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# Long-Term Effects of Sulphur Dioxide on Crops: An Analysis of Dose-Response Relations

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## Long-term effects of sulphur dioxide on crops: an analysis of dose–response relations

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Research into the effects of long-term SO<sub>2</sub> exposures on crop growth in the absence of visible foliar injury has progressed to a point where the data are being examined for (a) threshold concentrations that avoid damage and (b) dose–response relations that assist cost–benefit analysis of emission control. The data from 125 exposures of 21 crops to constant concentrations of SO<sub>2</sub> alone in chambers have been analysed with a view to identifying threshold values and dose–response relations. The most appropriate functional form for the dose–response relation was a linear regression between SO<sub>2</sub> concentration and percentage yield loss. The correlation was not improved by a number of transformations of either variable, nor by normalizing for duration of exposure. Exclusion of the studies with chambers using low airflows did not significantly alter the regression equations, but did result in a substantial improvement in the correlation between SO<sub>2</sub> and yield loss.

This analysis confirms that there is considerable variability in response between species and both between and within different exposure chambers. Reasons for the differences between chambers are discussed with reference to recent information on the effect of restricted SO<sub>2</sub> flux, growth rate, plant age and other stresses on responses to long-term SO<sub>2</sub> exposures.

Recent research has focused on the interactions between SO<sub>2</sub> exposure and other stresses particularly pests and diseases, frost injury, wind, frequent cutting, nutrient deficiency and possibly drought. The effects of long-term exposures to SO<sub>2</sub> in outdoor chambers were greatest over winter when the metabolic capacity to de-toxify SO<sub>2</sub> absorbed during periods of slow growth was limited by low temperatures and low irradiance. The lower sensitivity of crops to SO<sub>2</sub> under optimal conditions of indoor chambers may also be because of the reduced intensity of other stresses.

Dose–response relations used in recent cost–benefit analysis of sulphur oxide emission control in Europe predict much greater economic losses than the regression equations developed in this paper. However, the relevance of dose–response relations developed from chamber studies with constant levels of SO<sub>2</sub> alone will also depend upon (a) the effects of fluctuating concentrations in the field and (b) the effects of pollutant mixtures rather than SO<sub>2</sub> alone.

It should soon be possible to develop improved dose–response relations solely from studies carried out in outdoor chambers over the complete annual cropping cycle. Many of the problems inherent in chamber studies on cereals in particular, will be avoided by the recent developments in field fumigation systems.

### 1. INTRODUCTION

Information on the effects of sulphur dioxide on crops is used in the pollution control process either as a basis for setting standards, or in the cost–benefit analysis of emission control options. In order to set an ambient air quality standard, data are required on the threshold concentrations at which there is a reasonable probability that effects, such as foliar injury or

yield losses, will occur. Historically, studies of the short-term effects of the main phytotoxic gases ( $\text{SO}_2$ ,  $\text{O}_3$ ,  $\text{NO}_x$  and HF) have focused on determining the thresholds for onset of visible foliar injury. The current United States air quality standards for the protection of vegetation (e.g.  $500/10^9$  sulphur dioxide for 3 h and  $120/10^9$   $\text{O}_3$  for 1 h not to be exceeded more than once per annum) are good examples of the use of this information in the regulatory process.

More recently, research has focused on determining the threshold for long-term effects on economically-important yield parameters irrespective of foliar injury. The implication is that long-term seasonal or annual standards may be required and attention is currently focused on the adequacy of the European Economic Community  $\text{SO}_2$  standard. It was initially promulgated to protect human health and recommends (a) when particulate levels are below  $40 \mu\text{g m}^{-3}$ , then  $45/10^9$   $\text{SO}_2$  should be the maximum yearly median of daily means and  $130/10^9$  should be the 98th percentile of the daily cumulative frequency distribution and (b) when particulates are above  $40 \mu\text{g m}^{-3}$ , then the yearly median should be below  $30/10^9$   $\text{SO}_2$  and the 98th percentile below  $95/10^9$ .

In contrast, cost-benefit analysis requires dose-response relations between pollutant concentration and yield losses as the basis for an economic evaluation of the effects which can then be set against the cost of emission control options. Many attempts have been made to produce empirical models relating short-term doses of  $\text{SO}_2$  (usually expressed as concentration multiplied by time) to visible foliar injury on plants (Larsen & Heck 1976). This relation can be very variable as foliar injury is more closely related to  $\text{SO}_2$  absorption than concentration and duration of exposure. Consequently, the responses vary with the degree of stomatal opening which is affected by environmental factors (such as light, temperature and humidity), and metabolic factors (such as water status and nutrient supply). As there are considerable differences in response between species, 'SO<sub>2</sub> dose-foliar injury models' have often concentrated on the most susceptible species under the environmental conditions which give the greatest sensitivity. However, research over the past decade has shown that these models are not applicable to long-term exposures at low concentrations where yield losses can occur in the absence of foliar injury (Unsworth & Ormrod 1982). For example, the relative sensitivity of crops to long-term exposures cannot be predicted from rankings based on foliar injury. The lack of such a correlation has been reported for genotypes of *Lolium perenne* (ryegrass) by both Horsman *et al.* (1979) and Ayazloo & Bell (1981).

Recent models which predicted substantial costs for crop losses in Europe (O.E.C.D. 1981) and the UK (S.A.R.U. 1980), assumed that percentage yield reductions increased linearly with the logarithm of  $\text{SO}_2$  concentrations. These models were derived from the conclusions of an O.E.C.D. Workshop held in 1978. The Workshop suggested that, although data on crop losses caused by  $\text{SO}_2$  emissions were wholly inadequate for the calculation of reliable dose-effect relations, some data were available for *Lolium perenne* (ryegrass) on which a 'conjectured dose-yield relation' was based for confirmation by future research (Jeffree 1980). More recently, Bell (1982) plotted the percentage change in shoot dry weight of *Lolium perenne* resulting from 32 exposures to constant levels of  $\text{SO}_2$  alone. He concluded that there was 'no indication of any correlation between the magnitude of growth reduction and  $\text{SO}_2$  dose'. In addition, Bell reported that the 'logarithm of yield loss normalized for duration of exposure' was not correlated with  $\text{SO}_2$  concentration. Nevertheless, Mansfield & Freer-Smith (1981) did find a significant correlation by omitting data from exposures of less than 40 days and more than 160 days duration 'to achieve some homogeneity in the types of experiment'.

The data on long-term effects of sulphur dioxide on crop yields has expanded considerably since the above analyses were carried out. This paper presents a new analysis aimed at (a) extracting threshold values for the effects on yield of  $\text{SO}_2$  alone, (b) extracting dose-response relations between  $\text{SO}_2$  concentrations and crop losses, (c) highlighting the factors that have produced such large variability in the data, and (d) detailing the factors that may limit extrapolation to field conditions from chamber studies. All data available from long-term chamber studies on the effects of constant levels of  $\text{SO}_2$  alone have been included in the analyses presented herein, with the exception of experiments that started with sulphur-deficient plants. The rationale for not excluding other studies is discussed later in the paper.

