced by 2 cm holes at 10 cm centres to allow adequate and even ventilation.

Two chambers received filtered air, and two unfiltered air. The air was blown directly or via activated charcoal filters along 15 cm diameter ducting to an essentially closed vertical acrylic tube at the side of each chamber (Fig. 6.1). From this clear vertical tube a torus of thin clear polythene tubing (10 cm diameter) went around the chamber; its height was variable according to crop height (Fig. 6.1). The torus was pierced by 2 cm diameter holes at ~15 cm intervals along its inner side to allow air to blow across the crop from around the edge of the chamber. Air-flow rate was checked using an anemometer, flow into each chamber being controlled to about 1.5 air changes per minute by a butterfly valve at the base of each vertical pipe. This check was performed occasionally throughout each study period to ensure air flow remained similar in each chamber.

The four chambers were located on a east-west line: chamber 1 on the west and chamber 4 on the east end. During the first winter (1980-81) chambers 3 and 4 received filtered air, but the treatments were reversed during the winter of 1981-82 so that chambers 1 and 2 received filtered air.

6.2.2 Pollutant monitoring

Using the SO_2 and NO_x analysers described in Section 4.2.6, ambient concentrations of SO_2 were monitored throughout both experiments, as were those of NO_2 in the 1981-82 experiment. In the 1980-81 experiment

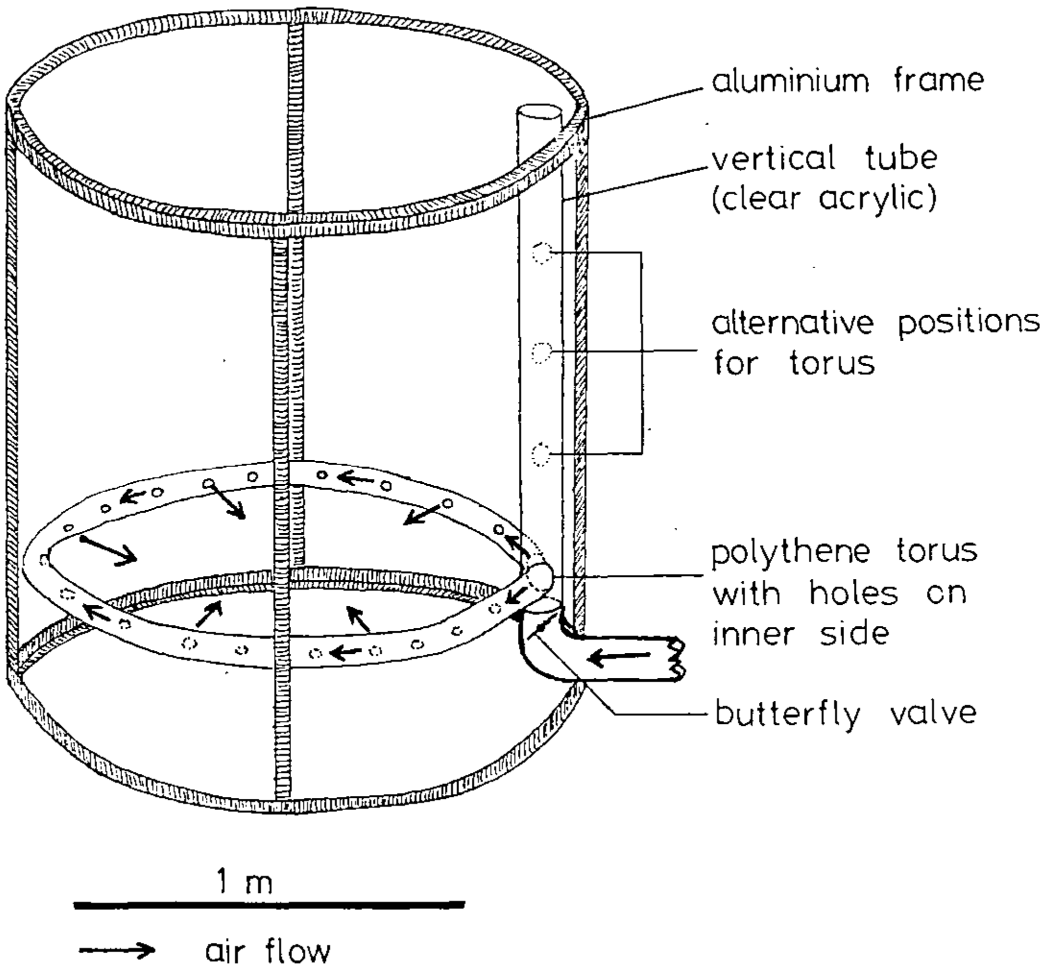


Figure 6.1 : Diagram illustrating construction of chambers used in filtered vs. unfiltered air experiments at CERL.

(Designed by Dr. M.R. Ashmore)

monitoring of NO_2 began on 13 February 1981. Concentrations of pollutants inside the chambers were occasionally monitored with these instruments to give an estimate of the relationships between levels in ambient air and in the filtered and unfiltered chambers. Monitoring inside the chambers required the use of a 30 m sample line (0.25 inch diameter PTFE). Loss of pollutants by adsorption onto the wall of the sample line was estimated by comparing ambient concentrations measured through 30 m and 2 m sample lines (loss on a 2 m line was assumed to be zero).

In addition, one other method of monitoring long-term mean NO_2 concentrations was used. (Originally described by Atkins, Healy & Tarrant, 1978.) Tubes, 70 mm long x 12 mm internal diameter, were cut from acrylic tube. Two discs of stainless steel gauze (100 mesh/linear inch) were soaked in 50% v/v triethanolamine (TEA)/acetone solution. Before being placed at one end of the tube the acetone was allowed to evaporate. A tight-fitting polythene cap held the discs in position (Fig. 6.2). TEA acts as an efficient collector of NO_2; the acetone is used only to thin the otherwise viscous TEA to allow a thin coat to be applied to the gauze. The other end of the tube was temporarily sealed with another cap to prevent contamination before placing in the field.

In use the tubes were positioned vertically with the gauze at the top (sealed by a cap) but with the cap at the lower end removed. NO_2 is absorbed by the TEA on the gauze creating a concentration gradient along the tube. NO_2 diffuses along this gradient in quantities dependent upon the concentration of NO_2 in the atmosphere (see Atkins *et al.*, 1978, for details). Subsequent colorimetric analysis of the amount of NO_2 absorbed by the TEA allows calculation of the mean NO_2 concentration over the period during which the gauze was exposed to the atmosphere. (Appendix 5 gives some details of the calculations and analytical method.)

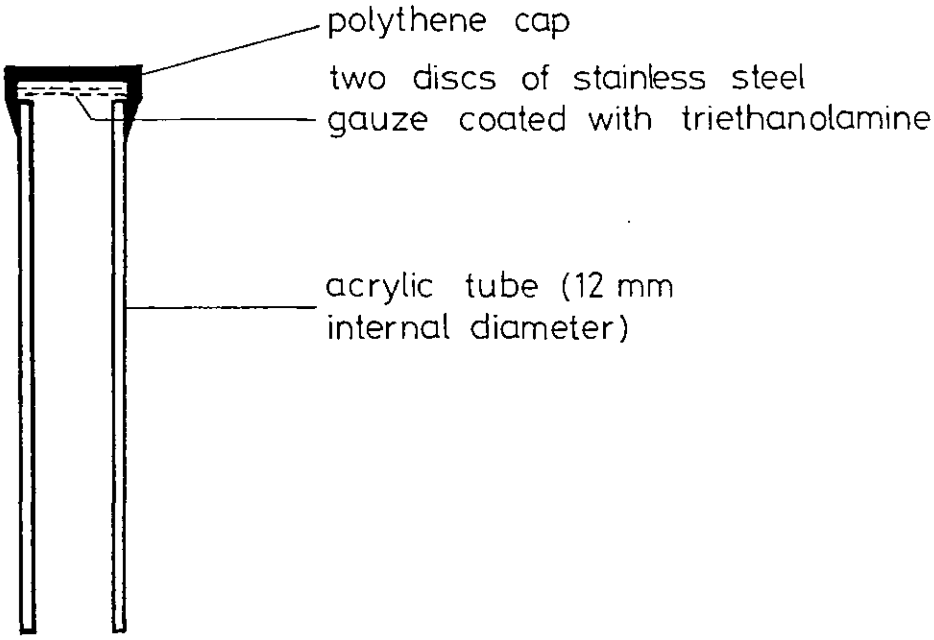


Figure 6.2 : Diagram illustrating construction of NO_2 diffusion tube.
(Approximately life size)

Diffusion tubes were designed for use in essentially still air. The amount of NO_2 reaching the gauze in a turbulent environment presumably would be greater than would reach it by diffusion alone. However, if one assumes conditions of approximately equal turbulence then comparisons between tubes, using proportional differences, should be valid.

In 1980-81 eight diffusion tubes were placed in each chamber: two 15 cm from the top of the chamber at the edge, two just above crop height at the edge, and four just above crop height near the centre of the chamber. In 1981-82 only 6 tubes were placed in each chamber (the central four were reduced to two) but 6 were also placed outside the chambers about 30 cm above ground level. Tubes were kept in position for about four weeks before being replaced with a fresh batch. Analysis was performed within one week of removal from the field.

6.2.3 Species, planting and harvesting

Two species were grown in each chamber: *Lolium perenne* cv. S24 and *Hordeum vulgare* cv. Maris Otter (winter barley). Both species were grown in a loam in plastic crates 33 cm x 43 cm x 24 cm deep. The crates were lined with black polythene, perforated on the base to allow drainage. Similar conditions were employed in both years.

L. perenne: 1980-81

Seeds of *L. perenne* cv. S24 were sown 1 cm deep at a rate equivalent to 30 kg ha^{-1} on 3 November 1980. At the same time a standard 15:15:15 NPK fertiliser was applied at 50 kg N ha^{-1}. Three crates were put in similar positions in the southern half of each chamber on 25 November, about three days after germination. On 10 February 1981, after 81 days growth, the plants were thinned to 160 plants per crate (≡ 1100 plants m^{-2}) and the removed plants were dried and weighed individually. Plants were finally harvested on 24 April 1981 after 154 days growth. At harvest, each crate was divided into quarters; within each quarter the numbers of plants and tillers were counted and the shoot dry weights were determined. (The plants were finally harvested in April because the chambers were on loan from Dr. M.R. Ashmore and were required for other experiments during the summer.)

L. perenne: 1981-82

Treatment was similar to the previous year except that seeds were sown and fertilised on 19 October 1981. The crates were put into the chambers on the day the seeds were sown. Germination began about 5 November. No thinning was carried out for reasons similar to those given in Section 4.2.6. Plants were harvested on 6 May 1982, after 183 days growth. In addition to the parameters measured in 1981, the shoot material from two quarters of each crate was divided into live leaf and dead leaf portions before drying (there was practically no stem). In 1981 there had been essentially no dead shoot material.

H. vulgare: 1980-81

Seeds of *H. vulgare* cv. Maris Otter were sown in rows (4 per crate) 1 cm deep and 11 cm apart in each of 12 crates on 3 November 1980. A standard 9:23:18 NPK fertiliser was applied at a rate of 23 kg N ha^{-1}. Germination had occurred by 20 November and three crates were put into similar positions in the north half of each chamber on 25 November. On 27 November the seedlings were thinned to 12 evenly spaced plants per row; the removed plants were dried and weighed.

Throughout the winter the maximum height (leaves extended) of 8 plants in each crate was measured at 7-14 day intervals. The same plants were measured on each occasion.

The plants were finally harvested on 23 April 1981, after 155 days growth. In each half-row the numbers of plants (6 unless death occurred) and tillers were counted; the shoots were divided into 'live leaves' and 'dead leaves plus stem' before drying and weighing. (Note the stem portions were included with the dead rather than live leaves, in contrast to the Solardome and Silwood grass harvests.)

H. vulgare: 1981-82

Treatment was similar to the previous year with the following exceptions. Seeds were sown and crates put into the chambers on 19 October 1981. Germination had occurred by 2 November and plants were thinned to 12 per row on 12 November. Harvesting was carried out on 4 May 1982, after 184 days growth. When the tillers were counted they were subjectively categorised as 'large' or 'small': the former would probably flower and develop heads of grain, the latter probably would not. The shoots were divided into 'live leaves', 'dead leaves' and 'stem' portions.

The following abbreviations are used:

LW = live leaf dry weight
DW = dead leaf dry weight
SW = stem dry weight
TW = total shoot dry weight
%D = % dead leaf, (DW/TW) x 100
%D+S = % dead leaf + stem, ((DW+SW)/TW) x 100

N.b. as previously, a 'leaf' was defined as the lamina only.

6.2.4 Maintenance

Watering was carried out as necessary to maintain moist soil. Weeds were removed occasionally. When required, plants were sprayed against powdery mildew with Benlate (Pan Britannica Industries, Ltd.), against aphids with Metasystox 55 (Bayer, UK Ltd.) and against brown rust with Bayleton (Bayer, UK Ltd.). No differential infection was observed between treatments and infection was never severe.

6.2.5 Nitrogen and sulphur analysis

Some of the dried samples of *L. perenne* grown during the winter of 1980-81 were analysed for sulphur and nitrogen content. Three samples (~4 g) were taken from each chamber (one from each crate) and ground to a powder. The powder was redried before analysis. A member of the technical staff at CERL performed the analyses using a LECO total sulphur analyser, and the Kjeldahl method for total nitrogen analysis (Allen *et al.*, 1978).

6.2.6 Statistics

The mean weights of the thinned plants (both *L. perenne* and *H. vulgare*) were tested for differences using one-way anovar (between chambers).

Yield data from the final harvests were converted to a per m^2 basis for *L. perenne* and a per m (of row) basis for *H. vulgare*. Data expressed as % were arcsine transformed before analysis. Weights per plant (or per tiller) were calculated as weight per unit divided by the number of plants (or tillers) per unit, where a unit was a quarter crate of *L. perenne* or a half-row of *H. vulgare*. Strictly, these results, $plant^{-1}$ or $tiller^{-1}$, are means, but for reasons given previously (Section 4.2.9) they are referred to simply as weight $plant^{-1}$ or $tiller^{-1}$. Transforming the data, using logarithms, did not improve its already acceptable fit to the assumptions required for anovar. Three-way anovars were performed on the data: the factors used were treatment (filtered, unfiltered), crate position (east, central, west) and chamber position (chambers 1 and 4 were classed as outer, 2 and 3 as inner). The use of inner or outer chamber positions, rather than east or west, in the anovar was recommended by Dr. M.R. Ashmore on the basis of previous work (pers. comm.).

The heights of *H. vulgare* were tested for differences using three-way anovar (as for yield), but only treatment-effects were noted.

Sulphur and nitrogen analyses were tested using two-way anovar (treatment and chamber position) on untransformed data.

6.3 Results

6.3.1 Pollutant concentrations

Using the SO_2 and NO_x analysers to monitor the concentrations of SO_2 and NO_2 in the chambers required the use of a 30 m sample line. Monitoring ambient concentrations of SO_2 and NO_2 showed that the measured concentrations using a 30 m line were > 90% of those using a 2 m line. For the purposes of these experiments the small loss of pollutants to the sample line wall was ignored: it will not have affected comparisons between ambient air, filtered and unfiltered chambers.

Occasional monitoring of the unfiltered chambers and ambient air, both via a 30 m sample line, and alternating samples every 15 minutes, showed essentially no differences in SO_2 or NO_2 concentrations. Some support for this was also obtained using the NO_2 diffusion tubes. Table 6.1 shows the NO_2 concentration in ambient air and in the two unfiltered chambers in 1981-82 (calculated as ppb but quoted as 'units' rather than ppb as it was expected that this method of measuring NO_2 would not be accurate due to turbulence, see Section 6.2.2). There was some evidence that the NO_2 concentrations in ambient air were ~10% greater than in the unfiltered chambers, but the variability found between individual tubes suggested that no importance should be attached to this difference.

During the winter of 1980-81 SO_2 was monitored in the filtered chambers and ambient air for a total of 390 hours (again alternating samples every 15 minutes). A mean filtering efficiency for SO_2 of 55% was found. The filtering efficiency for NO_2 was estimated from the diffusion tube results. Table 6.1 shows that the efficiency was ~70% in both winters, with the exception of the first sample period in 1980.

Monthly mean concentrations of SO_2 and NO_2 in ambient air (≡ unfiltered chambers) during the period of each experiment are shown in Figure 6.3. The seasonal means are listed in Table 6.2, along with the concentrations in the filtered chambers estimated using filtering efficiencies of 55% and 70% for SO_2 and NO_2 respectively. Although the mean SO_2 concentrations were similar during both winters, 11 and 13 ppb in 1980-81 and 1981-82 respectively, the monthly variations were different. In 1980-81 there was a maximum SO_2 concentration of 20 ppb in February, with lower levels in preceding and subsequent months; in 1981-82, SO_2 was highest in December (18 ppb), declining slightly in January and February but more in March and April. The NO_2 concentration exceeded that of SO_2 in both winters but the exact concentration in 1980-81 is unknown because it was not monitored during the first half of the experiment. (However, the mean NO_2 level in 1980-81 is unlikely to have been as high as the 29 ppb in 1981-82 because this would require mean monthly concentrations to have exceeded 50 ppb in December and January.) In 1980-81 NO_2 concentrations were at their highest in December (40 ppb), decreasing from then until May, similarly to SO_2.

Table 6.1 includes ambient NO_2 concentrations obtained from the NO_x monitor. There was no close relationship between the NO_2 concentrations measured by diffusion tubes in the unfiltered chamber and by NO_x monitor in ambient air. Taking the 'units' as ppb, in 1980-81 the diffusion tubes overestimated NO_2 as expected, but in 1981-82 they slightly overestimated, more than 50% underestimated and accurately estimated NO_2 concentrations

Table 6.1 : Mean NO_2 concentration in each chamber and ambient air measured over various sample periods during the two filtration experiments at CERL. Results from diffusion tubes are quoted as 'units' and from the NO_x monitor as ppb. (See text for reasons.)

