THE RELATIONSHIP BETWEEN SULFUR DIOXIDE CONCENTRATION AND YIELD OF FIVE CROPS IN AUSTRALIA

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ABSTRACT

Mass emissions of SO_2, in Australia have tripled in little over a decade, to a level at which Australia is now a major source of global SO_2 emissions. Almost half of these emissions is attributable to sources at Mount Isa, Queensland, and Kalgoorlie, Western Australia. SO_2 emissions are continuing to increase with expansions in the processing of sulfur-rich ores in the mineral processing industries in particular. Only local effects of SO_2 on the environment in Australia are currently occurring but air pollution control policies are increasing the potential for more widespread effects on vegetation around rural emission sources.

To examine the relationship between SO_2 concentration and crop yield, five crops (wheat, soybean, peanut, navy bean and maize) were grown from the seedling stage to harvest in open top chambers under ambient climatic conditions. SO_2 was introduced into the chambers for 8h/day throughout this period at concentrations of about <13, 138 or 285 $\mu g\ m^{-3}$. The responses of the plants varied. Wheat and soybean were very sensitive, with yield reductions of about 5% and 25% at 135 and 275 $\mu g\ m^{-3}$, respectively. Navy beans and maize were less sensitive with a yield increase of about 10% at 140 $\mu g\ m^{-3}$, and unchanged yield at 285 $\mu g\ m^{-3}$. Peanuts were intermediate between these categories with yield reductions of about 5% and 10% at 140 and 280 $\mu g\ m^{-3}$, respectively.

INTRODUCTION

Sulfur dioxide is an important air pollutant in Australia. Apart from effects on humans, animals, materials and aesthetics, it has caused crop losses and death or damage to trees at some locations in Australia (Scurfield, 1960; Blainey, 1967). In other parts of the world the effects of SO_2 on vegetation have been very severe, such that it is rated as the most important air pollutant in Europe (Knabe, 1978) and the second most important air pollutant in the USA (Heck, 1982) for causing injury to vegetation.

Emissions of SO_2 in Australia were estimated to be 713,000 tonnes per year in 1976 (Davey, 1980). More recently, eastern Australian emissions of SO_2 were estimated to be 1.75 million tonnes per year (Holden and Clarkson, 1986). Based on this, total Australian emissions are about 2.2 million tonnes per year (Murray, 1989), of which almost half is attributable to smelting and roasting operations at Mt Isa (Holden and Clarkson, 1986) and Kalgoorlie. There are large spatial variations in SO_2 concentrations. Large areas of the Australian land mass experience background ambient SO_2 levels, and although ambient SO_2 concentrations in some Australian cities are decreasing, in some mineral processing regions, ambient SO_2 concentrations are increasing. The spatial distribution of the emissions sources, and the dearth of regional monitoring data complicate a discussion of ambient SO_2 concentrations in Australia. However, it appears likely that SO_2 emissions in Australia will continue to increase with expansions in production in the electricity and mineral processing industries, especially increased processing of sulfur-rich ores by the gold industry.

Australian emissions of SO_2 will soon exceed the Federal Republic of Germany emissions which were estimated to be 3.5 millions tonnes of SO_2 per year (Holden and Clarkson, 1986) and decreasing, as the Federal Republic of Germany and most other European nations have agreed to reduce SO_2 emissions by at least 30% of 1980 emission levels by 1993/95 (Aniansson, 1987). British emissions of SO_2 are estimated to be 4.2 million tonnes per year, and the total of North American and European SO_2 emissions are 50 millions tonnes per year (Fowler and Cape, 1982).

Clearly, Australian SO_2 emissions are increasingly significant in comparison to other highly industrialised nations and a national assessment of the implications of the increasing rate of SO_2 emissions for the Australian environment may become necessary.

Until very recently the relationship between SO_2 concentrations and effects on important crop varieties grown in Australia and the native plants of Australia, under Australian climatic conditions, had not been studied to any significant extent, apart from a screening study by O'Connor et al. (1974). In fact, more work had been conducted on the effects of SO_2 on the predominant Australian tree genus *Eucalyptus* in North America (Howe and Woltz, 1981; Norby and Kozlowski, 1981; Elkiey and Ormrod, 1987) than in Australia.