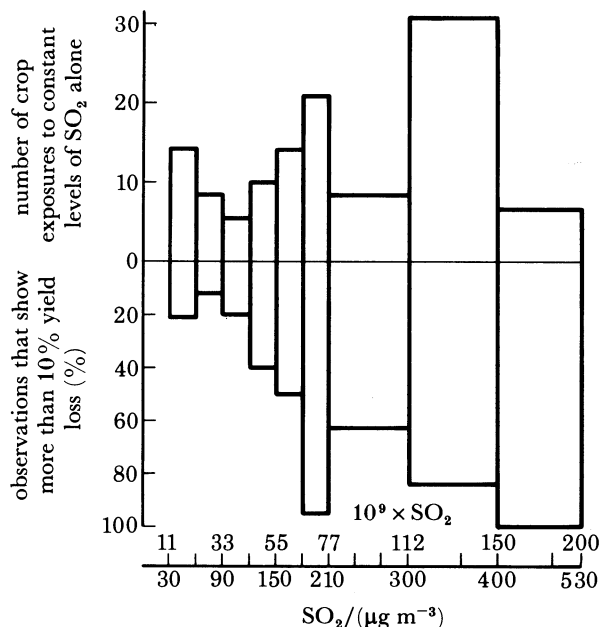


FIGURE 1. Effects on crop growth of continuous long-term exposures to  $\text{SO}_2$  alone in chamber studies. For original data see Lane (1983), tables 3.1, 3.2, 3.4 and I.E.R.E. (1981), tables 3.9 and 3.10.

## 2. THRESHOLD $\text{SO}_2$ CONCENTRATIONS FOR LONG-TERM EFFECTS ON YIELD

All the observations (up to mid-1983) on the effects of long-term exposures of grasses to constant concentrations of  $\text{SO}_2$  alone in chamber studies have been compiled by Lane (1983). There were 50 data points for *Lolium perenne* L. (ryegrass) and 48 records for 7 other grass species. A further 27 data points for 13 other crops were collated by I.E.R.E. (1981, tables 3.9 and 3.10). The predominance of data for grasses reflects the fact that most of the studies on long-term effects have been carried out in the U.K., where 73% of the mainland vegetation consists of some type of grassland, and *Lolium perenne* (ryegrass) is used for over 50% of new agricultural swards. Cereals are grossly under-represented in the list of 21 species studied, in comparison with their economic importance. This may be a reflection of the difficulties in growing cereals to maturity in most small experimental chambers.

The structure of the data is shown in figure 1. Of the 116 data points below  $200/10^9 \text{SO}_2$ , approximately half were for concentrations above  $66/10^9$  and only 35 lay within the range of ambient (including urban) levels in the U.K. (under  $50/10^9$ ). Clearly there is a relation

between SO<sub>2</sub> and crop growth with less than 20% of the observations below 44/10<sup>9</sup> SO<sub>2</sub> showing yield losses compared with greater than 80% at concentrations above 86/10<sup>9</sup>. There is a transition zone between 44 and 66/10<sup>9</sup> at which about 50% of the observations showed more than 10% yield losses. The occurrence of 5 significant effects out of 25 observations below 44/10<sup>9</sup> could be a chance event, or a reflection of the wide range of sensitivity which occurs, even within a species, under different experimental conditions (Bell *et al.* 1979). These 5 observations do not come from one experimental system nor are they all for a single 'sensitive' species. The problems in extracting threshold concentrations from a continuum of progressive effects such as this are self-evident. A clearer resolution of the range of SO<sub>2</sub> concentrations at which effects may be discernible under field conditions, requires further research into the reasons for different responses between fumigations systems and a better understanding of the physiological effects of SO<sub>2</sub>.

### 3. DOSE-RESPONSE RELATIONS FOR SO<sub>2</sub> EFFECTS ON CROP YIELD

#### (a) *Linear regressions between yield loss and SO<sub>2</sub> concentration*

The data on long-term effects of SO<sub>2</sub> (125 data points for 21 species of grasses, horticultural crops and cereals) have been progressed through a series of regression analyses in order to identify the most appropriate functional form of the dose-response curve (table 1). For all the data, SO<sub>2</sub> concentrations ranged from 16 to 263/10<sup>9</sup> (arithmetic mean = 82/10<sup>9</sup>, and the duration of exposures ranged from 7 to 252 days ( $\bar{X}$  = 74 days). Only experiments designed to study the utilization of SO<sub>2</sub> by sulphur-deficient plants have been omitted. The linear regression of yield loss against SO<sub>2</sub> was statistically significant ( $P < 0.001$ ), but the correlation coefficient indicated that this relation explained only 10.5% of the variability in the data (table 1, equation (1)). This is not unexpected as the response of crops to SO<sub>2</sub> is likely to vary with many factors including species, varieties, microclimate within growth chambers, nutritional status, growth rate etc. The data were reanalysed after omitting 9 experiments of either short duration (under 20 days) or very high concentrations (more than 200/10<sup>9</sup>) and the regression then accounted for 13.5% of the data variability (table 1 equation (2)). Close examination did not suggest that the outlying data points came from any single chamber system. The observation by Bell *et al.* (1979) of a 68% yield reduction, resulting from a 173 day exposure of ryegrass to 16/10<sup>9</sup>, was omitted from the further analysis as it was more than three times the standard deviation away from the regression estimate of the yield loss. The regression of yield loss for 115 data points against SO<sub>2</sub> (table 1 equation (3)) then had an intercept which was not significantly different from zero, a slope of 0.19, and the correlation coefficient indicated that the fit accounted for 17.3% of the data variability. Analysis of the 35 data points within the range of ambient SO<sub>2</sub> concentrations (0–50/10<sup>9</sup>) gave a correlation which was just significant ( $p = 0.05$ ) (table 1 equation (12); figure 2).

#### (b) *Alternative functional forms for the dose-response curve*

Jeffree (1980) reported that an O.E.C.D. workshop had proposed a functional form which related yield loss to the logarithm of SO<sub>2</sub> concentration 'as this relation held for some crops when attacked by insects and nematodes'. This form of the regression did slightly improve the variability accounted for by the correlation for the whole data between 0 and 200/10<sup>9</sup> ( $P < 0.001$ ) but was marginally worse than the linear regression over the ambient range