Sample period	NO_2 concentration ('units')					Mean(1) filtering efficiency (%)	Ambient NO_2 (ppb)
	Chamber				Amb.		
	1	2	3	4			
27 Nov.-29 Dec. 1980	23	17	12	11	-	43	-
30 Dec. 1980-3 Feb. 1981	47	50	10	17	-	72	-
4 Feb.-9 Mar. 1981	28	25	7	9	-	70	16(2)
10 Mar.-2 Apr. 1981	-	-	-	-	-	-	9
3 Apr.-23 Apr. 1981	21	19	5	6	-	72	17
27 Nov. 1980-23 Apr. 1981	31	29	9	11	-	67	17(3)
5 Nov.-14 Dec. 1981	9	7	25	30	25	71	22
15 Dec. 1981-27 Jan. 1982	7	7	17	20	22	62	44
28 Jan.-3 Mar. 1982	5	5	24	21	26	78	24
3 Mar.-4 May 1982	-	-	-	-	-	-	23
5 Nov. 1981-4 May 1982	-	-	-	-	-	-	29

(1) $\frac{\text{mean concentration in unfiltered chambers - mean in filtered chambers}}{\text{mean in unfiltered chambers}} \times 100$

(2) 13 Feb.-9 Mar. only

(3) 13 Feb.-23 Apr. only

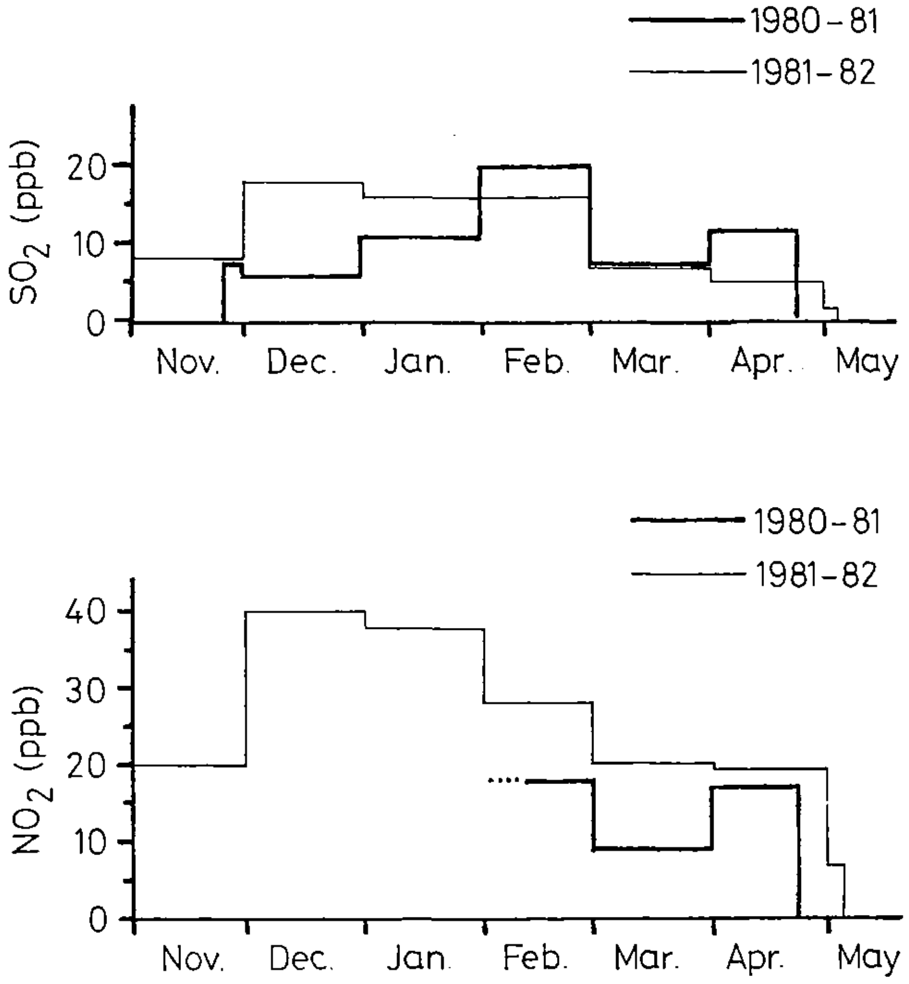


Figure 6.3 : Monthly mean concentrations of SO_2 and NO_2 in ambient air during the period of each filtration experiment at CERL.

Table 6.2 : Seasonal mean SO_2 and NO_2 concentrations during the filtration experiments at CERL.

Sample period	Pollutant	Mean concentration (ppb)	
		Unfiltered	Filtered (1)
27 Nov. 1980-23 Apr. 1981	SO_2	11	5
13 Feb. 1981-23 Apr. 1981	NO_2	17	6
5 Nov. 1981-4 May 1982	SO_2	13	6
5 Nov. 1981-4 May 1982	NO_2	29	9

(1) estimated for SO_2 as 45% and for NO_2 as 30% of the concentration in the unfiltered chamber (see text for reasons).

in the three monitoring periods respectively. No reasons for these differences were apparent. The lack of correlation between results from diffusion tubes and the NO_x monitor did not allow prediction of NO_2 concentrations in the first half of the 1980-81 experiment.

Checking NO_2 levels at various positions in the chambers indicated no consistent differences (Table 6.3).

6.3.2 Effects of treatment on growth

Lolium perenne cv. S24

The mean weight of the 81-day old plants, harvested on 10 February 1981, was ~5 mg and there were no significant differences in size between the chambers (Table 6.4).

Treatment means from the final harvests in 1981 and 1982, when the swards were 154 and 183 days old respectively, are listed in Tables 6.5 and 6.6. Means for each chamber are given in Appendix 6, Tables A6.1 and A6.2. Plant density was at the intended level of about 1100 m^{-2} in 1981 and about 10% higher in 1982 (as a result of not thinning) but this is unlikely to have substantially affected the results. There were about 7800 tillers m^{-2} in the unfiltered chambers in both years; in 1981 the number was reduced in filtered air by 12% ($p < 0.05$) but there was no treatment effect in 1982. Tiller number per plant was greater in 1981 than 1982, possibly caused by the lower plant density in 1981; in neither year was there a treatment effect.

In 1981 only TW was obtained as there was essentially no dead material at the harvest. Filtering the air resulted in a reduction of ~30% in TW m^{-2} and TW $plant^{-1}$, but of only 24% $tiller^{-1}$. Only one significant interaction (treatment x chamber position) occurred, indicating that in filtered air the TW $tiller^{-1}$ was greater in the inner than outer chamber, but that

Table 6.3 : Mean NO_2 concentration, measured using diffusion tubes, at 3 positions within each chamber during both filtration experiments at CERL. Results are averaged over each season.

Winter	Position in chamber	NO_2 concentration in each chamber ('units')			
		1	2	3	4
1980-81	Top - edge	36	33	9	15
	Crop height - edge	31	35	9	9
	Crop height - central	28	21	8	10
1981-82	Top - edge	8	7	21	18
	Crop height - edge	8	7	22	27
	Crop height - central	7	6	23	27

Table 6.4 : *L. perenne* cv. S24 : mean dry weight of 81 day old plants thinned on 10 February 1981 from filtered and unfiltered chambers at CERL.

	Chamber	Number of plants	Mean (± S.E.M.) dry weight (mg $plant^{-1}$)
Filtered	4	58	5.5 ± 0.3
	3	22	3.9 ± 0.5
Unfiltered	2	51	5.0 ± 0.5
	1	36	5.4 ± 0.4

There were no significant differences at $p = 0.05$

Table 6.5 : *L. perenne* cv. S24 grown in filtered and unfiltered chambers, 1980-81. Mean dry weights etc. at final harvest.

Parameter	Mean ± S.E.M.		Analysis of variance(1)						
	Filtered	Unfiltered	Tr	Cr	Ch	Tr Cr	Tr Ch	Cr Ch	Tr Cr Ch
Plants m^{-2}	1038 ± 42 94(2)	1102 ± 30	-	-	-	-	-	-	-
Tillers m^{-2}	6903 ± 282 88	7817 ± 209	*	-	-	-	-	-	-
Tillers $plant^{-1}$	6.71 ± 0.16 94	7.13 ± 0.14	-	-	-	-	-	-	-
TW g m^{-2}	265 ± 15 68	390 ± 18	***	-	-	-	-	-	-
TW mg $plant^{-1}$	255 ± 10 71	358 ± 17	***	-	-	-	-	-	-
TW mg $tiller^{-1}$	38 ± 1 76	50 ± 2	***	-	-	-	*	-	-

(1) Tr = Treatment (filtered, unfiltered); Cr = Crate position (east, central, west); Ch = Chamber position (inner, outer).

- not significant; * $p < 0.05$; *** $p < 0.001$

(2) Mean in filtered chambers expressed as % of mean in unfiltered chambers.

Table 6.6 : *L. perenne* cv. S24 grown in filtered and unfiltered chambers, 1981-82. Mean dry weights etc. at final harvest.

Parameter	Mean ± S.E.M.		Analysis of variance(1)						
	Filtered	Unfiltered	Tr	Cr	Ch	Tr Cr	Tr Ch	Cr Ch	Tr Cr Ch
Plants m^{-2}	1223 ± 34 97(2)	1262 ± 36	-	-	-	-	-	-	-
Tillers m^{-2}	7520 ± 241 96	7828 ± 268	-	-	-	-	-	-	-
Tillers $plant^{-1}$	6.17 ± 0.20 100	6.20 ± 0.17	-	-	-	-	-	-	**
LW g m^{-2}	428 ± 28 95	452 ± 22	-	-	-	-	-	-	-
DW g m^{-2}	47 ± 4 90	52 ± 5	-	-	**	-	-	-	-
TW g m^{-2}	501 ± 20 96	522 ± 23	-	-	**	-	-	-	*
LW mg $plant^{-1}$	353 ± 23 100	353 ± 9	-	-	-	-	-	-	*
DW mg $plant^{-1}$	38 ± 3 95	40 ± 2	-	-	***	-	-	-	-
TW mg $plant^{-1}$	411± 17 100	413 ± 13	-	-	**	-	-	-	*
LW mg $tiller^{-1}$	59 ± 3 102	58 ± 1	-	-	**	-	**	-	-
DW mg $tiller^{-1}$	6.5 ± 0.5 98	6.6 ± 0.4	-	-	***	-	-	-	-
TW mg $tiller^{-1}$	67 ± 2 102	66 ± 1	-	-	***	-	**	-	-
%D(3)	9.77 97	10.10	-	-	***	-	-	-	-

(1) Tr = Treatment (filtered, unfiltered); Cr = Crate position (east, central, west); Ch = Chamber position (inner, outer)

- not significant; * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$

(2) Mean in filtered chambers expressed as % mean in unfiltered chambers.

(3) Back-transformed after arcsine conversion.

in unfiltered air the situation was reversed (Appendix 6, Table A6.1).

In 1982 TW was greater than in 1981, presumably at least partly a reflection of the longer growing season (183 days in 1982, 154 in 1981). Also, ~10% of the shoot material was dead, allowing separation into LW and DW. There were no treatment effects in any of the parameters measured (Table 6.6). However, chamber position (inner vs. outer) showed significant differences in DW and TW m^{-2}, $plant^{-1}$ and $tiller^{-1}$, LW $tiller^{-1}$ and %D. In all these cases, yields and %D were greater in the inner than outer chambers (Table A6.2). Treatment x chamber position interactions occurred only in LW and TW $tiller^{-1}$, but inspection of Table A6.2 in Appendix 6 shows that LW and TW $tiller^{-1}$ were greater in the inner than outer filtered chamber but similar in the unfiltered chambers; almost the reverse of the situation in 1981. The ecological or biological significance of these and the treatment x chamber x crate interactions, if any, cannot be determined with the small quantity of data available.

Hordeum vulgare cv. Maris Otter

Seedlings of *H. vulgare* were thinned to 12 per row soon after germination. As expected, there were no significant differences in mean weights between chambers: seedlings harvested on 27 November 1980, 8 days after germination, had a mean shoot weight of ~10.0 mg; seedlings harvested on 12 November 1981, 11 days after germination, weighed ~11.5 mg.

The mean heights (leaves extended) of plants in each treatment during each winter are shown in Figure 6.4. Plants in filtered and unfiltered chambers in both years gained height in an essentially similar pattern: an initial burst of growth from germination until early December was followed by a slow increase in height until early March with a rapid increase from then until harvest. During January and February in both years plants were a similar mean height (100-140 mm), as they were at both harvests. On

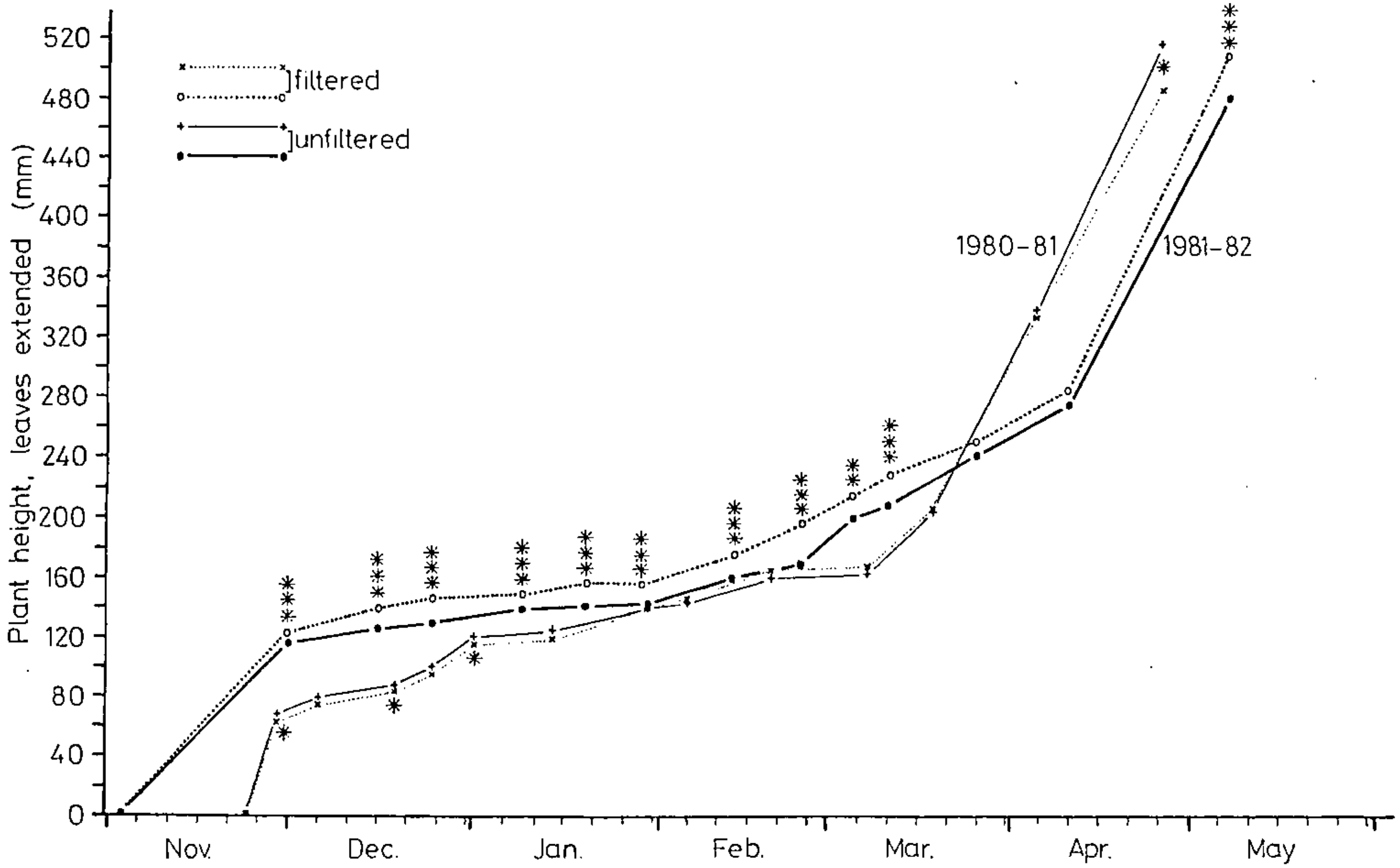


Figure 6.4 : Mean height of *H. vulgare* (leaves extended) in each treatment for the winters of 1980-81 and 1981-82. Significant differences are indicated: *, $p < 0.05$; **, $p < 0.01$; ***, $p < 0.001$.

three out of five occasions when height was measured from late November 1980 to early January 1981 plants were significantly shorter ($p < 0.05$) in filtered than in unfiltered chambers. There were no more differences until the final harvest when plants in unfiltered chambers were 6% taller than those in filtered chambers. In the 1981-82 experiment, plants in the filtered chambers were taller than those in the unfiltered chambers by about 10% from late November until early March. When heights were measured on 23 March and 8 April there were no significant differences, but at the harvest on 4 May 1982 plants in filtered chambers were 7% taller than those in unfiltered chambers (the reverse of the situation in 1981).

The mean results for each treatment at the harvests in 1981 and 1982 are given in Tables 6.7 and 6.8 respectively, means for each chamber are listed in Appendix 6, Tables A6.3 and A6.4. Very few plants died in either winter and therefore the number of plants was fairly constant at 35 m^{-1} of row. For this reason the results on a m^{-1} basis are essentially proportional to those on a $plant^{-1}$ basis, and only results $plant^{-1}$ and $tiller^{-1}$ are presented in Tables 6.7 and 6.8, although results m^{-1} are included in TablesA6.3 and A6.4 in Appendix 6.

In 1981 there were 5.4 tillers $plant^{-1}$ in unfiltered chambers and 14% less in filtered chambers ($p < 0.001$), but in 1982 there were 5.0 tillers $plant^{-1}$ in unfiltered air and a similar number in filtered air (Tables 6.7 and 6.8). The numbers of large (flowering?) and small (non-flowering?) tillers in 1982 were the same in both treatments and suggest that ~3 tillers $plant^{-1}$ would have produced grain.

Filtering the air reduced LW, DW+SW and TW $plant^{-1}$ by 11, 16 and 13% respectively in 1981, but weights $tiller^{-1}$ were not affected, i.e. the reduction in plant weight was due to a reduction in number rather than weight of tillers. %D+S was reduced ($p < 0.01$) in filtered air in 1981,

Table 6.7 : *H. vulgare* cv. Maris Otter grown in filtered and unfiltered chambers, 1980-81. Mean dry weights etc. at final harvest.