Recently the data base has expanded on the impact of SO_2 on important Australian crops and *Eucalyptus* (Murray, 1985 a,b; Murray and Wilson, 1988 a,b,c). This knowledge of the relationship between concentrations of SO_2 and the response of crops, native plants and forests is necessary for the development of predictive models for the effects of air pollutants on plants, as these data are used in scientific criteria for setting air-quality standards.

The objective of this paper is to synthesise some recent experimental data on yield changes in some of the most important crops grown in Australia, in response to exposure to selected SO_2 concentrations.

MATERIALS AND METHODS

The plants were exposed to SO_2 under ambient climatic conditions in open top chambers in the field, from the seedling stage until commercial harvest. The experimental procedures have been described in detail previously (Murray and Wilson, 1988c; Davieson, 1987) and are only summarised here.

The design of each experiment was varied as summarised in Table 1. All treatments were duplicated. The yield parameter was dry weight of seed per plant, except for maize and peanuts which were dry weight of cobs or peanuts per plant, respectively.

Each open-top chamber was 3m in diameter and 2.4m tall, consisting of a rigid aluminium frame covered by UV-treated PVC plastic. The upper half of the frame was covered by a single layer of PVC plastic and the lower half was covered by a double thickness of the PVC envelope with the inner layer perforatedby holes 25mm in diameter (Figure 1). Air was drawn by a fan through a dust filter and then forced along a duct,

TABLE 1: FUMIGATION CONDITIONS

COMMON NAME	Maize	Peanuts	Soybean	Navybean	Wheat
Botanical Name	Zea mays L.	Arachis hypogaea L.	Clycine max L	Phaseolus vulgaris L.	Triticum aestivum L.
Cultivar	QK958	Virginia Bunch	Dragon	Gallaroy cv.	Eradu
Mean SO_2 conc ± SD ($\mu g\ m^{-3}$)					
High	282±85	279±77	277±74	290±88	266±80
Low	136±37	137±40	138±40	141±40	133±53
Control	<13	<13	<13	<13	<13
Pattern of fumig. (h/d)	8	8	8	8	8
Length of exposure (d)	70	105	81	49	119
Plant replication	14	14	8	14	6
Mean daily max temp (°C)	29.1	27.3	28.3	30.5	20.9
Mean daily min temp (°C)	15.8	14.7	15.4	16.6	10.8
Mean daily max rel hum(%)	83.5	86.0	85.1	81.4	91.6
Mean daily min rel hum(%)	33.8	37.5	35.6	31.4	47.6

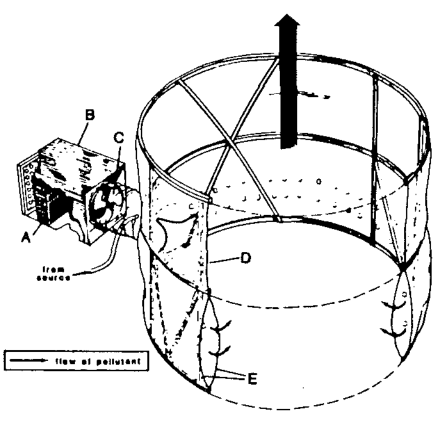

Figure 1: Open-top field chamber (A) dust filter; (B) filter box; (C) fan; (D) upper panel — single layer of PVC and (G) lower panel — double layer of PVC, inner layer perforated.

into the chamber through the holes in the lower envelope and then out through the open top. The output of the fan was 1 $m^3\ s^{-1}$, enabling an air exchange rate of about 3.5 air changes per minute. Dry air was mixed with bottled anhydrous sulfur dioxide from a temperature-controlled cylinder and passed through a regulator and series of needle valves to the inlets of the fumigated chambers. The concentration of sulfur dioxide was measured in each chamber using a timer controlled electrical sequencer in conjunction with solenoid valves. The concentration of sulfur dioxide was monitored using a Thermo Electron, Series 43 pulsed fluorescent ambient sulfur dioxide analyser, calibrated with a Thermo Electron, Model 145 calibrator, with NBS traceable certified permeation tubes.