ANALYSIS OF DOSE-RESPONSE RELATIONS

TABLE 1. REGRESSION ANALYSIS<sup>1</sup> ON THE YIELD LOSS OF CROPS RESULTING FROM LONG-TERM EXPOSURES TO CONSTANT LEVELS OF SO<sub>2</sub> ALONE IN CHAMBER STUDIES

equation number	X-axis	Y-axis	omitted data	data points	intercept	slope	r	100 × r <sup>2</sup>	p
(1)	SO <sub>2</sub> <sup>(2)</sup>	yield loss (%)	none	125	-7.86	-0.126	0.32	10.5	< 0.001
(2)	SO <sub>2</sub>	y.l. (%)	< 20 d > 200/10 <sup>9</sup>	116	-5.12	-0.169	0.37	13.5	< 0.001
(3)	SO <sub>2</sub>	y.l. (%)	< 20 d > 200/10 <sup>9</sup> -1 data point	115	-3.18	-0.188	0.42	17.3	< 0.001
(4)	lg SO <sub>2</sub>	y.l. (%)	< 20 d > 200/10 <sup>9</sup> -1 data point	115	+42.2	-33.0	0.48	22.7	< 0.001
(5)	[SO <sub>2</sub> × duration <sup>(3)</sup> ]	y.l. (%)	< 20 d > 200/10 <sup>9</sup> -1 data point	115	-11.1	-0.0012	0.30	9.10	< 0.001
(6)	lg [SO <sub>2</sub> × duration]	y.l. (%)	< 20 d > 200/10 <sup>9</sup> -1 data point	115	+51.7	-19.3	0.38	14.6	< 0.001
(7)	SO <sub>2</sub>	[lg (1 - y.l. (%)) 1000/duration]	< 20 d > 200/10 <sup>9</sup> -1 data point	115	-0.114	0.023	0.34	11.6	< 0.001
(8)	SO <sub>2</sub>	[y.l. (%) (365/duration)]	< 20 d > 200/10 <sup>9</sup> -1 data point	115	-8.06	-1.48	0.36	12.8	< 0.001
(9)	SO <sub>2</sub>	y.l. (%)	all horticultural and cereal crops (13 species) < 20 d > 200/10 <sup>9</sup>	25	-1.26	-0.189	0.33	11.2	n.s. <sup>4</sup>
(10)	SO <sub>2</sub>	y.l. (%)	all grasses (8 species) < 20 d > 200/10 <sup>9</sup> -1 data point	91	-3.7	-0.187	0.44	19.2	< 0.001
(11)	SO <sub>2</sub>	y.l. (%)	ryegrass ( <i>Lolium perenne</i> ) < 20 d > 200/10 <sup>9</sup> -1 data point	45	+2.75	-0.179	0.59	35.2	< 0.001
(12)	SO <sub>2</sub>	y.l. (%)	ambient range only (0-50/10 <sup>9</sup> ) all data (9 species) < 20 d > 200/10 <sup>9</sup>	35	+6.40	-0.310	0.35	12.1	= 0.05
(13)	lg SO <sub>2</sub>	y.l. (%)	< 20 d > 200/10 <sup>9</sup> -1 data point	35	+27.0	-20.6	0.33	10.7	n.s.
(14)	SO <sub>2</sub>	y.l. (%)	ryegrass ( <i>Lolium perenne</i> ) < 20 d > 200/10 <sup>9</sup> -1 data point	24	+13.6	-0.544	0.62	38.6	< 0.01
(15)	SO <sub>2</sub>	y.l. (%)	excluding low airflow exposures < 20 d > 200/10 <sup>9</sup>	96	-0.76	-0.218	0.46	21.2	< 0.001
(16)	SO <sub>2</sub>	y.l. (%)	ryegrass ( <i>Lolium perenne</i> ) < 20 d > 200/10 <sup>9</sup>	33	+7.33	-0.215	0.81	65.9	< 0.001

<sup>1</sup> A complete analysis is given in Roberts *et al.* (1983c).  
<sup>2</sup> All SO<sub>2</sub> concentrations are given in parts per 10<sup>9</sup> (/10<sup>9</sup>).  
<sup>3</sup> Duration was converted to days.  
<sup>4</sup> n.s.: not significant.

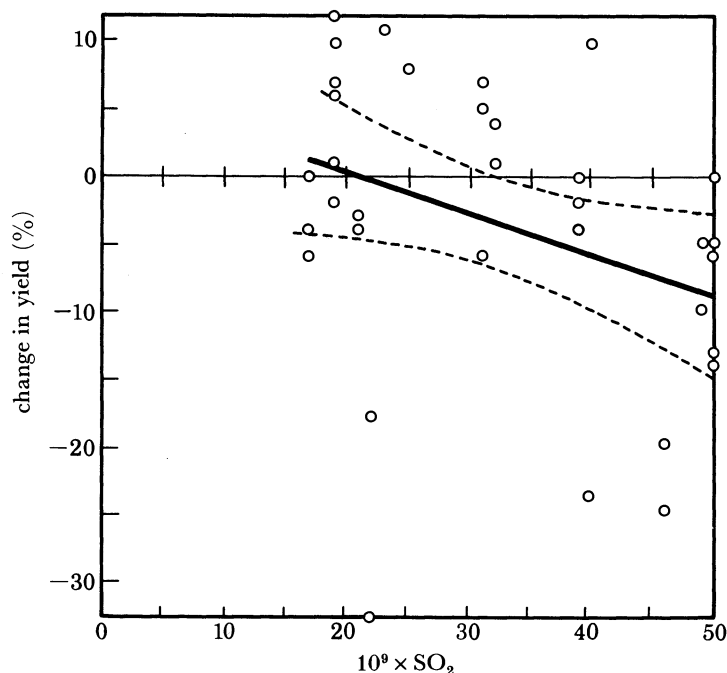


FIGURE 2. Linear regression of  $\text{SO}_2$  concentration and percentage yield reduction for all exposures in chambers for more than 20 days and less than  $50/10^9$ ; 35 data points were included from 9 species. The regression equation was: yield loss (%) =  $+6.40 - 0.31 \text{SO}_2$  ( $/10^9$ ) ( $p = 0.05$ ). The dotted lines show the 95% confidence limits for the regression.

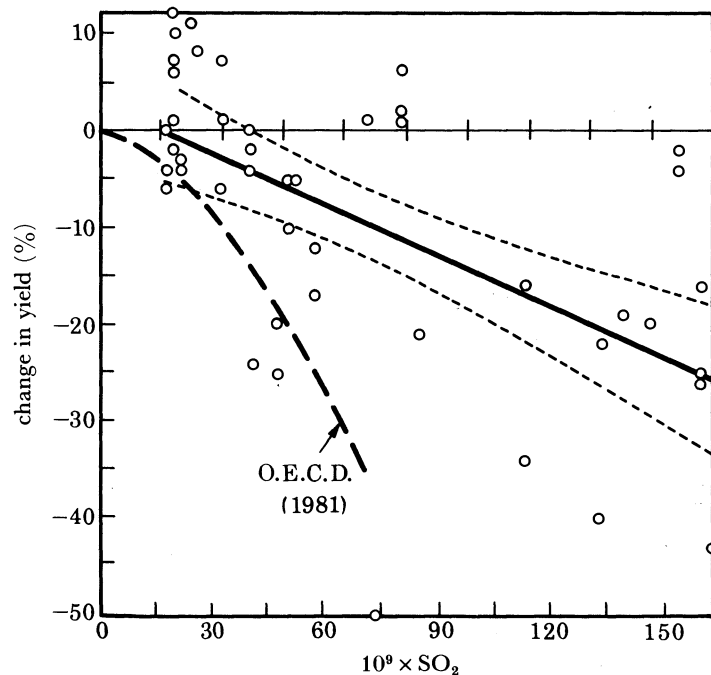


FIGURE 3. Linear regression of  $\text{SO}_2$  concentration and percentage yield reduction for all chamber exposures of *Lolium perenne* (ryegrass) for more than 20 days and less than  $200/10^9$ ; 45 data points were included. The regression equation was: yield loss (%) =  $+2.75 - 0.18 \text{SO}_2$  ( $/10^9$ ) ( $p < 0.001$ ). The dotted lines show the 95% confidence limits. The dashed line shows the Logit form of the dose-response curve used in the cost-benefit analysis of sulphur oxide emission control by O.E.C.D. (1981).