Parameter	Mean ± S.E.M.		Analysis of variance(1)						
	Filtered	Unfiltered	Tr	Cr	Ch	Tr Cr	Tr Ch	Cr Ch	Tr Cr Ch
Plants m^{-1}	35.1 ± 0.4 100(2)	35.0 ± 0.4	-	-	-	-	*	*	-
Tillers plant^{-1}	4.64 ± 0.13 86	5.40 ± 0.10	***	**	-	-	-	-	-
LW mg plant^{-1}	433 ± 15 89	486 ± 17	*	-	-	**	-	-	-
DW+SW mg plant^{-1}	446 ± 21 84	528 ± 21	**	-	-	*	-	*	-
TW mg plant^{-1}	879 ± 34 87	1014 ± 36	**	-	-	**	-	*	-
LW mg tiller^{-1}	94 ± 3 104	90 ± 3	-	-	-	***	-	-	-
DW+SW mg tiller^{-1}	97 ± 4 99	98 ± 3	-	*	-	***	-	-	-
TW mg tiller^{-1}	191 ± 6 102	188 ± 6	-	-	-	***	-	-	-
%D+S(3)	50.1 97	51.9	**	***	**	*	**	**	*

(1) Tr = Treatment; Cr = Crate position; Ch = Chamber position.
- not significant; * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$

(2) Mean in filtered chambers expressed as % mean in unfiltered chambers.

(3) Back-transformed after arcsine conversion.

Table 6.8 : *H. vulgare* cv. Maris Otter grown in filtered and unfiltered chambers, 1981-82. Mean dry weights etc. at final harvest.

Parameter	Filtered	Unfiltered	Analysis of variance(1)						
			Tr	Cr	Ch	Tr Cr	Tr Ch	Cr Ch	Tr Cr Ch
Plants m^{-1}	34.9 ± 0.5 98(2)	35.7 ± 0.3	-	-	*	-	-	-	-
Tillers $plant^{-1}$ - small	2.37 ± 0.08 109	2.18 ± 0.09	-	*	-	*	-	-	-
- large	2.95 ± 0.06 105	2.82 ± 0.08	-	-	*	-	-	**	-
- total	5.33 ± 0.11 107	5.00 ± 0.14	-	-	*	-	-	-	-
LW mg $plant^{-1}$	296 ± 8 100	297 ± 9	-	***	-	-	-	-	*
DW mg $plant^{-1}$	227 ± 7 110	207 ± 6	*	***	-	-	-	-	-
SW mg $plant^{-1}$	1072 ± 32 116	924 ± 34	***	***	***	-	-	-	*
DW+SW mg $plant^{-1}$	1299 ± 38 115	1131 ± 39	***	***	***	-	-	-	*
TW mg $plant^{-1}$	1595 ± 45 112	1428 ± 46	**	***	**	-	-	-	*
LW mg $tiller^{-1}$	56 ± 1 93	60 ± 1	*	-	-	**	-	**	*
DW mg $tiller^{-1}$	43 ± 1 102	42 ± 1	-	***	***	-	-	-	**
SW mg $tiller^{-1}$	202 ± 5 108	187 ± 6	**	***	***	-	*	-	***
DW+SW mg $tiller^{-1}$	245 ± 6 107	229 ± 7	*	***	***	-	-	-	**
TW mg $tiller^{-1}$	301 ± 7 105	288 ± 8	-	***	***	-	-	-	**
%D(3)	14.2 97	14.6	-	**	*	-	**	-	-
%D+S(3)	79.0 97	81.4	***	***	***	**	-	***	***

(1), (2), (3) as Table 6.7

but only from 51.9 to 50.1% (sic). In 1982 plants were ~50% heavier than in 1981 even though they were the same height and had a similar number of tillers. Filtering the air increased many weights plant^{-1} (Table 6.8), at least partly due to an increase in weight tiller^{-1} (SW, DW+SW) but also due to a combination of non-significant increases in tiller number and weight tiller^{-1} (DW and TW). Tiller height in filtered air was 7% greater than in unfiltered air and SW (presumably largely responsible for height) was increased by 8% in filtered air. In 1982 the DW+SW was about 80% of TW, compared with 50% in 1981, and was reduced ($p < 0.001$) from 81.4 to 79.0% (sic) by filtering the air but %D was unaffected (Table 6.8).

Crate and chamber position in 1982 caused many significant differences in weight parameters (Table 6.8). Inner chambers outyielded outer chambers (Appendix 6, Table 6.4), similarly to *L. perenne*. The crate effects were due to less yield in the centre crates than in the east and west crates. This may have been caused by rain dripping from the roof of the chamber onto the centre crates of *H. vulgare*, resulting in waterlogging of the soil and/or undermining of roots in the early part of the season. Similar 'dripping' occurred in 1981 but there were few significant crate effects. In 1981 there were treatment x crate interactions in all the weight parameters and %D+S (Table 6.7); in 1982 treatment x chamber x crate interactions were found in %D+S and all weight parameters except DW plant^{-1}. As with *L. perenne*, the ecological/biological significance (if any) of the interactions cannot be determined from the available data.

6.3.3 Sulphur and nitrogen content

The sulphur content of *L. perenne* cv. S24 was around 0.4% in all the chambers and the content of nitrogen varied from 2.9 to 3.8%, but there were no treatment or chamber effects (Table 6.9). Both the sulphur and nitrogen contents were similar to those of *L. perenne* cv. S24 in the

Table 6.9 : Mean sulphur and nitrogen contents of *L. perenne* cv. S24 in each chamber at harvest on 24 April 1981.

Chamber		% sulphur	% nitrogen
unfiltered	1	0.37 ± 0.01	2.92 ± 0.17
	2	0.40 ± 0.04	3.23 ± 0.22
filtered	3	0.40 ± 0.01	3.82 ± 0.41
	4	0.41 ± 0.03	3.06 ± 0.16

There were no significant differences at $p = 0.05$

control treatment in the Solardomes and were normal for ryegrass (see Section 4.4.3).

6.4 Discussion

The SO_2 concentrations in the unfiltered chambers (≡ ambient air) were similar in both winters: 11 ppb in 1980-81 and 13 ppb in 1981-82 (Table 6.5). These were surprisingly low, being similar to the mean found from the analysis of WSL country sites (Section 2.1.1, Fig. 2.4) and to the means at Bottesford. The latter, a rural site in the Midlands, received mean concentrations of 12-14 ppb SO_2 over the winters of 1977 to 1979 (Martin & Barber, 1981). The mean ambient NO_2 concentrations were 17 ppb in 1980-81 and 29 ppb in 1981-82, exceeding SO_2 by more than twofold in the second winter. Again a surprising result as NO_2 and SO_2 usually occur in similar concentrations (Table 2.6).

The filtering efficiency was such that it decreased the SO_2 concentrations in the filtered chambers to about half that in the unfiltered chambers, a reduction of only 6-7 ppb (Table 6.5). NO_2 concentrations were reduced by approximately 11 and 20 ppb in 1980-81 and 1981-82 respectively.

The main responses of the plants to filtering may be summarised as follows:

L. perenne, 1980-81, decrease of 30% in TW due to smaller tillers,
1981-82, no effect on LW, DW or TW,
H. vulgare, 1980-81, decrease in height of 6% and a decrease in TW of ~13% due to fewer tillers,
1981-82, increase in height of 7% and an increase in TW of ~12% due to a combination of non-significant increases in tiller weight and number.

Thus, in 1980-81 a difference in pollutant concentrations of 6 ppb SO_2 and

11 ppb NO_2 resulted in a 30% decrease in TW in the filtered chambers, whereas in 1981-82, a difference of 7 ppb SO_2 and 20 ppb NO_2 between the filtered and unfiltered chambers produced no effects on the dry weights of *L. perenne* cv. S24.

Filtering air containing < 20 ppb SO_2 has been found to have no effect or to increase the yield of several grass species by various authors (Table 3.11), and on one occasion filtering air containing only 9 ppb SO_2 was found to increase the total plant weight of *L. perenne* cv. S23 by over 50% (Crittenden & Read, 1978b; also see Table 3.12). No previous filtration experiments have suggested that filtration of similar pollutant concentrations would cause a decrease in TW. In the present studies the fumigation experiment utilising pollutants at concentrations most similar to those in the unfiltered chamber was the low treatment in the Solardomes over the winter of 1981-82 (19 ppb SO_2 and 24 ppb NO_2; 4 and 13 ppb SO_2 and NO_2 respectively in the control treatment). At the March 1982 harvest the mean TW of *L. perenne* cv. S24 was not significantly different from control but by May it was 39% greater than control.

The lack of effect in 1981-82 produced by filtering the air therefore fits reasonably well with published data but the results from 1980-81 have no precedent, although the results from the Solardomes suggest that it may be a real pollutant-induced effect (rather than due to, say, environmental factors). The difference in effects from one year to the next may have been due to variation in the pollutant concentrations throughout each season and/or between seasons. For example, the SO_2 concentrations were slightly higher from February to April in 1981 than in 1982 (and therefore may have stimulated growth, see Section 5.4.3) but the NO_2 concentrations showed an opposite pattern.

The results for *H. vulgare* showed an almost perfect reversal of effect from 1980-81 to 1981-82, strongly suggesting that the same chambers (1 and 2) caused the increases in height and TW, presumably due to small environmental differences between chambers caused by their positions. (It should be remembered that the treatments were reversed between the two winters.) This reversal of effect was so well marked that it seems reasonable to assume there was no effect of pollutants on dry weight or height. However, in both years the %D+S in the unfiltered chambers were slightly greater than in the filtered chambers.

Buckenham *et al.* (1982) grew spring barley (*H. vulgare* cv. Magnum) for two seasons in chambers receiving filtered and unfiltered air. Filtering air containing 17-18 ppb SO_2 (plus a small amount of fluoride) increased the total dry weight by 6 and 19% at anthesis in 1979 and 1980 respectively, but by maturity these increases were 17 and 51% respectively. Buckenham *et al.*'s (1982) experiments were conducted during spring and summer and involved a different barley cultivar than the present work. Therefore their results are not directly comparable with the experiments described here, but it is worth noting that filtering air containing ~17 ppb SO_2 did not significantly affect the total plant dry weight at anthesis in 1979, although the effect was larger, and significant, later in the season. The presence of fluoride may have increased the response due to filtering the air.

Assuming *H. vulgare* was affected by environmental differences between chambers, but not by pollutants, then in 1980-81 the filtered chambers were detrimental to growth but the unfiltered chambers were detrimental in 1981-82. These adverse conditions may have acted similarly on *L. perenne*, and if this was the case then the reduction in yield found in the filtered chambers in 1980-81 (Table 6.5) may be at least partially explained by environmental factors other than pollution. Similarly, in 1981-82 the presumed adverse effect of the unfiltered chambers themselves may have been counteracted by the (beneficial) presence of low levels of pollutants, resulting in no net effect (Table 6.6). Thus there is the possibility that *L. perenne* benefited by the presence of low levels of pollution in both winters.

6.5 Conclusions

The growth of *H. vulgare* cv. Maris Otter was probably affected to a greater extent by the position of the chambers than by filtering the air. However, it is possible that the observed reversal of effects found on reversing the treatments between each experiment was coincidental or due to the different pollutant concentrations in each winter. The response of *L. perenne* cv. S24 to filtering the air apparently varied between winters, but there was very tentative evidence that unfiltered air may have been beneficial in both years. In neither experiment was there evidence that unfiltered air containing ~12 ppb SO_2 and 17-29 ppb NO_2 decreased the yield of *L. perenne*. As with *H. vulgare* the variations in pollutant concentrations between each experiment may have caused the differences in effects from one winter to the next. In addition, it is possible that interactions of pollutants with the weather may have been important, but without more extensive research further comments are not worthwhile.

CHAPTER 7

DISCUSSION

7.1 Introduction

The purpose of this thesis was to study the effects of UK ambient levels of SO_2 and NO_x on the growth of crops, particularly grasses. Three sets of experiments were carried out: their design and the results obtained may be summarised briefly as follows.

Solardomes. SO_2 and NO_2 concentrations were fluctuated on a daily basis to represent fringe, typical urban and heavily polluted urban environments. Mean concentrations of SO_2 and NO_2 were approximately 18, 34 and 50 ppb of each pollutant in the three treatments respectively, compared with 2 ppb SO_2 and 9 ppb NO_2 in the control treatment. By the end of each experiment, in the most polluted treatment there were essentially no effects on the cumulative total yields of *L. perenne* cvs S23 and S24 or *L. multiflorum* cv. RvP, but there was some evidence for increased yields in the chambers representing fringe and typical urban environments. During spring growth all three treatments often increased the yields of both cultivars of *L. perenne*, compared with control, but did not affect *L. multiflorum*. Root dry weights showed some evidence of decreasing in proportion to increases in pollutant concentration.

Silwood chambers. SO_2, NO_2 and NO concentrations were fluctuated on an hourly basis, both singly and in mixtures, to represent cumulative frequency distributions and diurnal patterns typical of an urban or urban fringe environment. The mean concentrations used were about 30 ppb SO_2 and 25 ppb NO_2, slightly less than in the 'urban' treatment in the Solardomes. (NO levels were not successfully controlled and treatments which included NO will not be considered here.) By the end of each experiment, the cumulative total shoot yields of *L. perenne* cv. S23 and *Phleum pratense* cv. Odenwalder did not differ significantly from the controls. In one case, the total shoot dry weight of *Dactylis glomerata* cv. S26 was 16% greater in SO_2 + NO_2 than in the controls by the end of the experiment. In the spring, only *D. glomerata* showed an increased yield in the presence of SO_2 + NO_2, but SO_2 alone appeared to increase yield in all species. There was very little evidence that SO_2 and NO_2 produced significant interactive effects on yield. Roots of *L. perenne* were unaffected by treatment.

Filtration experiments. In the two experiments the pollutant concentrations were low: approximately 12 ppb SO_2 and 17-29 ppb NO_2 in the unfiltered chambers, compared with 5 ppb SO_2 and 7 ppb NO_2 in the filtered chambers. There was some evidence that unfiltered air increased the yield of *L. perenne* cv. S24 but *Hordeum vulgare* cv. Maris Otter was probably more affected by differences in microclimate than pollutant levels.

In Chapter 3, previously published work on the effects of SO_2 and NO_2 on grass growth was discussed. It was concluded that fumigations with mean concentrations of 50-60 ppb SO_2 generally produced a reduction in yield compared with clean air, and that this reduction was greater in the presence of SO_2 + NO_2. In particular, workers at the University of Lancaster, using mean concentrations of 62-68 ppb SO_2 (+ NO_2), have found large reductions in yield, particularly in winter (Ashenden & Mansfield, 1978; Whitmore & Freer-Smith, 1982). In addition, in Chapter 3 it was noted that in general filtering urban air increased the yields of ryegrass, particularly when the mean SO_2 concentration exceeded 20 ppb (Table 3.11). This strongly suggests that urban air was responsible for reducing grass yields, even with apparently low pollutant concentrations.

Thus there appear to be two anomalies. Firstly, in the present study fumigation with up to 50 ppb SO_2 + NO_2 had no adverse effect on yield, whereas 62-68 ppb SO_2 + NO_2 had previously been shown to reduce yield severely, particularly overwinter. Secondly, in previous studies filtering polluted air improved grass growth, but when similar concentrations of pollutants were used for fumigations in the present work there were few detrimental effects. (The lack of marked effects due to filtering air in this study may be ascribed to the relatively low levels of pollutants.)

The aim of this chapter is to discuss possible causes for the differences between both these seemingly contradictory findings. Some of the factors which may affect the interpretation of results from fumigation experiments are discussed below, with particular reference to the present work and that at Lancaster. Following this, there is a discussion of possible reasons for differences between results obtained from fumigation and filtration experiments. Finally, the results are considered with respect to UK ambient pollution and its effects on crops in the field.

7.2 Factors Influencing the Response of Grass Species to Pollutants During Fumigation Experiments

Many factors have been shown to influence the response of grass species to pollutants. These are discussed in detail below.

7.2.1 Design of fumigation systems

Two factors in the design of fumigation systems have been shown to affect the interpretation of results. Firstly, in some studies the concentration of pollutant has been measured at the inlet to the chamber (e.g. Lockyer, Cowling & Jones, 1976). Unsworth & Mansfield (1980) have pointed out that in such systems, adsorption onto the walls of the chambers and uptake by the plants is ignored which may lead to a serious overestimation of the concentration being received by the plants. Depending on the air flow rate, plant size and the deposition velocities of SO_2 onto the walls and plants, Unsworth & Mansfield (1980) showed that in an extreme case the concentration of pollutant reaching the plants may be only 25% of the inlet concentration.

In the present work, an accurate assessment of the concentrations of pollutants reaching the plants was ensured by sampling from near the centre of each chamber (Silwood) and midway out from the centre (Solardomes). In neither case were spatial variations detected within the chambers.

The second factor shown to be very important in chamber design is windspeed. Ashenden & Mansfield (1977) demonstrated that 110 ppb SO_2 caused substantial reductions in shoot and root dry weights of *L. perenne* when the windspeed was 25 m min^{-1}, but these parameters were not affected by the same concentration of SO_2 with a windspeed of 10 m min^{-1}. The reason for this difference was that at the lower windspeed the boundary layer resistances were high, limiting SO_2 flux into the plants, whereas at 25 m min^{-1} the boundary layer resistances were greatly reduced and were not limiting SO_2 uptake (typical of most field situations). Achieving a high enough windspeed, and therefore low boundary layer resistances, is essential to ensure that pollutants in the atmosphere reach the plants at a rate characteristic of their behaviour in the field.

The aerodynamic resistance of *L. perenne* swards in the Solardomes was measured, using the method of Sheehy & Tearle (1976), and found to be 40-60 s m^{-1} (Roberts, pers. comm.). In a previous study using the Silwood chambers (with an air flow rate of ~2 air changes min^{-1}, similar to this study), Bell, Rutter & Relton (1979) found that the aerodynamic resistance of *L. perenne* swards in the chambers was 38 s m^{-1}. Both these results compare favourably with the external diffusion resistance of 89 s m^{-1} found by Ashenden & Mansfield (1977) at a windspeed of 25 m min^{-1}. It may also be noted that in both the Silwood chambers and the Solardomes the air flows and turbulence were sufficient to cause continuous slight leaf movement. In addition, it was shown that the sulphur contents of the rye-grasses in the Solardomes were proportional to the SO_2 content of the atmosphere (Fig. 4.7): proof that SO_2 was being taken up by the plants (or possibly deposited on the leaf surface), although not necessarily at the same rate as in the field.

The exact boundary layer resistances in the outdoor-chamber fumigation system at Lancaster (Ashenden *et al.*, 1982) have not been reported although the air movement has been described as sufficient to prevent the formation of high boundary layer resistances around leaves (Ashenden, 1979b; Ashenden & Williams, 1980).

In conclusion, it seems probable that plants, in both the present work and that at Lancaster, were exposed in a manner which permitted the transfer of pollutants to the leaf surface at a rate comparable to that in the field. Hence, inadequate air movement is not likely to explain differences in results obtained from the two systems.