The concentrations selected for this work were based upon field experience. The concentrations stated in Table 1 are eight hour averages. Daily averages were almost a third of these concentrations. In 1979-80 in a market garden region near an industrial area south of Perth, Western Australia, the 24-hour average concentration of SO_2 exceeded 100 $\mu g\ m^{-3}$ on 49 occasions, and 150 $\mu g\ m^{-3}$ was exceeded on 19 occasions (Department of Conservation and Environment, 1982). Although SO_2 concentrations have now decreased considerably at this site, much higher concentrations for shorter durations occur in the Kalgoorlie area (Environmental Protection Authority, personal communication).

RESULTS AND DISCUSSION

The data for SO_2 and yield change in the crop species were used to establish a concentration-response relationship for SO_2 (Figure 2). This provides a useful basis for predicting yield changes for these particular species, at various SO_2 concentrations. It can be seen that at concentrations of about 130 $\mu g\ m^{-3}$ two out of five crops had an increased yield. At SO_2 concentrations of about 270 $\mu g\ m^{-3}$ navy beans had a slight increase in yield but wheat and soybean had decreases of more than 20%. On the basis of these response curves, the crops may be arbitrarily categorised into response groupings.

A plot of SO_2 concentration against average yield change for all species shows a small increase (about 2%) in yield at about 130 $\mu g\ m^{-3}$ and a decrease of about 13% at 270 $\mu g\ m^{-3}$, in comparison with controls (<13 $\mu g\ m^{-3}$). The critical concentration of SO_2 for zero yield loss is established to be about 150 $\mu g\ m^{-3}$ (Figure 2).

A linear regression of percentage yield change and $\log_{10}$ transformed dose (SO_2 concentration x exposure duration in hours) provides a description of yield loss potential with the following regression (Figure 3):

$$\%\ \text{yield change} = 81.11 - 52.06\ (\log_{10}\ \text{dose}) \quad (r = -0.90)$$

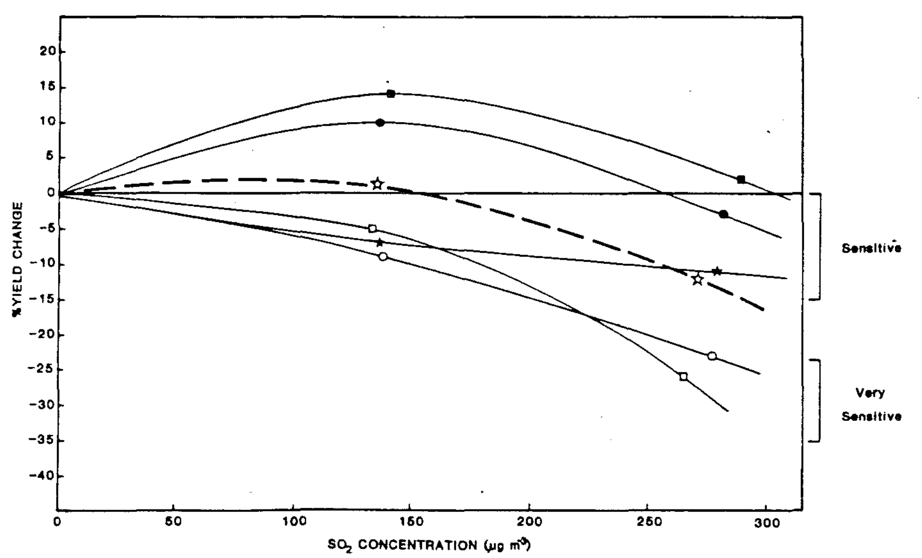

Figure 2: SO_2 concentration — response relationships for 5 crop species: wheat (□), navybeans (■), peanuts (★) soybeans (O) and maize (●). A generalised curve for the data is represented by (☆).

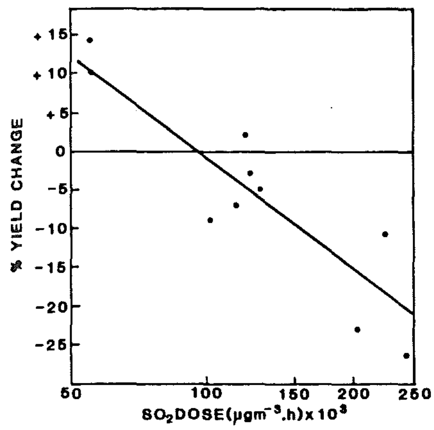

Figure 3: The effect of increasing dose on yield.