(0–50/10<sup>9</sup>) (table 1, (4) and (13)). The O.E.C.D. (1981) study of the costs and benefits of sulphur oxide emission control used a logit transformation of this dose–response curve which essentially, had the effect of forcing the curve through zero (i.e. any SO<sub>2</sub> produced a small yield reduction). The O.E.C.D dose–response curve which was based on data for ryegrass has been plotted on figure 3 along with the data currently available and the ‘best fit’ regression (i.e.

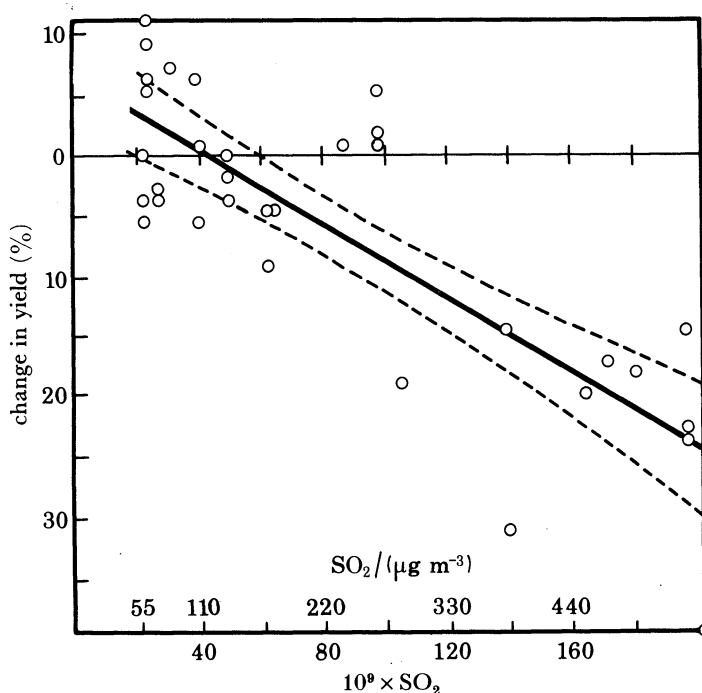


FIGURE 4. Linear regression of SO<sub>2</sub> concentration and percentage yield reduction of *Lolium perenne* (ryegrass) exposed for more than 20 days at less than 200/10<sup>9</sup> in chambers with more than one air change per minute; 33 data points were included. The regression equation was: percentage yield loss = +7.33–0.21 SO<sub>2</sub> (/10<sup>9</sup>) ( $p < 0.001$ ). The dotted lines show the 95% confidence limits of the regression.

the linear dose–response line, table 1, (11)). At SO<sub>2</sub> concentrations above 50/10<sup>9</sup> the yield loss predicted by the O.E.C.D. curve was substantially higher than has been found experimentally. The statistical uncertainty was so large within the range of ambient concentrations (below 50/10<sup>9</sup>), that there is little justification for using any particular form for the dose–response curve. However, the occurrence of sulphur deficiency in high-yielding crops in areas where the SO<sub>2</sub> concentrations was below *ca.* 5/10<sup>9</sup>, suggests that a threshold concentration should be incorporated in dose–response models (Roberts *et al.* 1983 *b*). Indeed, the linear regression of SO<sub>2</sub> concentration against yield loss, for the 35 points from 9 species exposed to less than 50/10<sup>9</sup> SO<sub>2</sub>, suggests that the threshold may be as high as 20/10<sup>9</sup> (figures 2 and 3). Nevertheless, the extrapolation of this analysis to field conditions is severely limited by the absence of data between 0 and 20/10<sup>9</sup>: the concentration range for 85% of the crop-growing areas in the U.K. (S.A.R.U. 1980).

There is some experimental evidence that yield loss may be more closely related to SO<sub>2</sub> dose (concentration × time). Whitmore (1984) exposed *Poa pratensis* to 40, 70 and 100/10<sup>9</sup> SO<sub>2</sub> + NO<sub>2</sub> mixtures for 8–40 days in a controlled-environment cabinet, and found a highly significant correlation between yield loss and  $\ln[(\text{SO}_2 + \text{NO}_2) \times \text{time}]$ . However, regression of



the yield loss for 115 data points against dose (concentration  $\times$  time), or the logarithm of dose, gave a poorer fit than the untransformed data (table 1, (5) and (6)). Bell (1982) proposed that the  $\text{SO}_2$  concentration should be related to the logarithm of the ratio of fumigated and control plant yield, normalized for duration of exposure. The rationale for this transformation was that 'as shoot growth in grasses is exponential, so small differences in shoot weight should increase logarithmically with the duration of exposure'. However, regression of  $\text{SO}_2$  against this index of yield loss for the whole data set (115 data points), or for ryegrass only (45 data points), gave no improvement on the regressions against untransformed data (table 1, (7)). Similarly, simply correcting the percentage yield loss for duration of exposure also gave no improvement of the regression against  $\text{SO}_2$  (table 1, (8)). The absence of any improvement in the correlations by normalizing for duration of exposure is rather striking. Evidence for changes in sensitivity with season, growth conditions, acclimation and compensatory mechanisms, which may counteract reduced photosynthetic efficiency, are discussed in §4.

(c) *Differences in response between species*

The complete data set analysed above consisted of 21 crops and it is likely that much of the variability noted in the above regressions, can be ascribed to differences in response between species or varieties. However, there have been only a small number of studies that have compared the relative sensitivity of a range of crops with long-term  $\text{SO}_2$  exposures. Fujiwara (1975) fumigated 8 horticultural or arable crops for 14–112 days at 65 and 130/10<sup>9</sup>  $\text{SO}_2$ . The sensitivity ranking of the species varied with increasing  $\text{SO}_2$  stress but the general response in increasing order of susceptibility was: tomato < lettuce < cabbage < soybean < pea < turnip < sweet potato < rice < buckwheat. Regression analysis of percentage yield loss for the 13 horticultural and arable species (25 data points) was not significant ( $p = 0.07$ ) and the correlation accounted for 11% of the variability as compared to 17.3% for the complete data set (table 1, (9)).