7.2.2 Pollutant concentrations

In many early studies on the effects of pollutants on crop growth the major factor considered to influence the response was the mean pollutant concentration. Now, however, it is clear that many other factors are significant. Nevertheless, pollutant concentrations are important and should be considered in detail. Most fumigation experiments have used constant concentrations of pollutants which are adequately described by the mean (e.g. the work of Bell and coworkers or Cowling and coworkers). Many experiments conducted at Lancaster have used 100-110 ppb for 104 hours per week and clean air for 64 hours, a mean weekly concentration of 62-68 ppb. Until the present work, only one attempt had been made to simulate log-normal distributions of pollutant concentrations in semi-controlled conditions (Roberts *et al.*, 1983; Colvill *et al.*, 1983). (In some open-air fumigations SO_2 concentrations were inversely proportional to windspeed and therefore were approximately log-normally distributed, e.g. Lee *et al.*, 1979; Runeckles *et al.*, 1981.)

There is very little information on the comparative effects of low mean concentrations of pollutants supplied at constant or varying concentrations. Jones & Mansfield (1982b) exposed *Phleum pratense* to clean air or mean concentrations of 60 ppb SO_2 for 6 weeks. The SO_2 was supplied as (a) 60 ppb constantly, (b) 800 ppb for 1.5 hours on 5 days per week, otherwise 27 ppb, or (c) 400 ppb for 3 hours on 5 days per week, otherwise 28 ppb. There were no signficant treatment effects on total shoot dry weight. Garsed, Mueller & Rutter (1982) exposed *Pinus sylvestris* to mean concentrations of 38 ppb SO_2 either constantly or as fluctuating levels. The latter formed a factorial design with peaks of up to 113 or 282 ppb, each of 5 or 21 hours duration (each treatment mean was 38 ppb and therefore peaks varied in their frequency). After 650 days of treatment, Garsed *et al.* (1982) found that 21 hour peaks, up to 113 or 282 ppb, caused a greater reduction (23%) in dry weight than a constant concentration (14% reduction). The main factor affecting growth was the presence of SO_2 which in all cases caused a significant reduction in yield compared with control. Neither of these studies are directly applicable to comparing the effects of the present work (using log-normal distributions of concentrations) with other studies, although both suggest that there is not a great difference between the effects of fluctuating and constant concentrations of SO_2 with the same mean.

In the present study, the log-normal distributions may be considered to produce peaks of varying duration and concentration, based on daily (Solardomes) or hourly (Silwood) fluctuations. It is possible that the use of different pollutant regimes was responsible for the differences in effects seen between the Silwood chambers and the medium treatment in the Solardomes (e.g. the increases in yield of *L. perenne* in spring in the Solardomes were not found in the SO_2 + NO_2 treatments in the Silwood chambers). Although the mean SO_2 concentrations were ~32 ppb in the Silwood chambers and ~34 ppb in the medium treatment in the Solardomes the cumulative frequency distributions varied. For example, SO_2 exceeded 60 ppb for ~15% of the time at Silwood but for only 7-9% of the time in the medium treatment in the Solardomes. Similarly, SO_2 exceeded 100 ppb for 5% of days in the high treatment in the Solardomes (mean ~50 ppb), but for 60% of the time in the experiments at Lancaster supplying 100-110 ppb for 104 hours per week (mean 62-68 ppb). Whether these differences are important is a subject that requires investigation.

Furthermore, the degree of coincidence of SO_2 with NO_2 may be important if pollutants interact in their effects when present simultaneously or when a relatively high concentration of one pollutant is followed by a relatively high concentration of the other. In the present study, the ratio of SO_2:NO_2 varied throughout each experiment (see Fig. 5.11 for the Silwood chambers; a similar situation occurred in the Solardomes, data not presented), whereas at Lancaster the ratio was constant (1:1 on a ppb basis) during all fumigation periods. The importance of the 'instantaneous' ratios of SO_2:NO_2 is another subject requiring investigation.

7.2.3 Light and temperature

Jones & Mansfield (1982a) have shown that both light intensity and temperature affect the response of *Phleum pratense* to 120 ppb SO_2. When plants were growing fast, at a high light intensity or temperature (400 µE m^{-2} s^{-1}; 19°C night, 30°C day), the adverse effects of SO_2 on growth were less than when the plants were growing slowly due to lower light intensity or temperature (100 µE m^{-2} s^{-1}; 12°C night, 26°C day). Since no supplementary lighting or heating was used in the Solardomes or the Silwood chambers, both light intensity and temperature will have varied in a similar manner to ambient.

No measurements of microclimatic conditions within the Silwood chambers were made in the present study, but, using the same chambers, Farrar, Relton & Rutter (1977) monitored radiant flux density and temperature for a week in October. Inside the chambers the flux density was 85% of ambient and temperatures were 2-3°C higher at night but up to 9°C higher on sunny days. In similar chambers, Ayazloo (1979) found that the internal air temperature was usually 2-7°C higher than ambient. In the Solardomes the temperatures were generally 0.5-1.5°C above ambient, and only 3°C higher when the ambient temperature exceeded about 25°C; the light intensity was about 70% (winter) to 80% (summer) of ambient (calculated from data supplied by Dr. T.M. Roberts). The fact that the temperatures within the chambers were higher than ambient may have decreased the potential for pollutant injury, although the decrease in light intensity may have increased it, but in both cases by an unknown amount.

It is worth noting that in the present study, in winter and spring, when light intensities and temperatures were low there were often increases in yield in polluted air, whereas in summer when light intensities and temperatures were higher, there were generally no effects of pollutants on yield. The lack of effects under good growing conditions is in accordance with the suggestion of Mansfield & Jones (1982a), but the beneficial effect of pollutants under poor growing conditions appears to be contrary to their ideas. On the other hand, Whitmore & Freer-Smith (1982) showed that the yield of *Poa pratensis* was reduced overwinter, but recovered the following summer, when exposed continously to mean concentrations of 62 ppb SO_2 + NO_2 (see Fig. 3.1), supporting the idea of greater growth reductions at low temperatures and light intensities.

7.2.4 Growth rate and plant size

Jones & Mansfield (1982a) have suggested that the size of a plant may affect its response to SO_2. They combined the results from two similar experiments and found that the shoot dry weight of *Phleum pratense* cv. S48, exposed to 120 ppb SO_2, was reduced by a greater amount on smaller than on larger plants. These results were obtained from single harvests at the end of two 44 day fumigations at various light intensities and temperatures. Table 7.1 summarises the conditions and results, and includes some similar data from an experiment conducted by Davies (1980a). In all the experiments the plants were 7-10 days old at the start of the fumigation periods, but their weights were not determined and so relative growth rates could not be calculated.

At the end of two fumigations the control plants were similar in size (0.504 and 0.681 g, Table 7.1): in one case there was no effect of 120 ppb SO_2, but there was a 24% reduction in yield in the other. Conversely, there were yield reductions of ~25% after two of the fumigations but the

Table 7.1 : Fumigation of *Phleum pratense* cv. S48 with 120 ppb SO_2 under various environmental conditions.
(From: Davies, 1980a, b; Jones & Mansfield, 1982a)

Irradiance ($\mu E\ m^{-2}\ s^{-1}$)	Daylength (hours)	Tempaerature (^{o}C)		Duration of fumigation(1)	Shoot dry weight (g)		Shoot dry wt as % of control
		Day	Night		Control	120 ppb SO_2	
480	16	20	16	35	0.504	0.507	101
125	12	20	16	35	0.026	0.013	50
400	16	30	19	44	1.964	2.405	122
100	16	30	19	44	0.227	0.171	75
400	16	26	12	44	0.681	0.516	76
100	16	26	12	44	0.078	0.049	63

(1) Plants 7-10 days old at start of fumigation.

weights of the control plants differed by a factor of 3.0. Thus, although plant size tends to affect response to SO_2, the relationship is not clearly defined.

Jones & Mansfield (1982a) also suggested that under the conditions of their experiments growth rates may have been an important factor in determining the results from fumigations with SO_2: the slower the growth rate, the greater the effect of a given concentration of SO_2. If the effect of SO_2 is measured as a reduction in growth rate (either whole plant relative growth rate, RGR, or relative shoot growth rate, RSGR), then if plants in the control treatment are growing slowly one might expect SO_2 to cause a greater reduction in R(S)GR than if the plants in the control treatment were growing fast. Also, if the effect of SO_2 is expressed as the ratio of 'RGR in SO_2'/'RGR in control' then this ratio would decrease with decreasing RGR in the control (for a given SO_2 concentration).

Bell, Rutter & Relton (1979) calculated the RGRs of *L. perenne* cv. S23 during three overwinter fumigations with mean concentrations of 16, 25 and 159 ppb SO_2. The changes in RGR caused by the SO_2 treatments were not obviously related to the RGRs in the control treatments (Fig. 7.1). Mean RSGRs from two experiments with *Phleum pratense* are shown in Tables 7.2 and 7.3. Again the changes in RSGRs in the SO_2 treatments were not obviously related to the RSGRs in the control treatments (compare 'RSGR in control' with 'RSGR in SO_2 as % of control'). It is also interesting to note that in the two experiments quoted in Tables 7.2 and 7.3 the RSGRs differed by more than an order of magnitude. Since they also involved different cultivars and SO_2 concentrations, comparison between the two experiments is difficult, but it appears that RSGR per se is probably not important in determining the effect of SO_2 on grass growth, except under very similar experimental conditions (as illustrated in Table 7.1). (A

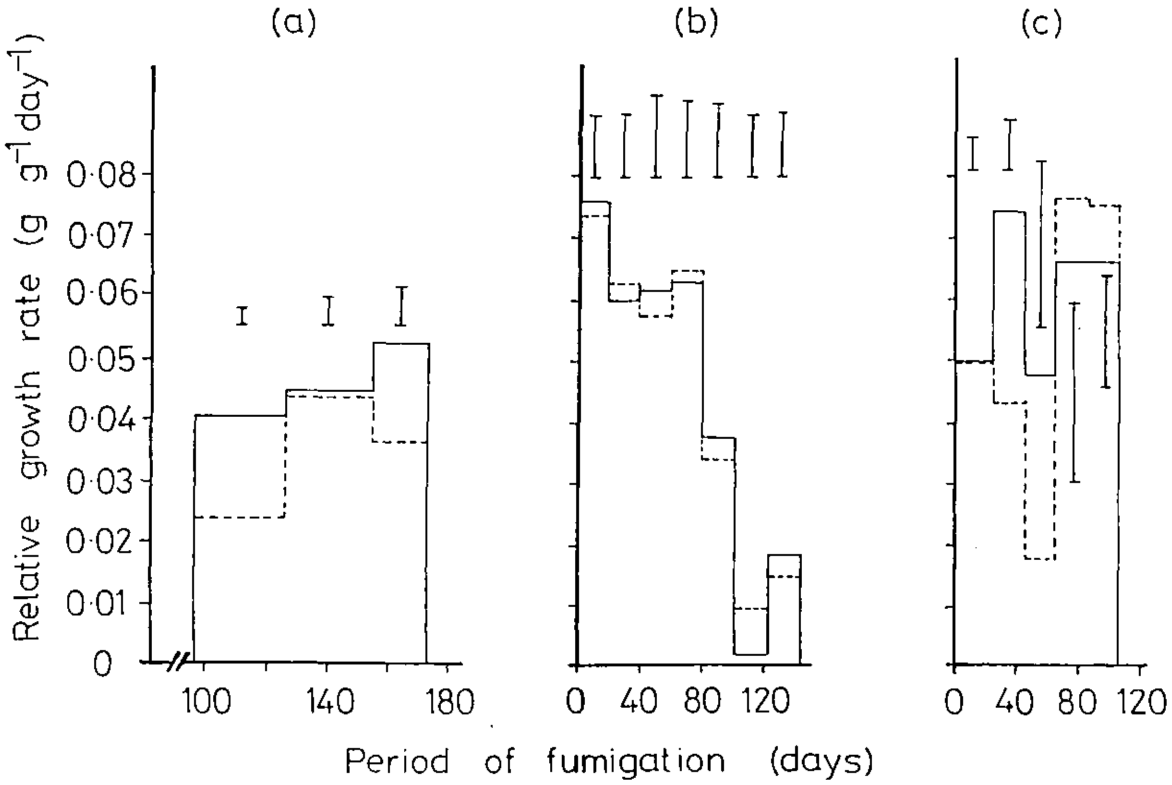


Figure 7.1 : Relative growth rates of *Lolium perenne* cv. S23 after overwinter exposure to SO_2 (-----) or filtered air (———).

SO_2 concentrations were (a) 16 ppb, (b) 25 ppb and (c) 159 ppb.

Bars indicate LSD at p = 0.05

(Redrawn from Bell, Rutter & Relton, 1979)

Table 7.2 : Mean shoot dry weights and estimated relative shoot growth rates of *Phleum pratense* cv. Eskimo, grown over-winter in clean air or 68 ppb SO_2. (Calculated from data in Ashenden & Williams, 1980)

Length of fumigation (days)$^{(1)}$	Shoot dry weight (g)		Shoot dry wt in SO_2 as % of control	Relative shoot growth rate (g g^{-1} day^{-1})$^{(2)}$		RSGR in SO_2 as % of control
	Control	68 ppb SO_2		Control	68 ppb SO_2	
28	0.110	0.063	57	0.0168	0.0270	161
56	0.176	0.134	76	0.0121	0.0105	87
84	0.247	0.180	73	0.0160	0.0101	63
112	0.387	0.239	62	0.0084	0.0096	114
140	0.489	0.313	64			

(1) plants ~35 days old at start of fumigation

(2) estimated as: $(\log_n W_2 - \log_n W_1)/(T_2-T_1)$, where W_n = mean shoot dry weight

Table 7.3 : Mean shoot dry weights and estimated relative shoot growth rates of *Phleum pratense* cv. S48, grown in clean air or 120 ppb SO_2. (From Jones & Mansfield, 1982a)

Length of fumigation (days)(1)	Shoot dry weight (g)		Shoot dry wt in SO_2 as % of control	Relative shoot growth rate ($g\ g^{-1}\ day^{-1}$)(2)		RSGR in SO_2 as % of control
	Control	120 ppb SO_2		Control	120 ppb SO_2	
0	0.00033	0.00036	109	0.249	0.224	90
10	0.0040	0.0034	85	0.203	0.167	82
20	0.0304	0.0180	59	0.175	0.160	97
30	0.175	0.098	56	0.142	0.145	91
40	0.789	0.387	49			

(1) plants ~7 days old at start of fumigation

(2) estimated from their Figure 4.

similar analysis of RSGRs was carried out on data for *Poa pratensis*, *Dactylis glomerata* and *Lolium multiflorum* given by Ashenden (1979b) and Ashenden & Williams (1980): again there were no relationships between RSGRs and the effect of SO_2.)

When R(S)GRs are analysed throughout long-term experiments the results are complicated by two factors: there are changes in plant age (and therefore physiology) and the length of time for which they have been exposed to SO_2 (and therefore of time in which to compensate for SO_2 induced damage, see Jones & Mansfield, 1982a). It is probable that both plant age and RGR are involved in determining the effects of SO_2, but that they interact with other factors, complicating interpretation of all experimental results.

Strictly, relative growth rates cannot be calculated from the experiments in the present work because harvests were carried out by cutting and allowing regrowth. Nevertheless, one can make the assumption that after harvesting, growth will depend, in part at least, on the growth that preceded the harvest (represented by the stubble and roots). Thus a measure of RSGR can be made using cumulative shoot weight as the weight at the start of a growth period, although with the exception of the first growth period after thinning most of the shoot material was removed. Using this technique to provide a rough estimate of RSGR for the Solardomes and Silwood chambers showed no relationship between RSGR in the control treatments and the effects caused by SO_2 and/or NO_2. Some examples are given in Tables 7.4 and 7.5.

Since R(S)GRs are not directly related to the effects of pollutant on yield then growth rates cannot explain the lack of detrimental effects of SO_2 and/or NO_2 found in the present study. As mentioned above, RGRs may interact with other factors (such as plant size, plant age, light intensity

Table 7.4 : Relative shoot growth rates of *L. perenne* cv. S23 grown in the Solardomes, 1981 and 1982.

Growth period	RSGR(1) ($g\ g^{-1}\ day^{-1}$) in each treatment(2)				RSGR in treatment as % of RSGR in control		
	Control	Low	Medium	High	Low	Medium	High
6 Jan.-25 Mar. 1981	0.0174	0.0342	0.0296	0.0310	197	170	178
26 Mar.-11 May 1981	0.0508	0.0397	0.0442	0.0388	78	87	76
12 May-15 June 1981	0.0259	0.0182	0.0245	0.0162	70	95	63
16 June-11 Aug. 1981	0.0088	0.0077	0.0063	0.0079	88	72	90
16 Feb.-23 Mar. 1982	0.0255	0.0156	0.0261	0.0268	61	102	106
24 Mar.-18 May 1982	0.0195	0.0282	0.0239	0.0264	145	123	135
19 May-9 July 1982	0.0227	0.0173	0.0168	0.0150	76	74	66

(1) See text for method used to calculate RSGR.

(2) Approximate pollutant concentrations were: control, 2 ppb SO_2, 7 ppb NO_2; low, 17 ppb SO_2, 18 ppb NO_2; medium, 34 ppb SO_2, 30 ppb NO_2; high, 50 ppb SO_2, 50 ppb NO_2. (See Tables 4.3 and 4.4)

Table 7.5 : Relative shoot growth rates of *L. perenne* cv. S24 grown in the Silwood chambers, 1981 and 1982. (See text for method used to calculate RSGRs)

Growth period	RSGR(1) (g g^{-1} day) in each treatment(2)						RSGR in treatments as % of RSGR in control(s)				
	Control	NO_2	SO_2	SO_2+NO_2	NO	SO_2+NO_2+NO	NO_2	SO_2	SO_2+NO_2	NO	SO_2+NO_2+NO
17 Feb.-3 May 1981	0.041	0.037	0.044	0.041	0.039	0.042	90	107	100	95	102
4 May-8 June 1981	0.032	0.043	0.034	0.039	0.036	0.037	134	106	122	113	116
9 June-4 Aug. 1981	0.011	0.011	0.011	0.012	0.012	0.012	104	96	107	111	109

	Control				SO_2+NO_2				SO_2+NO_2		
	A	B	NO_2	SO_2	A	B	NO_2	SO_2	A	B	
22 Feb-18 Apr. 1982	0.045	0.054	0.043	0.058	0.049	0.054	87	118	99	109	
19 Apr.-9 June 1982	0.027	0.027	0.023	0.019	0.022	0.024	85	70	81	88	

(1) as Table 7.4

(2) Pollutant concentrations varied during each season but were about 35 ppb SO_2, 25 ppb NO_2 and 15 ppb NO. (See Tables 5.5 and 5.6)

etc.) to determine the effect of SO_2 (or NO_2) on growth. This is again an area where detailed study may prove helpful in explaining the results obtained from various experiments.