Comparison of the relative sensitivity of a range of grasses has been made in the outdoor chambers at Lancaster and Imperial College, and in the indoor chambers at the Grassland Research Institute (table 2). It is difficult to reach firm conclusions from such incomplete data but *Dactylis glomerata* repeatedly appeared to be sensitive along with *Poa pratensis* and one cultivar of *Phleum pratense*, while *Lolium multiflorum* consistently appeared to be resistant. These rankings may vary with the growth stage, as well as the severity of the  $\text{SO}_2$  effect. Whitmore & Mansfield (1983) reported that the ranking for grass species exposed from emergence was reversed when 42 day-old tillers were used (table 2). The regression of percentage yield loss for all 8 grasses (90 data points) against  $\text{SO}_2$  concentration was highly significant and the correlation accounted for 19% of the data variability (table 1, (10)). Approximately half the data for grasses came from studies on the effects of  $\text{SO}_2$  on *Lolium perenne* (ryegrass), which reflects its importance in grasslands in the U.K. Based on foliar injury produced by short-term peaks, this species was considered to be sensitive to  $\text{SO}_2$  but recent data (table 2) indicate that both *Lolium perenne* S23 and S24 show only intermediate responses to long-term  $\text{SO}_2$  exposures. Regression of percentage yield loss against  $\text{SO}_2$  concentration for 45 observations on *Lolium perenne* of more than 20 days duration and less than 200/10<sup>9</sup> (table 1, (11) and figure 3) gave a much better fit to the data than the regressions for all 21 species or all 8 grasses ( $r^2 = 0.35$  compared with 0.17 and 0.19 respectively). Further regressions with transformations of the percentage yield loss (after Bell 1982) or converting the  $\text{SO}_2$  concentration to dose or

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[logarithmic dose] (after Whitmore 1984) gave no further improvement on the correlation obtained by relating percentage yield loss to  $\text{SO}_2$  concentration.

The above analysis has identified the extent to which variability in the data set can be ascribed to differences in species response. Nevertheless, despite the improved correlation for ryegrass alone over the whole (0–200)/ $10^9$  concentration range, there remains much unexplained variation even for the single species. Much research effort has been devoted to identifying the causes of variability both between and within different exposure systems.

TABLE 2. INTERSPECIES VARIABILITY IN RESPONSES TO LONG-TERM EXPOSURES TO  $\text{SO}_2$ 

	Lancaster <sup>1</sup>		Lancaster <sup>2</sup>	Imperial College <sup>3</sup>	Imperial College <sup>4</sup>	G.R.I. (Hurley) <sup>5</sup>
	62/10 <sup>9</sup> × 200 d A	B	68/10 <sup>9</sup> × 140 d	138/10 <sup>9</sup> × 131 d	119/10 <sup>9</sup> × 123 d	180/10 <sup>9</sup> × 42 d
<i>Holcus lanatus</i>	—	—	—	–44	—	—
<i>Dactylis glomerata</i>	–40	+5	–46	–26	–34	–33
<i>cv S37</i>						
<i>Poa pratense</i>	–45	–12	–39	—	—	—
<i>cv Monopoly</i>						
<i>Phleum pratense</i>	–42	–5	–36	—	—	—
<i>cv Eskimo</i>						
<i>Phleum pratense</i>	–21	–6	—	—	–21	+15
<i>cv S48</i>						
<i>Festuca rubra</i>	—	—	—	–18	–57	—
<i>Lolium perenne</i>	+20	–25	—	–8	–27	–16
<i>cv S23</i>						
<i>Lolium perenne</i>	–15	–20	—	—	—	—
<i>cv S24</i>						
<i>Lolium perenne</i>	—	—	—	—	—	–10
<i>cv Sabalas</i>						
<i>Lolium perenne</i>	—	—	—	—	–22	—
<i>cv RVP</i>						

Data from: 1, Whitmore & Mansfield (1983); 2, Ashenden (1979) and Ashenden & Williams (1980); 3, Ayazloo & Bell (1981); 4, Wilson (1983); 5, Cowling *et al.* (1980). A: exposed from emergence; B: exposed from 42 days.

## 4. VARIABILITY IN RESPONSES RELATED TO EXPERIMENTAL CONDITIONS

Much of the variability in growth responses to long-term low-level  $\text{SO}_2$  exposures has been ascribed to inadequacies in the design of some chambers, which resulted in unusually low rates of gas absorption. However, it is becoming clear that responses also vary with factors that determine the physiological condition of the exposed plants, such as growth rate, plant age and density.

## (a) Differences in pollutant flux

Early research on the long-term growth effects of continuous  $\text{SO}_2$  exposures concluded that the threshold was in excess of (100–200)/ $10^9$  (Thomas 1958; Katz 1949). However, this work was carried out in chambers with less than one air change per minute. With such low airflows: (a) the  $\text{SO}_2$  concentration in the chamber was depleted by absorption so that gas measurements at the inlet overestimated the exposure concentration; (b) the aerodynamic resistance increased to values which equal or exceed stomatal resistances thus restricting pollutant flux;

and (c) depletion of CO<sub>2</sub> occurred in the chamber. Indeed, some of these problems were still present in the chambers used at the outset of the more recent investigations. These were stimulated by reports of a 50% reduction in ryegrass yield after exposure to 72/10<sup>9</sup> SO<sub>2</sub> for 180 days, without any signs of visible injury (Bell & Clough 1973). However, as these early studies using chambers with low airflows produced some of the largest effects reported (see, for example, Bell & Clough 1973, whose used 0.5 air changes per minute and Bell *et al.* 1979, who used 1 air change every 8 minutes for the first four experiments), while others produced very small effects (see, for example, Cowling & Koziol 1978, who used 0.6 air changes per minute), all the data irrespective of rate of airflow have been incorporated in most of the analyses presented in this paper. Separate regressions were carried out of yield loss against SO<sub>2</sub> concentration after removing 20 data points from chambers with less than 1 air change per minute and no internal mixing fan. The regression equation was not significantly altered by the omission of low airflow studies but there was a large improvement in the correlation coefficient for all data and for *Lolium perenne* data in particular (table 1, (15) and (16), figure 4). These results suggest that low airflow may have affected the apparent response to SO<sub>2</sub> in a non-systematic manner in the early studies. Certainly the experiments producing small responses are not all from low airflow chambers.

Ashenden & Mansfield (1977) then showed experimentally that the sensitivity of plants was greatly dependent on air movement, and recent chamber designs have attempted to minimize the aerodynamic resistance. A large part of the data on ryegrass responses to SO<sub>2</sub> was produced in the chambers described by Lockyer *et al.* (1976), which operated at 2 air changes per minute and were located within a greenhouse. Unsworth & Mansfield (1980) pointed out that the concentrations were measured only at the inlet and calculated that the chamber concentrations could have been 25–40% lower. However, careful measurements by Cowling *et al.* (1981) showed that the depletion at 2 air changes per minute was only 5–11%, and that the SO<sub>2</sub> flux to leaves was within the normal range. The data have therefore been included in these analyses by using the revised exposure concentrations. This debate highlighted the need to maintain adequate turbulence in exposure chambers and to measure the concentrations within the chamber. However, it is not possible to rationalize the variability in growth response between different chambers solely on the basis of different gas fluxes and SO<sub>2</sub> depletion.

(b) *Variation in sensitivity related to growth rate*

It has been known for some time that SO<sub>2</sub> exposures in experimental conditions giving slow growth of grasses (e.g. over-winter exposures in outdoor chambers) generally produced much larger effects than experimental conditions giving high growth (e.g. chambers in greenhouses, or wind tunnels in controlled-environment rooms). However, it was only recently that two rather different experiments have clearly demonstrated that sensitivity to SO<sub>2</sub> is much greater over winter, and this effect may even be reversed during the rapid spring and summer growth (figure 5). Whitmore & Mansfield (1983) sequentially harvested *Poa pratensis* grown as spaced plants in large outdoor chambers from October 1980 until September 1981, fumigated with 62/10<sup>9</sup> SO<sub>2</sub>, 62/10<sup>9</sup> NO<sub>2</sub> and 62/10<sup>9</sup> SO<sub>2</sub>+NO<sub>2</sub>. A 45% reduction in total plant weight (shoot+root) was observed between October and May in the SO<sub>2</sub> chamber when the plants had been growing at less than 0.5 mg per plant per day. However, during rapid summer growth (greater than 20 mg per plant per day), plants in the SO<sub>2</sub> and SO<sub>2</sub>+NO<sub>2</sub> chambers grew faster than the controls to produce a slight stimulation in overall yield by the end of the summer.

Colvill *et al.* (1983) exposed *Lolium perenne* swards to fluctuating SO<sub>2</sub> concentrations in open-top chambers from October–August in 1978–1979 and 1979–1980. Mean concentrations of 44 and 63/10<sup>9</sup> produced 11–25% yield reductions over winter (with growth rates of <0.5 g m<sup>-2</sup> d<sup>-1</sup>) but the swards recovered during the summer growth period (with monthly growth rates of 4–7 g m<sup>-2</sup> d<sup>-1</sup>). The stimulation in shoot growth observed by Whitmore & Mansfield (1983) was due to a shift in carbon allocation from the roots and followed by maintenance of vegetative growth at the expense of flowering.

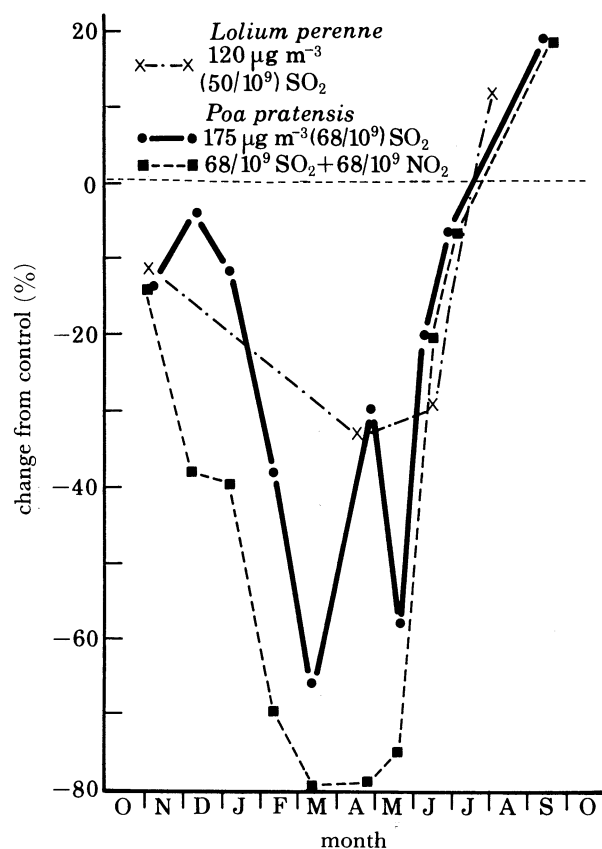


FIGURE 5. Seasonal differences in the effects of SO<sub>2</sub> (and SO<sub>2</sub> + NO<sub>2</sub>) on the growth of grasses. Data for *Lolium perenne* (shoot weight only) taken from Colvill *et al.* (1983). Data for *Poa pratensis* (shoot + root weight) taken from Whitmore & Mansfield (1983).

Davies (1980) showed from experiments in controlled-environment chambers that *Phleum pratense* could tolerate 120/10<sup>9</sup> SO<sub>2</sub> for 35 days under high irradiation and long days, but growth was reduced by 50% at low irradiance and short days. Subsequently, Jones & Mansfield (1982a) have shown that the effects of SO<sub>2</sub> were greater under conditions of slow growth induced by (a) low irradiance and short days, (b) low irradiance irrespective of daylength, and (c) low temperature.

It now seems likely that the effect of growth rate on the response to long-term SO<sub>2</sub> exposures may be the major factor in producing the large variability between different studies. For example, Bell *et al.* (1979) generally found large effects of SO<sub>2</sub> in outdoor chambers with a moderate growth rate for swards of 3 g m<sup>-2</sup> d<sup>-1</sup> whereas Cowling *et al.* (1980) reported much smaller effects on swards growing at 20 g m<sup>-2</sup> d<sup>-1</sup> in chambers located in a greenhouse with

supplementary lighting. Similarly the growth of spaced plants of *Lolium perenne* incorporated in the data-set analysed in this paper, varied from under 5 mg per plant per day to 30 mg per plant per day. Therefore, it is not surprising that such divergent results have been obtained. However, this is not to say that certain studies are not applicable to field conditions. Each result must be viewed in context of the experimental conditions. To overcome these problems, current research aimed at producing dose-response data has concentrated on fumigating crops over the normal duration of the annual growth cycle.

(c) *Variation in sensitivity with plant age*

The grasses used in the studies analysed in §3 varied in age at the start of the experiments from newly-emerged seedlings, freshly planted tillers, or 7–111 day-old established plants or swards. Bell *et al.* (1979) noted that the greatest effect on relative growth rate of *Lolium perenne* occurred at an early stage of long-term exposures. Whitmore & Mansfield (1983) compared the effect of  $62/10^9$  SO<sub>2</sub> for 7 months on newly-emerged seedlings with the effect on 42 day-old plants of 6 grass cultivars (table 2). Seedlings of *Poa pratensis*, *Dactylis glomerata* and two cultivars of *Phleum pratense* were more sensitive, whereas the older plants were more sensitive for two *Lolium perenne* cultivars. In general it appears that, as seedlings are the most sensitive growth stage, long-term studies on dose-response relationships of crops should commence at planting or at emergence.

(d) *Variation in sensitivity with plant density*

Much of the research on grasses has been carried out with spaced plants rather than swards, as this is a more convenient method of studying the physiological or genetic basis of plant responses. Ryegrass swards sown at the standard rate of 17 g m<sup>-2</sup> normally have more than 1 plant per 10 cm<sup>2</sup>, whereas the density of planting for the data presented in table 2, ranged from 1 plant per 40–60 cm<sup>2</sup> for the Lancaster and Imperial College chambers, to 1 plant per 5 cm<sup>2</sup> for the G.R.I. chambers. Horsman *et al.* (1979) pointed out the constraints on extrapolating from spaced plants in chambers to swards in field conditions. First, as a sward develops, the SO<sub>2</sub> dose per plant decreases because of the formation of SO<sub>2</sub> and flux gradients within the canopy. Second, competition between genotypes of differing SO<sub>2</sub> sensitivity in swards may compensate to some degree for growth reductions of susceptible individuals. The difference in response between swards and spaced plants has only recently been examined experimentally with rather contrasting results. Whitmore & Mansfield (1983) exposed *Poa pratensis* to  $62/10^9$  SO<sub>2</sub> from October–June 1980–1981 in outdoor chambers and found considerably greater reductions for swards (6 plants per 7.5 cm diameter pot) than for spaced plants (1 plant per pot). Roose (personal communication) found no differences between spaced plants (1 plant per 50 cm<sup>2</sup>) or swards (1 plant per 5 cm<sup>2</sup> in 0.1 m<sup>2</sup> pots) exposed in outdoor chambers to  $50/10^9$  SO<sub>2</sub>+NO<sub>2</sub> from November 1980 to July 1981. The lack of clear cut differences between spaced plants and swards may be, while dose per unit leaf area decreases with increasing density so does the weight per plant, and slow-growing plants are known to be more sensitive to SO<sub>2</sub>. Regression analyses of the *Lolium perenne* data divided into spaced plants (13 points) and swards (32 points) were both highly significant, but the slope of the spaced-plants regression was almost double that for the swards.