7.2.5 Species, cultivar and plant age

In Chapter 3 it was noted that the response to SO_2 and/or NO_2 varied between species. Results from the Silwood chambers provided more evidence for this (Chapter 5). Very recently, using the outdoor chambers at Lancaster, Whitmore & Mansfield (1983) exposed individual plants of *Poa pratensis* cv. Monopoly, *Dactylis glomerata* cv. S37, *Phleum pratense* cvs S48 and Eskimo and *Lolium perenne* cvs S23 and S24 to mean concentrations of 62 ppb SO_2 and/or NO_2 for 7 months (October to May). Each cultivar was exposed from emergence or from 42 days old. The effects of pollutants varied between species and age-groups: *D. glomerata* and both cultivars of *P. pratense* were unaffected when exposed from 42 days old (except that NO_2 reduced the yield of *P. pratense* S48), but showed 20-45% reductions in yield in all treatments when exposed from emergence (except that *D. glomerata* was unaffected by NO_2). Both cultivars of *L. perenne* showed the opposite effect, yield reductions of ~20% occurring in all treatments when exposed from 42 days old, but not when exposed from emergence (except that *L. perenne* cv. S23 produced a lower yield in NO_2). The yields of *Poa pratensis* were reduced by pollutants in both age groups, but to a greater extent when exposed from emergence. Unfortunately, only one harvest was carried out and so the progress of each cultivar during winter and spring is not known. Nevertheless, the study again confirmed inter-specific differences, and also showed differences in response depending on the age of the plant at the start of the fumigation, the latter also varying with species.

It is interesting to note that when *L. perenne* cvs S23 and S24 were exposed from emergence there was no effect of 62 ppb SO_2 + NO_2 after 7 months. This was similar to the results from the Solardomes (exposed from emergence) and the Silwood chambers in 1982 (exposed from 7 days old). In the Silwood chambers in 1981, plants of *L. perenne* on S24 were exposed from 52 days old; at the May harvest the yield was reduced by 27% in the presence of 40 ppb SO_2 + 25 ppb NO_2 (Table 5.7). Similarly, Whitmore & Mansfield (1983) found a ~20% reduction in yield of cultivars S23 and S24 exposed from 42 days old (see above). These similarities may be coincidental, and it is not known whether the growth overwinter followed a similar pattern in the two studies, but it does suggest that plants should be exposed from emergence, at least until more is known of the effects of pollutants on very young plants.

Whitmore & Mansfield (1983) have also shown that there are differences between cultivars in their response to pollutants. It was noted above that the yield of *P. pratense* cv. S48 was reduced by 62 ppb NO_2 but that of cv. Eskimo was unaffected when exposed from 42 days old; also the yield of *L. perenne* cv. S23, but not cv. S24, was reduced by NO_2 when exposed from emergence. In a further experiment, Whitmore & Mansfield (1983) again found a difference in response between cultivars to NO_2: the yield of *Poa pratensis* cv. Monopoly was reduced by 36% after exposure to 62 ppb NO_2 for 2 months, whereas *P. pratensis* cv. Arina was unaffected (both cultivars responded similarly to SO_2 and SO_2 + NO_2). Similarly, Elkiey & Ormrod (1981) found that cultivars of *Poa pratensis* differed in the amount of yield reduction caused by 150 ppb SO_2 or 150 ppb SO_2 + 150 ppb NO_2 + 100 ppb O_3, but not by O_3 or NO_2 alone, when exposed for only 10 days.

Clearly, the choice of species and cultivar will affect the response to a given pollutant exposure. However, since a total of 4 species (5 cultivars) was used in the present study, and none showed much evidence for yield reductions, it seems probable that other factors must be important in explaining the difference between the experiments reported here and those which have shown large yield reductions due to SO_2 and/or NO_2.

7.2.6 Swards or spaced plants

Bell (1982) has suggested that swards may be affected differently from spaced plants by SO_2. Inevitably, as swards develop, lower leaves are sheltered by upper leaves of a canopy and the former are therefore exposed to less wind, presumably with a resultant increase in boundary layer resistances (see Section 7.2.1). Two items of circumstantial evidence from the present experiments suggested that sward-formation was not necessarily important in preventing SO_2/NO_2 induced yield reductions. Firstly, when the swards were at their least dense (winter and spring) there were often increases in shoot weight in the presence of SO_2 (Silwood chambers) or SO_2 + NO_2 (Solardomes). Secondly, individual plants of *L. perenne* grown in the Silwood chambers were generally affected to a lesser degree than the swards.

Whitmore & Mansfield (1983) grew 1 or 6 plants of *Poa pratensis* per 7.5 cm pot and exposed them to 62 ppb SO_2 and/or NO_2 or clean air for 8 months from October to June. At harvest the plants grown as swards showed 40, 27 and 43% reductions of shoot dry weight in NO_2, SO_2 and SO_2 + NO_2 respectively, but the individual plants were unaffected by treatment at the June harvest.

Both studies suggest that swards are more likely to be affected by pollutants than individual plants. This is in contrast to the analysis of data on the effects of SO_2 on *L. perenne* cv. S23 which suggested swards were affected less than, or similarly to, spaced plants (Chapter 3, Fig. 3.1).

The swards used in Whitmore & Mansfield's (1983) study were very small, but the soil area per plant was 7.4 cm^2, similar to the ~9.5 cm^2 in the present study. As far as pollutant uptake is concerned, when swards are young they probably behave like spaced plants, and in the Silwood chambers it was not until the first major spring harvest that the plants were large enough to give the appearance of true swards, thus differential effects may have been expected during spring and summer, rather than overwinter. However, it must be remembered that most pollutant effects on yield were found overwinter, with few in the summer.

One other relevant point is that in the Silwood chambers the roots of the swards were more matted at the base and sides of each pot than were the roots of the individual plants. It is possible that this confinement of roots altered the effect of pollutants: for example, the matted roots may have been less efficient at water uptake, resulting in a decrease in stomatal aperture due to drought stress, and a consequent reduction in pollutant uptake (suggesting that swards would be less affected by pollutants than individual plants, the reverse of the observed situation). On the other hand it may also be noted that the roots of the swards in the Solardomes were able to grow freely and the effects of pollutants on shoot yield were broadly similar to those in the Silwood chambers, suggesting that root confinement may not be important in determining the effects of pollutants.

Thus, growing plants as swards, rather than as spaced plants, may affect their response to pollutants, but it appears that it is more likely to increase the yield reduction, rather than reduce it. Planting density, therefore, cannot satisfactorily explain the lack of yield reductions found in the presence of SO_2 (+ NO_2) in the present study.

7.2.7 Soil type and nutrient status

Different types of soil have been shown to affect the response of grass to SO_2 in some cases. For example, Cowling & Lockyer (1976) showed that when plants of *L. perenne* cv. S23 were grown in a S-deficient soil, exposure to 19 ppb SO_2 alleviated sulphur deficiency symptoms, but when sulphate-S was added to the soil exposure to 19 ppb SO_2 had no effect. Similar alleviation of S-deficiency by SO_2 when plants were grown in soils low in S was also reported by Lockyer, Cowling & Jones (1976) and Cowling & Lockyer (1978). On the other hand, Ayazloo, Bell & Garsed (1980) grew *L. perenne* cv. S23 in 'Perlite' and nutrient solutions containing high or low concentrations of sulphur and nitrogen. After exposure to 143 ppb SO_2 for 64 days there were no interactions between the S content of the nutrient solution and the effect of SO_2, and there was only one interaction between N content and SO_2 (after 24 days the number of living leaves was reduced by SO_2 when the plants were grown in low N but not when in high N). Bell *et al.* (1979) grew swards of *L. perenne* cv. S23 on two natural soil types (S content not given) and exposed them to ~50 ppb SO_2 for 72 days but found no interaction between gas treatment and soil type.

In the present study the amount of plant-available sulphur in the soil was not measured. In the Solardomes the soils were presumably not S-deficient since the S contents of the ryegrasses (about 0.5%) were above the deficiency level of ~0.2% (Section 4.4.3). In the Silwood chambers the S contents of the plants were not measured but the original soil mixture contained added sulphate-S (Section 5.2.5) and there were no S-deficiency symptoms, even in the summer after several months growth.

7.2.8 Water vapour pressure deficit and leaf wetness

In the present work, the water vapour pressure deficit (vpd) was not measured inside the Silwood chambers. However, Farrar, Relton & Rutter (1977), using the same Silwood chambers as in the present study, found that the vpd inside the chambers was always higher than ambient (up to

670 Pa higher when there was direct sunlight at an ambient temperature of only 10°C). During the day in the Solardomes, vpd's were generally from 100 to 300 Pa less than ambient in the summer, but the situation was reversed in winter, with vpd's up to 200 Pa greater than ambient. At night, the vpd's were generally within 100 Pa of ambient, both in winter and summer (calculated from data supplied by Dr. T.M. Roberts).

Since most SO_2 enters leaves via stomata, rather than via the cuticle (Black & Unsworth, 1979) the stomatal resistance (r_s) is important in determining the rate of SO_2 entry into a plant, assuming boundary layer resistances are not limiting (Section 7.2.1). Vpd has been shown to affect the r_s of some plants, such that as vpd increases so does r_s (Black & Squire, 1979; Black & Unsworth, 1980). No detailed work on the effects of vpd on r_s appears to have been carried out on the grass species used in the present work, but Black & Squire (1979) note that the stomata of grasses generally do not respond to saturation deficit. However, Sheehy, Windram & Peacock (1977), studying swards of *L. perenne* in the field found that, although there was no strict relationship between vpd and r_s, maximum r_s's occurred when the vpd was relatively high. (It must be noted that since this was a field experiment, many factors other than vpd may have affected r_s.) Thus, since vpd may not affect the r_s of the grass species used in this study, the differences in vpd between ambient air and the chambers may not be important in determining the amount of SO_2 taken up by the plants.

In addition, SO_2 itself affects stomatal opening (Majernik & Mansfield, 1970; Biscoe, Unsworth & Pinckney, 1973). The r_s usually decreased in the presence of SO_2, but in plants whose stomata respond to vpd, SO_2 has been shown to increase r_s at relatively high vpd's, but decrease r_s at low vpd's (Mansfield & Majernik, 1970; Black & Unsworth, 1980). Thus, a higher vpd in chambers than in ambient air could result in a higher r_s due to SO_2 (but only if the stomata of grasses are sensitive to vpd), resulting in lower SO_2 uptake rates. In addition, a higher r_s may limit transpiration (reducing the potential for water stress) and CO_2 exchange (possibly reducing growth). Similarly, a lower vpd in the chambers than in ambient air may have the reverse effects.

It is therefore possible that, in the Silwood chambers and in winter in the Solardomes, the higher than ambient vpd's resulted in lower SO_2 uptake rates, but in the Solardomes in summer the lower than ambient vpd's may have resulted in increased SO_2 uptake rates. Whether any effects of SO_2 on the stomata of grasses are modified by the presence of NO_2 is not known but Ashenden (1979a) found that exposure to 100 ppb SO_2 increased the transpiration rate (and by implication, stomatal aperture) of *Phaseolus vulgaris* for 2-3 days and then had no effect, but that 100 ppb SO_2 + 100 ppb NO_2 had no effect for 1-2 days, after which the transpiration rate increased. Thus, the presence of NO_2 modified the effect of SO_2, but in addition it should be noted that, at least with SO_2 alone, the effects were temporary. Until more is known about the interactions of SO_2 and/or NO_2 with vpd on the stomatal aperture of grasses, the importance of differences in vpd between ambient air and chambers, and between various experiments, cannot be determined.

The importance of the wetness of leaf surfaces has received little attention, although Bell (1983a) has pointed out that the surfaces of leaves are wet for about 30% of the time in Britain. In contrast, during fumigation experiment leaves are wet only occasionally (when watered from above) or perhaps never (when sub-irrigated). Elkiey & Ormrod (1981) exposed three cultivars of *Poa pratensis* to 150 ppb SO_2, 150 ppb NO_2(both continuously) and 100 ppb O_3 (6 hours/day) for 10 days; half the plants were sprayed with deionised water for 5 minutes twice per day. One cultivar (Touchdown) showed a 24% decrease in fresh weight in the pollution treatment when misted but no effect when the foliage remained dry (the other two cultivars showed no differential response to misting). Although the misting treatments employed by Elkiey & Ormrod (1981) were unrealistic (5 minutes at 1000 and 1400 hours), it has been noted by Bell (1983a) that these results suggest moisture may be important, both for comparing results between fumigation experiments and for determining the effects of SO_2 on plants in the field in areas with relatively frequent rainfall.

In the present work, in both the Silwood chambers and the Solardomes, plants were watered from above but the leaf surfaces were wet only for a small proportion of the time (probably < 5%). In other work it is often not stated whether the plants were watered from above or below, but it is reasonable to assume that leaf surfaces were wet for a smaller or similar proportion of time to the present study. Thus, assuming wet leaf surfaces increase the effect of SO_2, then the potential for SO_2 damage will have been increased by the use of watering from above in comparison with experiments using sub-irrigation, but it will have been less than in the field.

7.2.9 Conclusions

From the foregoing discussion it is clear that the response of grass to pollutants is dependent upon many factors which in general are poorly understood. At least to some extent it is probable that these factors interact with each other, so that simple fumigation experiments alone cannot estimate the effects of ambient levels of pollutants on grass species growing in the field. In the fumigation experiments conducted in this study the pollutant concentrations were designed to simulate ambient conditions in a more realistic manner than previously attempted. In addition, grasses were grown as swards in the ground (in the Solardomes) or in pots (at Silwood); in the former the roots were unrestricted whereas in the latter the roots became matted at the base of the pots, but in both cases the shoots were able to grow in conditions similar to those in the field.

In this study, exposure of several grass species to mean concentrations of up to 50 ppb SO_2 + NO_2 produced little evidence that pollutants caused a reduction in yield. This was in contrast to the effects expected on the basis of other workers findings. Reasons for this are largely speculative, but it seems reasonable to suggest that since both the plants' growing conditions and the pollutant concentrations were more realistic than hitherto achieved (in fumigation experiments in chambers), then the results from this study may be regarded as more representative of a field situation than those from experiments using individual plants or unrealistic pollutant treatments. On the other hand, the results reported here must be regarded with some caution for two reasons: firstly, there were differences in microclimate (temperature, light intensity, vapour pressure deficit) within the chambers from those expected in the field (although these differences were very small in the Solardomes), and these are known to affect the response to pollutants. Secondly, pollutant concentrations within the chambers were not the same as in polluted ambient air: this point is discussed further in the next section.

7.3 Filtration Versus Fumigation Experiments

It was noted above (Section 7.1) that filtering ambient air has proved beneficial to grass yield when the mean SO_2 concentrations were ~20 ppb, less than half those generally shown to reduce yield in fumigation experiments. Some of the differences between the conditions used in filtration and fumigation experiments are discussed below.

7.3.1 Microclimate

Like most fumigation experiments, filtration experiments are performed with crops grown in chambers. Environmental conditions other than pollutant concentrations (i.e. the microclimate) may be similar to those in fumigation experiments, but, as in the latter, they will differ slightly from ambient. For example, Crittenden & Read (1978a) found that in their chambers temperatures were usually 3-5°C above ambient, but occasionally reached 10°C higher; saturation deficits were usually greater than in ambient air, but light intensities were about 40% less than ambient. Roberts *et al.* (1983) designed their chambers to minimise the variations of microclimate from ambient: in their chambers, the temperature usually exceeded ambient by < 2°C, relative humidity was very similar to ambient and light intensity only ~20% less than ambient on sunny days (similar to ambient in overcast weather).

Several groups of workers have grown plants in the open, adjacent to the chambers used in their filtration studies, to determine the effect of the chambers themselves on crop growth (i.e. the effect of the change in microclimate). Roberts *et al.* (1983) and Colvill *et al.* (1983), reporting three similar long-term experiments, noted that *L. perenne* grown in the unfiltered chambers tended to yield less than those grown in the open during summer, but overwinter the yields were sometimes greater than ambient. The use of unfiltered chambers has also been shown to reduce growth during summer, compared with outside plots, by Buckenham *et al.* (1982; for *Hordeum vulgare*) and by Howell, Koch & Rose (1979; for *Glycine max*). In contrast, MacLean & Schneider (1976) found that the yields of *Phaseolus vulgaris* were greater in unfiltered chambers than in outside plots. Similarly, Heggestad, Heagle, Bennett & Koch (1980) found some evidence that the presence of chambers increased the yields of *P. vulgaris* compared with outside plots, but generally the yields were unaffected or reduced.

Clearly the use of chambers may affect the yield of crops, presumably due to small differences in microclimate. Therefore, whether the effects of filtering air in chambers are truly representative of the effects of reducing pollutant concentrations in the field is open to debate.

7.3.2 Pollutant concentrations

In filtration experiments, pollutants in the unfiltered chambers are similar to those in ambient air but there is some loss due to adsorption onto the chamber walls etc. (Crittenden & Read, 1978a; Colvill *et al.*, 1983). As a consequence, in the UK at least, SO_2, NO_x and O_3 will probably be present (see Chapter 2), but in some cases other pollutants may be important (e.g. fluoride, Brough *et al.*, 1978; Buckenham *et al.*, 1982). Also, all these pollutants will vary in concentration according to time of day and the weather. Interactions of pollutants with microclimate will therefore be similar to those in the field.

Section 7.2.2 included a discussion of the available information on the effects of fluctuating levels of SO_2, with mean concentrations representative of ambient UK conditions. (There is no similar information for NO_x or O_3.) The importance of realistic variations in the levels of pollutants has not yet been determined, but since it is clear that the effects of a given level of pollutant(s) depend upon environmental conditions it seems reasonable to assume that near-ambient concentrations will give a more realistic result than constant concentrations, or even fluctuating levels that are not related to the weather (as in the present work).

The presence of other pollutants may be of particular importance in explaining differences between fumigation and filtration experiments. In this study, evidence for SO_2 and NO_2 interacting in their effects to reduce the yield of grass species was not found. Assuming this is a true reflection of the field situation, then another pollutant must be responsible for the observed reductions in yield seen in unfiltered air in filtration experiments and the most probable candidate is ozone (Section 3.3).