## 5. APPLICABILITY OF DOSE-RESPONSE DATA TO FIELD CONDITIONS

The dose-response data analysed in this paper were derived from studies that used constant concentrations of  $\text{SO}_2$  alone in chambers. Extrapolation of the results to field conditions must take into account possible interactions with other stress factors, the occurrence of fluctuating concentrations and mixtures of pollutants in the field.

(a) *Interactions with stress factors*

It has been demonstrated that grasses are most susceptible to prolonged low-level exposures of  $\text{SO}_2$  during periods of slow growth over winter. Davies (1980) found that while low irradiance (near the compensation point) reduced  $\text{SO}_2$  absorption by *Phleum pratense*, the metabolic capacity to detoxify the absorbed  $\text{SO}_2$  was reduced even more. Mansfield & Jones (1984) proposed that the consequent lowering in net assimilation rate is first seen as a reduction in root growth, which may increase drought susceptibility. The lower assimilate available for leaf growth may be compensated for by an increase in leaf area per unit weight, which could lead to increased frost sensitivity (figure 6).

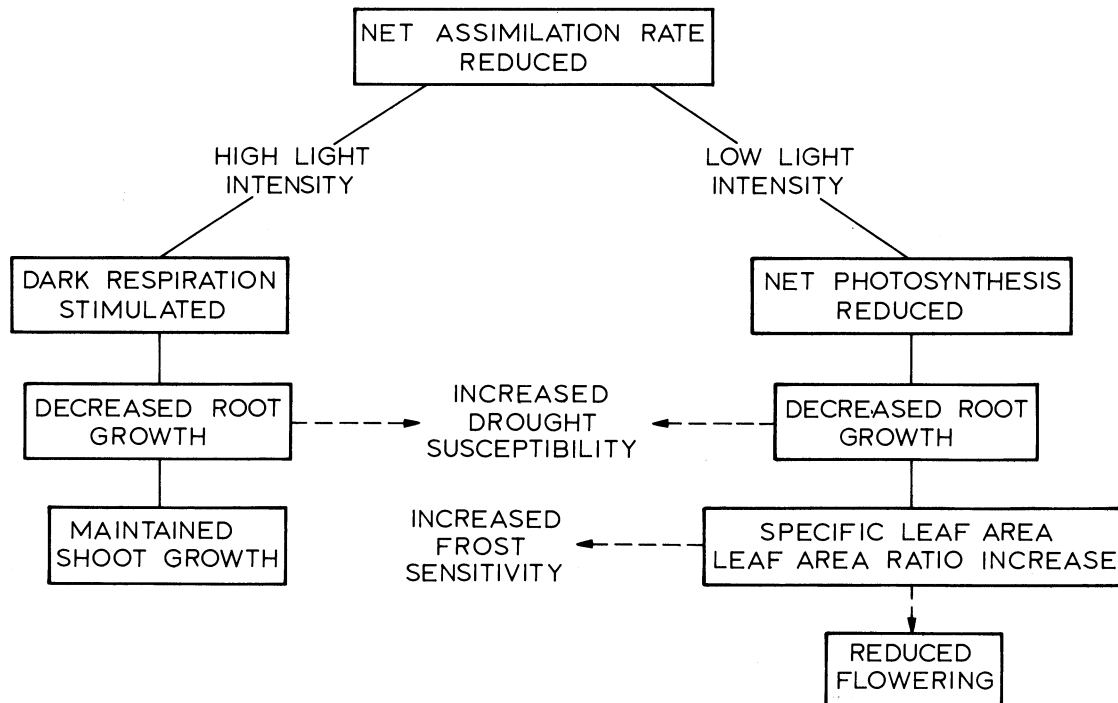


FIGURE 6. Conceptual model for responses of grasses to  $\text{SO}_2$  stress at high and low light intensity (after Bell 1982; Mansfield & Jones 1984).

The interaction with drought susceptibility has yet to be demonstrated experimentally but Bleasdale (1952) noted that  $\text{SO}_2$  reduced the winter hardiness of ryegrass in urban areas. This was confirmed recently by Davison & Bailey (1982) who found that exposure to  $94/10^9$   $\text{SO}_2$  for 35 days at low irradiance reduced that survival of *Lolium perenne* subsequently exposed to sub-zero temperatures. Increased frost injury occurred on winter wheat leaves exposed over winter to  $100/10^9$   $\text{SO}_2$  under field conditions (Baker *et al.* 1982). It may also be possible to

demonstrate an interaction between long-term SO<sub>2</sub> exposures and wind stress. Fujiwara (1975) reported a two-fold increase in foliar lesions on buckwheat after exposure to 65/10<sup>9</sup> for 50 days, when the wind velocity at crop height was increased from 2 to 4 m s<sup>-1</sup>.

Frequent cutting is another stress of importance particularly for amenity swards. Bell (1980) found that exposure to 180/10<sup>9</sup> for 42 days in a wind tunnel had no effect on ryegrass swards. However, similarly exposed swards which were cut weekly showed a 22% yield reduction over the six harvests and, at the final harvest, the yield was reduced to less than 20% of the controls.

Cowling & Lockyer (1978) reported a small increase in senescence in nitrogen-deficient ryegrass plants after exposure to 19/10<sup>9</sup> SO<sub>2</sub>. This may explain the report by Davies (1980) that SO<sub>2</sub>-induced senescence was greater in *Phleum pratense* when growth was limited by root restriction. There is little information currently available on the potential for interactions between long-term SO<sub>2</sub> exposures and biotic stresses, such as pests and diseases.

It is not clear how these interactions will moderate the magnitude of effects seen in exposure chambers. Certainly the potential for interactions between SO<sub>2</sub> and other stresses will be much less for indoor and controlled-environment chambers. For outdoor chambers with more than 2 air changes per minute, environmental factors more closely follow field conditions. However, in summer the chambers generally produce an increase in temperature and a decrease in humidity, which may enhance the potential for droughting unless frequent watering occurs. In winter any decrease in light intensity may be very important and, although temperatures are slightly higher, the continuous airflow during very cold periods may enhance the cold stress. The potential for interactions with other stresses is becoming increasingly clear, and it may well be that the absence of these interactions from studies that use indoor chambers is a major cause of the variability in the dose-response data examined in this paper.