In the UK, most filtration experiments have been carried out in the summer (when relatively high O_3 concentrations are present) and many have shown yield reductions in unfiltered chambers at very low mean SO_2 concentrations (Table 3.11). However it must also be mentioned that filtered air has improved crop yield overwinter when little O_3 was likely to have been present (Crittenden & Read, 1978b; Bleasdale, 1952).

Bell (1983b) has recently discussed the importance of considering the effects of O_3, both alone and superimposed on a background of SO_2 + NO_2. Only a few experiments have been carried out with SO_2 + NO_2, with and without O_3 present (Table 7.6). In most cases the presence of SO_2 + NO_2 + O_3 produced more damage than SO_2 + NO_2, but only in one case was the effect greater than additive (Fujiwara, Umezawa & Ishikawa, 1973). Wolting (1980) exposed several plant species (*Plantago major, Nicotiana tabacum, Trifolium incarnatum, T. repens, Achillea millefolium, Centaurea pratensis, Lapsana communis* and *Urtica urens*) to low pollutant concentrations, both singly and in combinations (< 40 ppb SO_2, < 45 ppb NO_2 and < 30 ppb O_3). Although full details were not given, the addition of O_3 to SO_2 + NO_2 appears to have had, at most, an additive effect. Mooi (1980) studied the effects of 23-38 ppb SO_2 (24 hours/day), 26-42 ppb NO_2 (day) with 10-20 ppb NO_2 (night), and 23-35 ppb O_3 (12 hours/day) on leaf drop in *Populus* spp. Again full details were not given but O_3 + SO_2 + NO_2 caused more leaf drop than SO_2 + NO_2 and no mention was made of interactive effects.

From this information, the addition of O_3 to a fumigation with SO_2 + NO_2 appears to increase the damage by an amount similar to that caused by O_3 alone. Therefore, it is of interest to know the probable effects of

Table 7.6 : The effects on plants of the addition of O_3 to SO_2 + NO_2 mixtures. (Expanded from Bell, 1983b)

Species	Pollutant concentration (ppb)			Duration of exposure	Parameter measured	Effect of pollutants			Reference
	SO_2	NO_2	O_3			SO_2 + NO_2	O_3	SO_2+NO_2+O_3	
Populus x *interamericana* cv. Donk	21	22	31	42 days	Numbers of fallen leaves	+430% cf. clean air	-	+770% cf. clean air	Mooi, quoted in Bell (1983b)
Pisum sativum	110	210	110	5 hours	% foliar necrosis	0	2%	18%	Fujiwara *et al.* (1973)
Raphanus sativus cv. Cherry Belle	400	400	400	6 hours	% foliar necrosis	11%	45%	57%	Reinert and Gray (1981)
					Hypocotyl dry weight(1)	-11% cf. clean air	-20% cf. clean air	-33% cf. clean air	
Raphanus sativus cv. Cherry Belle	300	300	300	3 hours on each of 9 alternate days	Root dry weight	-35% cf. clean air	-96% cf. clean air	-96% cf. clean air	Reinert and Sanders (1982)
Tagetes patula cv. King Tut (Marigold)	300	300	300	6 hours on each of 9 alternate days	Shoot dry weight	-12% cf. clean air	-19% cf. clean air	-12% cf. clean air	

(1) combined means of two experiments, using 200 ppb or 400 ppb of each of SO_2, NO_2 and O_3; dry weight measured 7 days after fumigation.

ambient UK concentrations of O_3 on the yield of grass species.

Bennett & Runeckles (1977a, b) have exposed *L. multiflorum* to 30 and 90 ppb O_3 for 8 hours per day for 6 weeks in two separate studies. In neither case did 30 ppb O_3 affect dry weight, and in only one study (Bennett & Runeckles, 1977a) did 90 ppb reduce dry weight (by 22%); in the other study (Bennett & Runeckles, 1977b) 90 ppb O_3 had no effect. Horsman, Nicholls & Calder (1980) exposed *L. perenne* cv. Victorian and *D. glomerata* cv. N.Z. grasslands to 90 ppb O_3 for 4 hours/day on 5 days/week. After 34 days the dry weights of the O_3 treated plants were 17% and 21% less than controls for *L. perenne* and *D. glomerata* respectively.

In the UK, mean summer O_3 concentrations are around 30 ppb and hourly means rarely exceed 80 ppb on more than 30 days per summer (Table 2.7). Obviously the experiments above do not typify UK O_3 concentrations, but it must be remembered that O_3 levels rarely go down to zero in summer and it is possible that low levels (20-40 ppb) interspersed with peaks of > 80 ppb (i.e. UK summer levels) may cause yield reductions.

Finally, Williams, Lloyd & Ricks (1971) have suggested that particulates may lodge in stomatal pores, keeping them permanently open and increasing pollutant uptake by leaves. Thus, they suggested that SO_2 (or presumably any pollutant) and particulates may act synergistically, but there are no data showing the effects of SO_2 and particulates singly or in combination to back up this idea.

7.3.3 Conclusions

The yield reductions seen in filtration experiments that are not found in fumigation experiments using similar concentrations of SO_2 + NO_2 may be caused by, (a) the presence of realistic fluctuating SO_2 + NO_2 concentrations with the attendant interactions with microclimate, and/or (b) the presence of additional pollutant(s) probably O_3.

If the presence of chambers affects yield in filtration experiments then the same is probably true for fumigation experiments. Thus, in both cases one is studying the effects of pollutants on crops whose growth is slightly different from that in the field. The significance of this difference must be determined before the effects of ambient levels of pollutants on yield may be defined

7.4 Summary and General Conclusions

In this study, under the conditions used, it was found that up to 50 ppb SO_2 and/or NO_2 did not reduce the shoot yield of several grass species after long-term fumigations. On the contrary, on occasions, particularly in spring, there were increases in shoot yield when mean pollutant concentrations were 18 to 35 ppb. There was some evidence that root growth was reduced as pollutant concentrations increased. SO_2 and NO_2 did not appear to interact in their effects to produce large decreases in shoot or root yield. These findings contrasted with previous studies using mean concentrations of 62-68 ppb SO_2 and/or NO_2 which found large decreases in yield due to pollutants, and in some cases greater than additive effects of SO_2 + NO_2. No single factor appeared to be responsible for the lack of pollutant-induced yield reductions in this study, but it is considered probable that the major reason was the use of fluctuating pollutant concentrations with log-normal distributions.

Filtration experiments conducted by other workers have tended to show an adverse effect of polluted air on yield at lower SO_2 (and presumably NO_2) concentrations than those used in fumigation experiments in this study. It is suggested that this is due to the presence of O_3 or fluctuating concentrations of SO_2 and NO_2 interacting with microclimate. The filtration experiments carried out in this study probably produced no clear pollutant induced effects on yield due to the low mean concentrations of SO_2 and NO_2

experienced.

This study has demonstrated the importance of attempting fumigations with low and fluctuating levels of SO_2 and NO_2 designed to simulate various UK environments. The results obtained were unexpected and suggest that ambient UK levels of SO_2 and NO_2 alone may not be responsible for reducing crop growth; indeed, it is possible that SO_2 and NO_2 may increase yield when present at concentrations below about 35 ppb (conditions typical of most of the UK). On the other hand, O_3 may be of equal or greater importance than SO_2 and NO_2, reducing crop yield, particularly in the summer. Only when many more detailed experiments have been carried out to determine the importance of fluctuating levels of SO_2, NO_2 and O_3 and their interactions with microclimate over long growth periods (more than one year in the case of perennial grasses) will it be possible to assess the reduction in grass yield attributable to ambient levels of pollution.

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APPENDIX 1

A BRIEF DESCRIPTION OF OZONE FORMATION

Ozone occurs naturally in the lower atmosphere at concentrations up to 50 ppb. At these concentrations ozone poses no threat to crops, but at higher concentrations growth reduction (exceeding 60-80 ppb on several days) or visible foliar injury (120 ppb for a few hours) may occur. Ozone concentrations above about 50 ppb may be due to intrusions of stratospheric air into the lower troposphere (Derwent & Eggleton, 1978) or, more frequently, formation of photochemical smog.

Photochemical smog formation is most pronounced on days with strong sunlight because the initial reaction involves nitrogen dioxide absorbing energy and dissociating into nitric oxide and an oxygen atom,

$$NO_2 + \text{light} \rightarrow NO + O \qquad \text{(A1)}$$

The oxygen atom quickly reacts with an oxygen molecule to form ozone,

$$O + O_2 + M \rightarrow O_3 + M \qquad \text{(A2)}$$

where M is another molecule, usually O_2 or N_2, which is required to remove the energy released in forming ozone. However, NO reacts with O_3 to form NO_2,

$$NO + O_3 \rightarrow NO_2 + O_2 \qquad \text{(A3)}$$

Reactions (A1) to (A3) form a cycle, the NO_2 generated in (A3) undergoing photolysis (A1). On their own these reactions form a steady state system and do not explain the build up of ozone that is known to occur in a photochemical episode. In order for this increase in ozone concentration to occur the cycle of reactions (A1) to (A3) must be broken. The initial reactions required to break this cycle involve the production of free radicals from hydrocarbons released by combustion processes or to a lesser extent by biological processes. These free radicals are involved in a series of reactions during part of which NO is converted to NO_2. The outcome of these reactions is that, in air polluted by carbon monoxide or hydrocarbons (released by automobiles in urban areas) and in the presence of sunlight, NO is converted to NO_2 resulting in a rise in NO_2 concentration. This increase in the NO_2:NO ratio results in an increase in ozone levels. The reason for this is that reaction (A3), converting NO to NO_2 using O_3, becomes less probable because NO is being oxidised to NO_2 by reactions involving free radicals but photolysis of NO_2 continues to generate O_3.

In the absence of strong sunlight photochemical smog production will not occur. However, NO will be oxidised to NO_2 by the reaction

$$2NO + O_2 \rightarrow 2NO_2 \qquad \text{(A4)}$$

This reaction is rapid until about 25% of the NO has been converted to NO_2, after which the reaction proceeds slowly (Smith, 1980). It is clear that, assuming a supply of nitrogen oxides and hydrocarbons, the concentrations of ozone, and to some extent of NO_2, depend on strong sunlight. Determination of trends in ozone levels is therefore as uncertain as trends in the weather.

APPENDIX 2

WARREN SPRING 'NATIONAL SURVEY' ANALYSIS

A2.1 Class Code (National Survey site classification)

(from WSL, 1960 et seq.)

The surroundings of the site of each daily instrument are classified by a code according to the following scheme:

A1 Residential area with high-density housing (probably terraced) or with medium-density housing in multiple occupation, in either case surrounded by other built-up areas.

A2 Predominantly A1, but interspersed with some industrial undertakings.

A3 Residential area with high-density housing or medium-density housing in multiple occupation surrounded by or interspersed with other areas with low potential air pollution output (parks, fields, coast).

B1 Residential area with medium-density housing, typically an inner suburb or housing estate, surrounded by other built-up areas.

B2 Predominantly B1, but interspersed with some industrial undertakings.

B3 Residential area with medium-density housing surrounded by or interspersed with areas with low potential air pollution output (parks, fields, coast), or any residential area with low-density housing.

C1 Industrial area without domestic premises.

C2 Industrial area interspersed with domestic premises of high density or in multiple occupation.

D1 Commercial area or one with predominantly central heating.

D2 Small town centre; limited commercial area mixed with old residential housing and possibly minor industry.

E Smoke control area or smokeless zone (the letter to be added to the primary classification).

R Rural community.

O1 Open country but not entirely without source(s) of pollution, e.g. airfields.

O2 Completely open country; no sources within at least ¼ mile.

X Unclassified site, or mixed area.

A2.2 Sites Used in the WSL Analysis

In each case the choice of sites was based on the following criteria:

(1) They should conform to the relevant description given in the text (Section 2.1.1).

(2) They should have provided data from the start of the decade (1968-9) until at least 1976-7 in order to minimise the effect of loss of data from one year to the next.

(3) For urban areas, 2 sites were randomly chosen from each of Birmingham, Manchester and Sheffield and 4 from London; for urban fringe, rural fringe and country areas, all sites conforming to criteria (1) and (2) were included; for Midlands fringe and NW country sites criterion (2) was relaxed.

Urban sites : Smethwick 1 (B2), West Bromwich 12 (D1/E), Manchester 11 (D1/E), Manchester 19 (A3), Sheffield 2 (D1/E), Sheffield 40 (A2), Camberwell 3 (= Camberwell 5) (A2/E), Hackney 7 (A1/E), Kensington 8 (X/E), Kew 1 (B2/E).

Urban fringe sites: Addlestone 1 (D2), Atherton 5 (D2), Birkenhead 4 (B3/E), Blackpool 1 (B3), Bradford 18 (B3/E), Cardiff 13 (B3), Cheadle & Gatley 2 (B3/E), Chigwell 1 (B3/E), Dartford

6 (D2), Halifax 12 (B3), Horsforth 3 (B3/E), Kingston-upon-Hull 15 (B3/E), Leigh 3 (D2/E), Middlesborough 1 (B3/E), Oldham 10 (B3/E), Rayleigh 2 (D2), Stoke-on-Trent 10 (B3/E), Swanley 1 (B3/E), Windsor 4 (B3), Wrexham 6 (B3).

Rural fringe sites: Blackrod 1 (R), Bolton 18 (B3), Fiddler's Ferry 3 (R), Cheshunt 3 (B3), Halton Runcorn 1 (R), Kingsnorth 12 (R), Saddleworth 1 (X), Tilbury & Thurrock 33 (R).

Country sites: (O2): Caenby 1, Cuddington Bridges 1, Dean Moor 1, Kelvedon Hatch 1, Kirkby Underwood 1, Rhydargaeau 1.

(O1): Burton 2, Cambourne 1, Cottam 24, Didcot 6, Ferrybridge 26, Fiddler's Ferry 8, Helmshore 1, Ironbridge 16, Minwear 1, Norton (Runcorn) 1, Ratcliffe 12, Sadberge 1, Sheffield 60.

(R): Cottam 27, Didcot 1, Fawley 20, Kingsnorth 1, Ruskington 1, Thursby 1, Weeley 1.

Midlands fringe sites: Bedworth 4 (D2), Carlton 3 (A2), Halesowen 6 (D2/E), Leamington Spa 8 (B1), Nottingham 2 (D2), Ratcliffe 7 (B3/E), Ratcliffe 11 (R), Sutton Coldfield 6 (B2), Walsall 16 (B3/E).

North-west region country sites: Blackrod 1 (R), Fiddler's Ferry 3 (R), Fiddler's Ferry 7 (O1), Fiddler's Ferry 9 (O1), Fiddler's Ferry 10 (X), Halton 1 (R), Hollingworth 2 (R), Norton (Runcorn) 1 (O1), Helmshore 1 (O1).

A2.3 Method for Calculating 'Derived Mean' Trends

The following method is taken from WSL (1972-76, volume 1, p. 13). For each pair of consecutive years (e.g. 1968 and 1969 or 1969 and

1970) the sites with data available for both years are selected. The arithmetic mean concentration for these sites in each of the two years is found and the difference is obtained. This difference is taken to represent the true difference in SO_2 levels from one year to the next. This difference is calculated for all pairs of years.

The pair of years with the most sites with valid data is assumed to best represent the national average (for that site type). Starting with the concentrations of SO_2 in this pair of years, and using the differences from one year to the next calculated as above, a trend can be produced. In this thesis these trends are referred to as 'derived mean trends'.

APPENDIX 3

DATA PERTAINING TO THE SOLARDOME EXPERIMENTS DESCRIBED IN CHAPTER 4

Table A3.1 : Mean total shoot weight of *L. perenne* cv. S23 grown in Solardomes (1981 and 1982). Data for each harvest and cumulative totals.

Harvest date	TW (mean ± S.E.M.)				LSD(1) p = 0.05
	control	low	medium	high	
6 Jan. 81	5.3	3.8	4.1	4.5	-
26 Mar. 81	21.4 ± 1.1	58.4 ± 3.0	43.6 ± 2.1	53.8 ± 3.8	8.1
12 May 81	201 ± 14	304 ± 25	289 ± 16	266 ± 25	49
16 June 81	328 ± 24	323 ± 25	452 ± 52	244 ± 27	97
11 Aug. 81	349 ± 78	367 ± 80	330 ± 53	316 ± 52	N.S.
Total to:					
12 May 81	222 ± 14	362 ± 23	333 ± 16	320 ± 28	54
16 June 81	550 ± 32	685 ± 42	785 ± 63	564 ± 48	134
11 Aug. 81	900 ± 95	1053 ± 111	1115 ± 102	880 ± 92	N.S.
16 Feb. 82	38.4	47.3	41.4	38.5	-
24 Mar. 82	96 ± 15	83 ± 9	106 ± 20	101 ± 9	N.S.
19 May 82	190 ± 27	320 ± 52	299 ± 52	343 ± 43	70
9 July 82	625 ± 35	573 ± 56	548 ± 36	510 ± 35	N.S.
Total to:					
19 May 82	286 ± 39	403 ± 59	405 ± 68	444 ± 47	80
9 July 82	911 ± 43	976 ± 89	952 ± 63	954 ± 59	N.S.

(1) Least significant difference; - = not calculated; N.S. = no significant differences.

Table A3.2 : Mean total shoot weight of *L. perenne* cv. S24 grown in Solardomes (1981 and 1982). Data for each harvest and cumulative totals.

Harvest date	TW (mean ± S.E.M.)				LSD(1) p = 0.05
	control	low	medium	high	
6 Jan. 81	6.4	5.0	6.0	4.7	-
26 Mar. 81	46.7 ± 2.4	54.9 ± 3.2	64.0 ± 3.1	54.8 ± 3.8	7.4
12 May 81	301 ± 32	419 ± 19	450 ± 40	340 ± 33	57
16 June 81	338 ± 31	366 ± 43	391 ± 44	389 ± 51	N.S.
11 Aug. 81	476 ± 68	501 ± 74	473 ± 47	545 ± 86	N.S.
Total to:					
12 May 81	348 ± 32	474 ± 21	514 ± 42	394 ± 33	55
16 June 81	686 ± 50	840 ± 50	905 ± 73	783 ± 80	132
11 Aug. 81	1162 ± 105	1341 ± 118	1377 ± 108	1328 ± 153	N.S.
16 Feb. 82	50.1	64.7	42.7	47.3	-
24 Mar. 82	88 ± 19	106 ± 13	120 ± 17	97 ± 10	N.S.
19 May 82	336 ± 65	467 ± 48	487 ± 41	441 ± 52	96
9 July 82	457 ± 39	507 ± 70	469 ± 44	443 ± 37	N.S.
Total to:					
19 May 82	425 ± 83	573 ± 58	607 ± 54	538 ± 59	112
9 July 82	882 ± 92	1080 ± 94	1077 ± 49	981 ± 79	N.S.