(b) *Effects of fluctuating concentrations under field conditions*

The majority of experimental fumigations in chambers have been carried out with constant concentrations. Contrasting opinions have been expressed as to whether fluctuating concentrations below the threshold for foliar injury will produce greater or lesser effects on growth. It could be argued that periods of low concentrations between peaks will allow for recovery and compensatory processes to occur. However, the presence of peaks could exceed the threshold for effects on some metabolic processes which would not be affected by a lower constant concentration.

Jones & Mansfield (1982*b*) found no greater inhibition of shoot or root growth when *Phleum pratense* was exposed for 41 days to 27/10<sup>9</sup> continuously with peaks of 400 or 800/10<sup>9</sup> for 3 h or 1.5 h on 30 days, compared with 60/10<sup>9</sup> continuously. Roberts exposed *Lolium perenne* for 77 days in indoor chambers to (a) 80/10<sup>9</sup> continuously, (b) 125/10<sup>9</sup> for 105 hours per week, and (c) 80/10<sup>9</sup> as a logarithmic-normal distribution of daily values between 20 and 250/10<sup>9</sup>. All three treatments gave similar reductions in total plant weight but leaf dry weight was decreased by 25–30% in the two fluctuating treatments as compared with 10% in the constant treatment. These very preliminary observations suggest that fluctuating concentrations below the threshold for visible injury produce similar or marginally greater effects on growth than constant exposure.

*(c) Effects of SO<sub>2</sub> when mixed with other gases*

A major constraint in applying the dose-response relations developed in this paper to field conditions, is the absence of interactive effects between SO<sub>2</sub> and the other pollutants normally found in ambient air (particularly NO<sub>x</sub> and O<sub>3</sub>). In general, the addition of two pollutants, at concentrations above the threshold for long-term effects on growth of each gas separately, produced additive or more-than-additive reductions in yield. This has been clearly demonstrated for the interactive effect of more than 60/10<sup>9</sup> SO<sub>2</sub> and NO<sub>2</sub> on *Poa pratensis* growing slowly over winter (Ashenden 1979; Ashenden & Williams 1980). However, mixtures of SO<sub>2</sub> + NO<sub>2</sub> at concentrations below the individual gas thresholds do not appear to produce such large interactive effects. For example, Whitmore & Mansfield (1983) reported that while 62/10<sup>9</sup> SO<sub>2</sub> + NO<sub>2</sub> reduced *Poa pratensis* growth over winter, final yield was stimulated after the more rapid summer growth. Similarly, Lane (1983), using fluctuating concentrations of SO<sub>2</sub> and NO<sub>2</sub> more typical of urban areas in the U.K., found no effects of single gases or mixtures of 31/10<sup>9</sup> SO<sub>2</sub> and 23/10<sup>9</sup> NO<sub>2</sub> on *Lolium perenne*, *Phleum pratense* or *Dactylis glomerata*.

There is a greater possibility of interactive effects of SO<sub>2</sub> and O<sub>3</sub> although there is very little experimental evidence for the U.K. The British Isles has neither the volume of emissions nor the climatic conditions required to produce photochemical smogs on the scale experienced in California. However, in good summers the magnitude of peaks and the frequency of episodes may not be very different from the eastern United States.

Two recent publications report the effects of mixtures of SO<sub>2</sub> and O<sub>3</sub>, studied in field chambers that contain ambient photochemical oxidants. In the study by Oshima (1978), carried out at Riverside (California), 100/10<sup>9</sup> SO<sub>2</sub> was added to an ambient, filtered or part-filtered airstream in replicated chambers for 6 hours each day. SO<sub>2</sub> alone had no effect on the crop *Phaseolus vulgaris* (red kidney bean), but addition to 50% filtered air significantly reduced both total plant dry mass and seed dry mass. Heggestad & Bennett (1981) added three SO<sub>2</sub> concentrations (60, 120 and 300/10<sup>9</sup>) for 6 h per day to the background of ambient ozone at Beltsville (Maryland), and found a linear correlation ( $r = -0.99$ ) between increasing SO<sub>2</sub> concentration and decreasing yields of three *Phaseolus vulgaris* (snap bean) cultivars. Yield losses arising from the SO<sub>2</sub> treatments were threefold greater in the presence of ambient oxidants than when added to charcoal-filtered air.

The only studies in the U.K. in which SO<sub>2</sub> was added to the background concentrations of NO<sub>x</sub> and O<sub>3</sub> present in rural areas was carried out in open-top chambers by Roberts *et al.* (1983a) and Colvill *et al.* (1983). These authors concluded that over 45/10<sup>9</sup> SO<sub>2</sub> had to be added continuously to unfiltered rural air to produce significant and repeatable reductions in the yield of *Lolium perenne*. The recent development of field fumigation systems (Greenwood *et al.* 1982; McLeod *et al.* 1983) will provide further information on the long-term effects of SO<sub>2</sub> added to the background of other pollutants found in rural areas.

## CONCLUSIONS

Regression analysis of the yield losses reported for 21 crops against long-term exposures to sulphur dioxide alone showed that this relation explained less than 17% of the variability in published chamber studies. Compilation of recent data showed that much of this variability could be ascribed to differences in responses between species and cultivars. Analysis of the data



for *Lolium perenne* (ryegrass), which has an intermediate sensitivity to long-term SO<sub>2</sub> exposures, showed that the regression of yield loss against SO<sub>2</sub> concentration explained up to 39% of the variability. This relation was not improved by a number of transformations of either variable. However, removal of all studies that use chambers with low airflows produced a substantial improvement in the correlation between yield loss and SO<sub>2</sub> concentrations, without significantly altering the regression equation. Clearly, chamber designs producing low turbulence and restricted SO<sub>2</sub> flux should be avoided.

Examination of the published data showed that much of the remaining variability in response between different exposure systems could be ascribed to (i) decreasing sensitivity to SO<sub>2</sub> with increasing rate of growth, (ii) decreasing sensitivity with increasing plant age, and (iii) greater sensitivity in outdoor chambers due to the greater potential for interactions with other stresses.

The application of dose–response data developed in chamber studies to field conditions will depend on (a) the extent to which selection for tolerance occurs in long-lived swards, (b) the interactions between SO<sub>2</sub> and other stresses (particularly pests and diseases, low irradiation, low temperature, wind, frequent cutting, nutrient deficiency and possibly drought stress), and (c) the magnitude of interactions between SO<sub>2</sub> and other pollutants present in urban and rural areas (particularly NO<sub>x</sub> and O<sub>3</sub>). The limited data available do not suggest that the effects of fluctuating concentrations, typical of ambient levels found in multiple-source areas in the U.K., will be very different from the constant levels used in chamber studies.

Future research will be increasingly influenced by the use of dose–response relations in cost–benefit analysis of sulphur oxide emission controls. Problems arise when (a) hypothetical relations are assumed in the absence of good data, and (b) the linearity of dose–response relations are presumed to justify extrapolation from effects at high concentrations to lower ambient concentrations. The economic losses predicted by dose–response relations extrapolated through zero are considerably reduced by the assumption that there is even a very low SO<sub>2</sub> threshold for the onset of yield losses. The hypothetical dose–response relations used in recent cost–benefit analysis of sulphur oxide emission control in Europe, predict much greater economic losses than any of the regression equations, derived from all the published data (figures 2–4) cited in this paper.

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