(1) as Table A3.1

Table A3.3 : Mean total shoot weight of *L. multiflorum* grown in Solardomes (1981 and 1982). Data for each harvest and cumulative totals.

Harvest date	TW (mean ± S.E.M.) g m^{-2}				LSD(1) p = 0.05
	control	low	medium	high	
6 Jan. 81	6.1	7.9	7.6	6.4	-
26 Mar. 81	134 ± 9	118 ± 13	154 ± 16	152 ± 7	N.S.
12 May 81	476 ± 27	516 ± 47	447 ± 30	506 ± 30	N.S.
16 June 81	498 ± 51	516 ± 75	469 ± 52	532 ± 57	N.S.
11 Aug. 81	514 ± 46	631 ± 81	485 ± 52	555 ± 73	N.S.
Total to:					
12 May 81	610 ± 25	635 ± 57	601 ± 41	658 ± 30	N.S.
16 June 81	1107 ± 68	1151 ± 123	1070 ± 77	1189 ± 75	N.S.
11 Aug. 81	1622 ± 108	1782 ± 197	1554 ± 116	1744 ± 138	N.S.
16 Feb. 82	57.2	68.8	55.1	46.9	-
24 Mar. 82	217 ± 34	242 ± 34	189 ± 27	165 ± 28	51
19 May 82	548 ± 64	591 ± 68	588 ± 83	514 ± 69	N.S.
9 July 82	878 ± 89	965 ± 70	925 ± 74	776 ± 67	N.S.
Total to:					
19 May 82	765 ± 98	833 ± 93	777 ± 108	680 ± 96	N.S.
9 July 82	1644 ± 132	1798 ± 122	1702 ± 144	1455 ± 132	N.S.

(1) as Table A3.1

Table A3.4 : Number of plants m^{-2} and total shoot weight $plant^{-1}$ on 11 August 1981 (a) and 9 July 1982 (b), stubble weights are included for the latter harvest.

		Cultivar	Mean ± S.E.M.				LSD(1) p = 0.05
			control	low	medium	high	
(a)	Plants m^{-2}	S23	1030 ± 31	1092 ± 69	1168 ± 53	1007 ± 53	N.S.
		S24	1143 ± 29	1180 ± 31	1237 ± 43	1190 ± 64	N.S.
		Italian	977 ± 51	945 ± 68	980 ± 47	985 ± 31	N.S.
	TW (mg $plant^{-1}$)	S23	873 ± 90	979 ± 89	951 ± 65	874 ± 85	N.S.
		S24	1014 ± 80	1137 ± 97	1114 ± 83	1156 ± 161	N.S.
		Italian	1694 ± 135	1882 ± 152	1616 ± 146	1796 ± 160	N.S.
(b)	Plants m^{-2}	S23	1165 ± 47	1022 ± 69	1150 ± 65	1148 ± 72	N.S.
		S24	1130 ± 89	1120 ± 43	1168 ± 31	1093 ± 36	N.S.
		Italian	940 ± 70	925 ± 35	883 ± 39	865 ± 30	N.S.
	TW (mg $plant^{-1}$)	S23	774 ± 24	972 ± 97	832 ± 45	802 ± 47	N.S.
		S24	791 ± 79	949 ± 80	916 ± 40	853 ± 68	N.S.
		Italian	1755 ± 74	1918 ± 143	1982 ± 179	1614 ± 109	N.S.
	Stubble (g m^{-2})	S23	147 ± 13	125 ± 12	123 ± 6	106 ± 8	20
		S24	130 ± 9	146 ± 14	129 ± 5	125 ± 9	N.S.
		Italian	173 ± 13	182 ± 8	173 ± 16	136 ± 10	31

(1) as Table A3.1

Table A3.5 : %D of plants grown in Solardomes (1980-81).

Cultivar	Harvest date	%D			
		control	low	medium	high
S23	16 June 81	2.4	2.2	1.9	3.9
	11 Aug. 81	9.1	8.0	11.7	8.8
	Total to:				
	11 Aug. 81	4.0	3.4	3.9	4.0
S24	16 June 81	2.0	2.3	2.4	3.1
	11 Aug. 81	15.9	17.6	18.7	24.2
	Total to:				
	11 Aug. 81	6.9	6.4	6.5	10.1
Italian	16 June 81	2.3	2.1	3.2	2.8
	11 Aug. 81	8.7	8.1	10.8	11.7
	Total to:				
	11 Aug. 81	3.6	3.2	4.1	4.2

Table A3.6 : %D of plants grown in Solardomes (1981-82).

Cultivar	Harvest date	%D			
		control	low	medium	high
S23	19 May 82	2.3	6.5	8.8	7.1
	9 July 82	19.2	23.0	18.8	29.3
	Total to:				
	9 July 82	14.2	16.5	14.3	18.4
S24	19 May 82	2.3	4.7	5.2	8.4
	9 July 82	21.9	21.5	25.3	28.0
	Total to:				
	9 July 82	13.7	12.7	13.8	16.6
Italian	19 May 82	3.5	3.4	3.5	3.9
	9 July 82	11.9	12.7	15.1	17.8
	Total to:				
	9 July 82	7.8	8.1	9.8	11.4

Table A3.7 : Number of spikes m^{-2} of plants grown in Solardomes (1980-81).

Cultivar	Harvest date	Number of spikes m^{-2}				LSD(1) p = 0.05
		control	low	medium	high	
S23	16 June 81	665 ± 68	615 ± 35	1092 ± 135	270 ± 62	193
	11 Aug. 81	362 ± 142	205 ± 73	115 ± 24	190 ± 50	N.S.
	Total to:					
	11 Aug. 81	1027 ± 181	820 ± 79	1208 ± 151	460 ± 97	325
S24	16 June 81	763 ± 55	760 ± 57	680 ± 64	680 ± 70	N.S.
	11 Aug. 81	182 ± 48	125 ± 52	93 ± 29	128 ± 36	N.S.
	Total to:					
	11 Aug. 81	945 ± 63	885 ± 91	773 ± 69	808 ± 91	N.S.
Italian	16 June 81	1180 ± 126	1288 ± 145	1113 ± 138	1152 ± 96	N.S.
	11 Aug. 81	1947 ± 126	2202 ± 256	1905 ± 180	1953 ± 155	N.S.
	Total to:					
	11 Aug. 81	3127 ± 224	3490 ± 392	3018 ± 274	3105 ± 232	N.S.

(1) as Table A3.1

Table A3.8 : Number of spikes m^{-2} of plants grown in Solardomes (1981-82).

Cultivar	Harvest date	Number of spikes m^{-2}				LSD(1) p = 0.05
		control	low	medium	high	
S23	19 May 82	0	0	0	0	-
	9 July 82	875 ± 81	1043 ± 135	902 ± 114	880 ± 114	N.S.
S24	19 May 82	1530 ± 314	2105 ± 247	2312 ± 225	1943 ± 206	415
	9 July 82	875 ± 131	910 ± 130	740 ± 48	907 ± 102	N.S.
	Total to:					
	9 July 82	2405 ± 145	3015 ± 332	3052 ± 220	2850 ± 278	N.S.
Italian	19 May 82	672 ± 113	872 ± 122	893 ± 148	695 ± 112	N.S.
	9 July 82	2055 ± 158	2158 ± 214	2298 ± 183	1935 ± 185	N.S.
	Total to:					
	9 July 82	2727 ± 190	3058 ± 273	3190 ± 276	2620 ± 266	N.S.

(1) as Table A3.1

APPENDIX 4

DATA PERTAINING TO THE SILWOOD CHAMBER EXPERIMENTS DESCRIBED IN CHAPTER 5

Table A4.1 : Mean TW (g m^{-2}) of *L. perenne* swards grown in Silwood chambers, 1981 and 1982.

Harvest date	TW m^{-2} (mean ± S.E.M.)						LSD(1) p = 0.05
	Control	NO_2	SO_2	$SO_2 + NO_2$	NO	$SO_2 + NO_2 + NO$	
17 Feb. 81	5.75	4.86	4.33	4.34	5.25	3.90	-
4 May 81	132.0 ± 5.1	81.0 ± 2.6	120.6 ± 8.3	95.3 ± 3.3	100.8 ± 3.8	96.6 ± 8.0	15.6
9 June 81	287 ± 11	295 ± 9	290 ± 14	295 ± 8	273 ± 10	268 ± 10	N.S.
4 Aug. 81	338 ± 8	314 ± 7	343 ± 12	360 ± 10	353 ± 7	345 ± 10	26
Total to:							
9 June 81	419 ± 13	376 ± 10	411 ± 21	390 ± 8	374 ± 12	365 ± 17	39
4 Aug. 81	757 ± 16	690 ± 12	754 ± 25	750 ± 8	727 ± 15	710 ± 22	48

Harvest date	TW m^{-2} (mean ± S.E.M.)						LSD p = 0.05
	Controls				$SO_2 + NO_2$		
	A	B*	NO_2	SO_2*	A	B*	
22 Feb. 82	13.4	8.9	19.7	10.7	15.6	8.9	-
19 Apr. 82	169 ± 6	179 ± 6	217 ± 9	281 ± 20	242 ± 10	190 ± 6	32
9 June 82	492 ± 12	526 ± 12	486 ± 16	527 ± 11	516 ± 13	492 ± 13	N.S.
Total to:							
9 June 82	661 ± 15	704 ± 16	703 ± 20	729 ± 15	743 ± 17	648 ± 15	46

* wind damaged treatments

(1) Least significant differences; '-' indicates not calculated; N.S. = no significant differences.

Table A4.2 : Mean TW (mg plant^{-1}) of individual plants of *L. perenne* grown in Silwood chambers).

Harvest date	TW plant^{-1} (mean ± S.E.M.)						LSD$^{(1)}$ p = 0.05
	Controls				SO_2 + NO_2		
	A	B*	NO_2	SO_2*	A	B*	
22 Feb. 82	9.72 ± 0.83	-	15.87 ± 1.36	8.12 ± 0.98	10.95 ± 1.17	9.66 ± 1.28	-
19 Apr. 82	229 ± 29	230 ± 34	263 ± 28	236 ± 49	195 ± 24	278 ± 26	N.S.
9 June 82	2174 ± 78	2217 ± 107	2195 ± 57	2034 ± 61	2315 ± 109	2242 ± 62	N.S.
Total to:							
9 June 82	2403 ± 90	2447 ± 132	2458 ± 73	2270 ± 87	2511 ± 127	2520 ± 82	N.S.

*, (1) as Table A4.1.

Table A4.3 : Mean TW (g m^{-2}) of *P. pratense* swards grown in Silwood chambers, 1981 and 1982.

Harvest date	TW m^{-2} (mean ± S.E.M.)						LSD p = 0.05
	Control	NO_2	SO_2	SO_2 + NO_2	NO	SO_2 + NO_2 + NO	
4 Mar. 81	3.02	3.26	3.09	3.27	3.78	3.71	-
7 May 81	77.3 ± 3.1	79.0 ± 3.7	92.4 ± 4.5	83.8 ± 2.9	52.4 ± 1.7	96.4 ± 4.3	9.9
8 June 81	323 ± 10	365 ± 14	335 ± 12	302 ± 9	311 ± 12	300 ± 10	32
1 Aug. 81	516 ± 16	462 ± 13	529 ± 21	501 ± 17	516 ± 19	556 ± 15	48
<u>Total to:</u>							
8 June 81	400 ± 11	444 ± 16	427 ± 14	386 ± 11	363 ± 13	396 ± 11	36
1 Aug. 81	916 ± 20	907 ± 23	956 ± 27	887 ± 18	879 ± 27	953 ± 15	N.S.

Harvest date	TW m^{-2} (mean ± S.E.M.)						LSD p = 0.05
	Controls				SO_2 + NO_2		
	A	B*	NO_2	SO_2*	A	B*	
19 Feb. 82	7.81	7.60	9.90	4.55	7.41	5.01	-
22 Apr. 82	138 ± 4	162 ± 6	176 ± 6	168 ± 7	165 ± 6	140 ± 5	16
17 June 82	755 ± 18	954 ± 18	957 ± 16	882 ± 22	956 ± 23	879 ± 21	56
<u>Total to:</u>							
17 June 82	892 ± 18	1116 ± 23	1133 ± 18	1050 ± 24	1121 ± 26	1019 ± 22	61

*, (1) as Table 4.1

Table A4.4 : TW (g m^{-2}) of *D. glomerata* swards grown in Silwood chambers.

Harvest date	TW m^{-2} (mean ± S.E.M.)						LSD(1) p = 0.05
	Controls				SO_2 + NO_2		
	A	B*	NO_2	SO_2*	A	B*	
28 Jan. 82	2.54	2.68	2.51	2.68	2.17	2.59	-
11 May 82	111 ± 7	120 ± 7	136 ± 6	138 ± 6	151 ± 7	160 ± 8	19
30 June 82	449 ± 14	489 ± 15	470 ± 14	451 ± 12	490 ± 11	519 ± 11	36
Total to:							
30 June 82	560 ± 17	609 ± 17	606 ± 16	589 ± 12	641 ± 12	679 ± 15	43

*, (1) as Table A4.1

Table A4.5 : Number of tillers plant^{-1} and TW tiller^{-1} for *L. perenne* swards in Silwood chambers, 1981.

Parameter	Harvest date	Control	NO_2	SO_2	SO_2 + NO_2	NO	SO_2 + NO_2 + NO
Tillers plant^{-1}	4 May 81	6.46 ± 0.15(1) 100(2) a(3)	5.75 ± 0.06 89 b	6.02 ± 0.17 93 b	6.00 ± 0.11 93 b	5.68 ± 0.09 88 b	5.89 ± 0.17 91 b
	9 June 81	11.0 ± 0.3 100 a	12.4 ± 0.3 113 bc	11.0 ± 0.2 100 a	12.6 ± 0.3 114 c	11.8 ± 0.3 108 b	12.2 ± 0.2 111 bc
	4 Aug. 81	13.7 ± 0.4 100 a	14.1 ± 0.4 104 ab	14.9 ± 0.3 109 bc	15.4 ± 0.3 113 cd	15.8 ± 0.3 116 d	14.7 ± 0.3 108 bc
TW tiller^{-1} (mg)	4 May 81	21.5 ± 0.7 100 a	14.9 ± 0.5 69 d	20.7 ± 1.0 96 ab	16.7 ± 0.5 78 cd	18.7 ± 0.6 87 bc	16.9 ± 0.9 78 c
	9 June 81	27.6 ± 1.0 100 a	25.5 ± 1.3 93 ab	28.0 ± 1.5 101 a	25.0 ± 1.1 91 ab	24.8 ± 1.1 90 ab	23.3 ± 0.8 85 b
	4 Aug. 81	26.3 ± 0.7 100 -	23.6 ± 0.7 90 -	24.3 ± 0.8 93 -	24.8 ± 0.7 94 -	23.9 ± 0.7 91 -	24.9 ± 0.8 95 -
	Total to:						
	9 June 81	49.1 ± 1.3 100 a	40.4 ± 1.4 82 b	48.7 ± 2.3 99 a	41.7 ± 1.2 85 b	43.5 ± 1.6 88 b	40.2 ± 1.5 82 b
	4 Aug. 81	75.4 ± 1.7 100 a	64.0 ± 1.9 85 b	73.0 ± 2.5 97 a	66.5 ± 1.3 88 b	67.3 ± 2.1 89 b	65.2 ± 1.3 86 b

(1) mean ± S.E.M.

(2) mean as % of control

(3) means above the same letter are not significantly different at $p = 0.05$; '-' = no significant differences

Table A4.6 : Number of tillers plant^{-1} and TW tiller^{-1} for *P. perenne* swards in Silwood chambers, 1982.

Parameter	Harvest date	Controls		NO_2	SO_2*	SO_2 + NO_2	
		A	B*			A	B*
Tillers plant^{-1}	19 Apr. 82	9.0 ± 0.2(1) 98(2) a(3)	9.3 ± 0.2 102 ab	9.0 ± 0.2 99 a	10.3 ± 0.4 113 c	9.9 ± 0.2 108 bc	8.8 ± 0.2 97 a
	9 June 82	11.3 ± 0.3 94 a	12.8 ± 0.4 106 cd	12.0 ± 0.3 100 abc	13.4 ± 0.7 112 d	11.6 ± 0.3 97 ab	12.5 ± 0.4 104 bcd
TW tiller^{-1} (mg)	19 Apr. 82	20.5 ± 0.9 90 a	25.0 ± 0.7 110 bc	25.0 ± 0.9 110 bc	26.8 ± 1.0 118 c	24.4 ± 0.9 107 b	21.6 ± 0.5 95 a
	9 June 82	47.6 ± 1.3 94 ab	53.5 ± 1.4 106 cd	42.3 ± 1.2 84 a	54.4 ± 1.4 108 d	47.6 ± 1.7 94 ab	48.5 ± 1.8 96 bc
	Total to: 9 June 82	68.1 ± 1.8 93 a	78.5 ± 1.7 107 b	67.4 ± 1.5 92 a	81.2 ± 2.1 111 b	72.0 ± 2.1 98 a	701.1 ± 1.8 96 a

* wind damaged treatments

(1) - (3) as Table A4.5

Table A4.7 : Number of tillers plant^{-1} and TW tiller^{-1} for individual plants of *L. perenne* in Silwood chambers, 1982.

Parameter	Harvest date	Controls		NO_2	SO_2*	SO_2 + NO_2	
		A	B*			A	B*
Tillers plant^{-1}	12 Apr. 82	14.6 ± 1.3(1) 101(2) -(3)	14.3 ± 1.4 99 -	17.3 ± 1.1 120 -	14.3 ± 1.2 99 -	15.4 ± 0.8 107 -	15.8 ± 1.1 109 -
	9 June 82	31.3 ± 1.9 104 -	28.6 ± 2.1 96 -	33.7 ± 2.0 113 -	33.2 ± 3.4 111 -	37.9 ± 2.8 127 -	32.1 ± 1.9 107 -
TW tiller^{-1} (mg)	19 Apr. 82	15.8 ± 1.6 100 -	15.6 ± 2.2 100 -	15.6 ± 1.6 99 -	17.1 ± 3.5 109 -	12.8 ± 1.5 81 -	18.1 ± 1.6 115 -
	9 June 82	73.9 ± 5.2 94 -	83.2 ± 6.1 106 -	68.4 ± 3.8 87 -	66.5 ± 5.2 85 -	69.0 ± 7.1 88 -	73.3 ± 4.2 93 -
	Total to: 9 June 82	89.7 ± 6.1 95 -	98.9 ± 7.6 105 -	84.0 ± 4.7 89 -	83.6 ± 6.3 89 -	81.8 ± 8.2 87 -	91.4 ± 5.4 97 -

* wind damaged treatments

(1)-(3) as Table A4.5

Table A4.8 : Number of tillers plant^{-1} and TW tiller^{-1} for *P. pratense* swards in Silwood chambers, 1981.

Parameter	Harvest date	Control	NO_2	SO_2	$SO_2 + NO_2$	NO	$SO_2 + NO_2 + NO$
Tillers plant^{-1}	7 May 81	1.28 ± 0.04(1) 100(2) ab(3)	1.39 ± 0.06 109 b	1.33 ± 0.06 104 ab	1.35 ± 0.04 105 ab	1.14 ± 0.03 89 c	1.24 ± 0.04 97 ac
	8 June 81	3.46 ± 0.10 100 –	3.56 ± 0.12 103 –	3.34 ± 0.12 97 –	3.43 ± 0.08 99 –	3.22 ± 0.11 93 –	3.37 ± 0.10 97 –
	1 Aug. 81	4.51 ± 0.12 100 –	4.30 ± 0.11 95 –	4.16 ± 0.11 92 –	4.32 ± 0.11 96 –	4.37 ± 0.14 97 –	4.11 ± 0.12 91 –
TW tiller^{-1} (mg)	7 May 81	64.8 ± 2.2 100 a	61.0 ± 2.8 94 a	73.5 ± 2.7 113 b	66.3 ± 2.0 102 ab	48.7 ± 1.9 75 d	81.9 ± 3.0 126 c
	8 June 81	101 ± 4 100 –	113 ± 3 111 –	110 ± 7 109 –	94 ± 4 93 –	104 ± 6 103 –	96 ± 5 95 –
	1 Aug. 81	125 ± 7 100 ab	118 ± 5 94 a	136 ± 6 109 bc	124 ± 4 99 ab	129 ± 7 103 ab	147 ± 6 118 c
	Total to:						
	8 June 81	166 ± 5 100 abc	174 ± 7 105 bc	183 ± 8 110 c	160 ± 5 96 ab	153 ± 7 92 a	178 ± 5 107 bc
	1 Aug. 81	291 ± 11 100 a	292 ± 10 100 a	319 ± 9 110 b	284 ± 6 98 a	281 ± 12 97 a	325 ± 7 112 b

(1) - (3) as Table A4.5

Table A4.9 : Number of tillers plant^{-1} and TW tiller^{-1} for *P. pratense* swards in Silwood chambers, 1982.

Parameter	Harvest date	Controls		NO_2	SO_2*	$SO_2 + NO_2$	
		A	B*			A	B*
Tillers plant^{-1}	22 Apr. 82	3.19 ± 0.10(1) 97(2) a(3)	3.36 ± 0.09 103 ab	3.72 ± 0.08 113 cd	3.47 ± 0.08 106 bc	3.89 ± 0.10 119 d	3.14 ± 0.09 96 a
	17 June 82	3.68 ± 0.12 101 a	3.64 ± 0.08 99 a	4.15 ± 0.06 113 b	4.14 ± 0.11 113 b	3.92 ± 0.13 108 ab	4.12 ± 0.10 113 b
TW tiller^{-1}	22 Apr. 82	46.9 ± 1.4 95 ab	51.4 ± 1.4 105 bc	50.1 ± 1.7 102 bc	51.8 ± 2.2 105 c	45.0 ± 1.3 91 a	48.5 ± 2.1 99 abc
	17 June 82	224 ± 8 89 a	282 ± 7 111 c	243 ± 6 96 ab	231 ± 11 91 a	262 ± 9 103 bc	233 ± 8 92 a
	Total to: 17 June 82	271 ± 9 90 a	334 ± 8 110 c	293 ± 5 97 ab	282 ± 12 93 a	307 ± 9 101 b	281 ± 7 93 a

* wind damaged treatments

(1)-(3) as Table A4.5

Table A4.10 : Number of tillers plant^{-1} and TW tiller^{-1} for *D. glomerata* swards in Silwood chambers, 1982.

Parameter	Harvest date	Controls A	Controls B*	NO_2	SO_2*	$SO_2 + NO_2$ A	$SO_2 + NO_2$ B*
Tillers plant^{-1}	11 May 82	6.14 ± 0.10$^{(1)}$ 103$^{(2)}$ bc$^{(3)}$	5.83 ± 0.11 97 a	5.97 ± 0.10 100 ab	6.12 ± 0.09 103 abc	6.11 ± 0.11 102 abc	6.40 ± 0.12 107 c
	30 June 82	6.83 ± 0.14 100 -	6.86 ± 0.13 100 -	6.93 ± 0.12 101 -	6.59 ± 0.18 96 -	7.06 ± 0.17 103 -	6.72 ± 0.13 98 -
TW tiller^{-1}	11 May 82	19.1 ± 1.0 93 a	21.7 ± 1.3 107 ab	24.3 ± 1.1 119 bc	24.0 ± 0.9 117 bc	26.3 ± 1.4 129 c	26.3 ± 1.1 129 c
	30 June 82	71.2 ± 2.4 96 a	76.8 ± 2.6 104 ab	73.0 ± 3.0 99 a	75.1 ± 3.0 102 a	75.4 ± 2.6 102 a	83.4 ± 2.5 113 b
	Total to:						
	30 June 82	90.3 ± 2.5 96 a	98.5 ± 3.3 104 ab	97.2 ± 3.4 103 ab	99.1 ± 3.3 105 ab	101.7 ± 3.4 108 bc	109.7 ± 3.1 116 c

* wind damaged treatments

(1)-(3) as Table A4.5

Table A4.11 : %D in Silwood chambers, 1982: (a) *L. perenne* swards, (b) *L. perenne*, individual plants, (c) *P. pratense*, (d) *D. glomerata*.

	Harvest date	%D Controls A	Controls B*	NO_2	SO_2*	$SO_2 + NO_2$ A	$SO_2 + NO_2$ B*
(a)	19 Apr. 82	3.98	3.33	5.35	3.46	6.06	5.11
	9 June 82	6.98	3.79	4.75	6.18	6.49	6.47
	Total to:						
	9 June 82	6.23	3.70	4.94	5.48	6.41	6.15
(b)	19 Apr. 82	0.45	0.35	0.75	0.32	1.53	0.81
	9 June 82	2.65	0.71	1.10	5.55	2.06	3.41
	Total to:						
	9 June 82	1.95	0.63	0.93	3.97	1.55	2.53
(c)	22 Apr. 82	2.19	2.50	2.34	14.01	21.35	22.07
	17 June 82	7.62	6.97	7.23	9.61	8.67	13.56
	Total to:						
	17 June 82	6.82	6.30	6.50	10.34	10.59	14.66
(d)	11 May 82	7.01	11.50	8.31	27.83	20.83	25.17
	30 June 82	7.61	4.97	7.94	11.99	11.33	11.26
	Total to:						
	30 June 82	7.60	6.44	8.05	15.80	13.49	14.56

* wind damaged treatments

Table A4.12 : Number of spikes on *L. perenne* in Silwood chambers, (a) swards 1981, (b) swards 1982, (c) individual plants.

(a)

Harvest date	No. spikes m^{-2} (mean ± S.E.M.)						$LSD^{(1)}$ p = 0.05
	Control	NO_2	SO_2	$SO_2 + NO_2$	NO	$SO_2 + NO_2 + NO$	
9 June 81	721 ± 62	391 ± 33	523 ± 54	521 ± 50	417 ± 32	425 ± 44	132
4 Aug. 81	24 ± 12	42 ± 13	42 ± 11	48 ± 14	69 ± 16	48 ± 15	N.S.
Total to:							
4 Aug. 81	745 ± 61	433 ± 35	565 ± 54	568 ± 52	486 ± 34	473 ± 41	131

(b)

Harvest date	No. spikes m^{-2} (mean ± S.E.M.)						LSD p = 0.05
	Controls				$SO_2 + NO_2$		
	A	B*	NO_2	SO_2*	A	B*	
9 June 82	2441 ± 86	2307 ± 73	1892 ± 80	2297 ± 95	2127 ± 95	2024 ± 90	241

(c)

Harvest date	No. spikes $plant^{-1}$ (mean ± S.E.M.)						LSD p = 0.05
	Controls				$SO_2 + NO_2$		
	A	B*	NO_2	SO_2*	A	B*	
9 June 82	8.1 ± 0.5	8.1 ± 0.7	8.4 ± 0.6	7.5 ± 0.7	7.6 ± 0.7	7.4 ± 0.6	N.S.

*, (1) as Table A4.1

Table A4.13 : Number of spikes m^{-2} on *P. pratense* swards in Silwood chambers, 1981 and 1982.

Harvest date	No. spikes m^{-2} (mean ± S.E.M.)						LSD$^{(1)}$ p = 0.05
	Control	NO_2	SO_2	SO_2 + NO_2	NO	SO_2 + NO_2 + NO	
8 June 81	82 ± 18	116 ± 26	214 ± 37	124 ± 20	40 ± 12	124 ± 20	66
1 Aug. 81	7.9 ± 4.3	15.9 ± 6.7	2.6 ± 2.6	10.6 ± 4.8	7.9 ± 4.3	7.9 ± 4.3	N.S.
Total to:							
1 Aug. 81	90 ± 18	132 ± 28	217 ± 38	135 ± 21	48 ± 14	132 ± 19	69

Harvest date	No. spikes m^{-2} (mean ± S.E.M.)						LSD p = 0.05
	Controls				SO_2 + NO_2		
	A	B*	NO_2	SO_2*	A	B*	
17 June 82	772 ± 18	824 ± 15	840 ± 21	764 ± 23	785 ± 22	764 ± 24	57

*, (1) as Table A4.1

Table A4.14 : RW, cumulative TW and TW/RW at final harvest of *L. perenne*, 1982: (a) swards, (b) individual plants.

	Parameter	Mean ± S.E.M.						LSD(1) p = 0.05
		Controls				$SO_2 + NO_2$		
		A	B*	NO_2	SO_2*	A	B*	
(a)	RW (g m^{-2})	287 ± 35	255 ± 34	313 ± 35	235 ± 25	322 ± 36	311 ± 51	N.S.
	TW to June	851 ± 34	846 ± 47	916 ± 65	923 ± 50	928 ± 16	823 ± 21	N.S.
	TW/RW	3.03 ± 0.39	3.37 ± 0.26	2.99 ± 0.44	3.87 ± 0.26	2.90 ± 0.29	2.94 ± 0.60	N.S.
(b)	RW (mg pl^{-1})	1227 ± 68	1122 ± 93	1371 ± 63	1156 ± 85	1192 ± 79	1306 ± 67	N.S.
	TW to June	2842 ± 119	2982 ± 181	3193 ± 130	2975 ± 179	2992 ± 156	3264 ± 153	N.S.
	TW/RW	2.56 ± 0.18	2.73 ± 0.14	2.35 ± 0.09	2.62 ± 0.12	2.58 ± 0.17	2.53 ± 0.14	N.S.

*, (1) as Table A4.1

APPENDIX 5

ANALYSIS OF NO_2 USING DIFFUSION TUBES

The following account is based very largely on that given by Atkins *et al.* (1978) and is produced here for convenience.

A5.1 Calculation of the Sampling Rate

The amount of NO_2 diffusing unidirectionally through air in a tube is given as:

$$Q = \frac{D\,c\,a\,t}{l}$$

where Q = quantity of NO_2 transferred in t seconds

c = concentration of NO_2 (moles cm^{-3})

D = molecular diffusion coefficient of NO_2 in air (= 0.154 cm^2 sec^{-1})

a = cross-sectional area of tube (cm^2)

t = time (seconds)

l = length of tube (cm)

If c = 1 ppm (0.0416 x 10^{-9} g moles NO_2 cm^{-3} at 20°C and 1 atmosphere pressure) and for a tube 7 cm long and 1.2 cm internal diameter then,

$$Q = \frac{0.154 \times 0.0416 \times 1.131 \times 3600}{7} \times 10^{-9}$$

$$= 3.73 \times 10^{-9} \text{ g moles ppm}^{-1}\text{ hr}^{-1}$$

At 1 ppm, for 3.73 x 10^{-9} g moles hr^{-1} to be sampled then 3.73 x 10^{-3} g moles air hr^{-1} must be sampled. Since 1 g mole air occupies 24040 cm^3 (at 20°C and 1 atm.) then this is equivalent to 90 cm^3 air per hour.

A5.2 Analysis of the NO_2 Collected on the Gauze

Since the NO_2 absorbed by the TEA on the gauze is converted to nitrite (NO_2^-) the concentration of NO_2 is determined by measuring NO_2^- using a variation of the Greiss diazotization method: nitrite ion diazotizes sulphanilamide in orthophosphoric acid solution and the diazonium salt produced is coupled with N-1- napthyl ethylene diamine to give a purple-red azo dye. Two reagents are required:

(1) Sulphanilamide (20 g) and 50 ml AR orthophosphoric acid (sp. gr. 1.8) dissolved in distilled water and made up to 1 litre.

(2) 1.4 g N-1- napthyl ethylene diamine dihydrochloride (NEDA) dissolved in 1 litre distilled water.

Both reagents were made up in 250 ml quantities and kept in a refrigerator.

The diffusion tubes were placed gauze downwards in a rack and 1.5 ml distilled water added. The tubes were shaken and allowed to stand for about 30 minutes to extract the nitrite. Following this, 1.5 ml of reagent (1) and 0.15 ml of (2) were added, the tubes were shaken and allowed to stand for a minimum of 30 minutes to allow the azo dye to develop full colour intensity. The optical density was measured at 520 nm. A calibration curve using 0-4 ppm AR sodium nitrite was also prepared.

From the NO_2^- concentration, the sampling rate and the duration of exposure the NO_2 concentration may be simply calculated.

APPENDIX 6

DATA PERTAINING TO THE FILTRATION EXPERIMENTS DESCRIBED IN CHAPTER 6

Table A6.1 : *L. perenne* cv. S24 grown in filtered and unfiltered chambers 1980-81. Means for each parameter in each chamber at the final harvest.

Parameter	Filtered		Unfiltered	
	4	3	2	1
Plants m^{-2}	1090	987	1113	1090
Tillers m^{-2}	7134	6672	7752	7881
Tillers $plant^{-1}$	6.57	6.84	6.97	7.30
TW (g m^{-2})	296	235	399	381
TW (mg $plant^{-1}$)	270	240	364	353
TW (mg $tiller^{-1}$)	41.2	34.9	52.0	48.1

Table A6.2 : *L. perenne* cv. S24 grown in filtered and unfiltered chambers 1981-82. Means for each parameter in each chamber at the final harvest.

Parameter	Filtered		Unfiltered	
	1	2	3	4
Plants m^{-2}	1252	1193	1311	1212
Tillers m^{-2}	7750	7289	8231	7423
Tillers $plant^{-1}$	6.21	6.13	6.28	6.13
LW g m^{-2}	396	460	478	426
DW g m^{-2}	37	56	61	42
TW g m^{-2}	469	532	568	475
LW mg $plant^{-1}$	321	385	353	352
DW mg $plant^{-1}$	30	47	45	35
TW mg $plant^{-1}$	379	448	432	393
LW mg $tiller^{-1}$	53	65	59	57
DW mg $tiller^{-1}$	5.0	8.0	7.5	5.6
TW mg $tiller^{-1}$	61	73	69	64
%D$^{(1)}$	8.67	10.94	11.20	9.05

(1) back transformed after arcsine conversion

Table A6.3 : *H. vulgare* cv. Maris otter grown in filtered and unfiltered chambers 1980-81. Means for each parameter in each chamber at the final harvest.

Parameter	Filtered		Unfiltered	
	4	3	2	1
Plants m^{-1}	36.1	34.1	35.1	34.9
Tillers m^{-1}	171	155	186	191
Tillers $plant^{-1}$	4.74	4.54	5.31	5.50
LW g m^{-1}	15.6	14.7	16.8	17.2
DW + SW g m^{-1}	17.1	14.2	18.3	18.6
TW g m^{-1}	32.7	28.8	35.0	35.8
LW mg $plant^{-1}$	433	433	478	494
DW + SW mg $plant^{-1}$	474	418	521	536
TW mg $plant^{-1}$	908	850	999	1030
LW mg $tiller^{-1}$	93	95	89	91
DW + SW mg $tiller^{-1}$	101	92	97	98
TW mg $tiller^{-1}$	194	188	186	189
%D+S(1)	51.8	48.3	51.9	51.9

(1) back transformed after arcsine conversion

Table A6.4 : *H. vulgare* cv. Maris otter grown in filtered and unfiltered chambers 1981-82. Means for each parameter in each chamber at the final harvest.

Parameter	Filtered		Unfiltered	
	1	2	3	4
Plants m^{-1}	33.8	35.9	35.9	35.6
Tillers m^{-1} - small	82	84	74	81
- large	105	100	100	102
- total	187	184	174	183
Tillers $plant^{-1}$ - small	2.41	2.34	2.06	2.30
- large	3.11	2.79	2.78	2.86
- total	5.52	5.13	4.84	5.16
LW g m^{-1}	10.3	10.2	10.7	10.4
DW g m^{-1}	7.5	8.3	7.7	7.1
SW g m^{-1}	34.7	39.9	37.1	28.9
DW + SW g m^{-1}	42.1	48.2	44.8	36.0
TW g m^{-1}	52.4	58.5	55.5	46.4
LW g $plant^{-1}$	305	286	300	294
DW g $plant^{-1}$	221	233	214	200
SW g $plant^{-1}$	1027	1117	1034	813
DW + SW g $plant^{-1}$	1248	1350	1249	1014
TW g $plant^{-1}$	1554	1636	1548	1308
LW g $tiller^{-1}$	56	56	62	57
DW g $tiller^{-1}$	40	46	45	39
SW g $tiller^{-1}$	186	218	215	159
DW + SW g $tiller^{-1}$	226	264	259	198
TW g $tiller^{-1}$	282	320	321	255
%D(1)	14.1	14.3	13.8	15.4
%D+S(1)	77.4	80.6	82.4	80.3

(1) back transformed after arcsine conversion