This regression provides a critical dose estimate of 95.8 x 10^3 $\mu g\ m^{-3}$ hours ($\mu g\ m^{-3}.h$) below which yield is not reduced.

The apparent growth stimulation at low concentrations of SO_2 is consistent with other studies which have shown that low concentrations of SO_2 can lead to increased growth of crops and trees. Sulfur is an essential element for plants. Field crops may require 10-40 kg ha^{-1} yr^{-1} of available sulfur (Noggle, 1980). However, plants can use SO_2 from the atmosphere and metabolise it to sulfur-containing metabolites to supplement root-acquired sulfur (Rennenberg, 1984). Low concentrations of SO_2 have caused growth-stimulation in crops and trees under controlled exposure conditions (Freer-Smith, 1985; Cowling & Lockyer, 1976), under field fumigations (Lauenroth et al., 1983; Murray, 1985 a,b; Milchunas et al., 1981; Baker et al., 1986) and around emission sources (Lambert et al., 1979). If soils are sulfur-deficient and sulfur is limiting growth, SO_2 can induce a growth stimulation (Cowling and Lockyer, 1976; Lockyer and Cowling, 1981). However, even plants with apparently adequate sulfur nutrition can show a small growth-stimulation when exposed to low concentrations of SO_2. This has been demonstrated in *Agropyron* (Milchunas et al., 1981) barley (Baker et al., 1986) and lucerne (Murray, 1985b). With increasing concentrations or duration of exposure, this initial stimulation becomes inhibitory as the derivatives of SO_2 within the plant accumulate to toxic levels. The concentrations and durations at which this occurs vary for different species or plant types. For example, many crop plants have high protein synthesis rates and consequently have a high demand for sulfur. Accordingly they may be less sensitive to SO_2 than plants with low protein synthesis rates, such as forest trees (Laisk et al., 1988). Under SO_2 exposure conditions in Australia, with many areas always exposed to very low SO_2 concentrations, with low natural sulfur contents of soils (Freney and Williams, 1980) and with crop sulfur deficiency occurring in some regions (Glendinning, 1980), there is the possibility of sulfur-induced growth stimulation. However, in localised areas near emission sources, ground level concentrations are high enough to damage crops, trees and other vegetation, although damage to economically important plants is not common.

It is known that plants are especially sensitive to air pollutants at certain stages in the growing cycle, especially the seedling stage for effects on growth, and the flowering stage for effects on grain and fruit yield. Plants may be very sensitive under certain climatic conditions, especially freezing temperatures (Davison and Bailey, 1982) accompanied by moderate wind speeds (Lane and Bell, 1984) and low light intensity (Davies, 1980). As this experiment continued from the seedling stage until harvest, the model represents a whole season dose response function, including all sensitive climatic and growth cycle stages experienced in the area in which the plants were grown.

The data used in the model were obtained from intermittent exposures of eight hours per day. The results may also be applicable to other situations involving fluctuating concentrations of pollutants as studies have shown that long-term mean concentrations, rather than peak fluctuations around the mean, are important in determining the effects of SO_2 on plants (Garsed et al., 1982; Jones and Mansfield, 1982; Lane and Bell, 1984).

Although it may be expected that continuous fumigations would result in quite different regressions between SO_2 concentration and yield reduction, compared to intermittent fumigations, this does not appear to be the case. In his review of yield changes after continuous exposure for more than 20 days to less than 50 ppb, 35 data points from 9 species gave a regression line very similar to the line for soybeans in Figure 2 (Roberts, 1984). The effect on yield of a concentration of SO_2 in chronic exposure, long duration experiments may be similar whether the exposure is continuous, 24h/day, or long intermittent, eg 8h/day. However, the concentrations required to produce a given response may be slightly lower for continuous fumigation. In contrast, the results of acute exposures to very high concentrations for short durations are quite different. Acute fumigations elicit a totally different plant response from chronic fumigations, at a biochemical and a whole plant level (Garsed, 1984). Accordingly, dose-response regressions for yield based on very high concentrations and short durations result in quite different response descriptors. Responses to both acute and chronic exposure need to be considered when evaluating data to establish air quality criteria.

CONCLUSION

The continuing increase in mass emissions of SO_2 in Australia requires an assessment of implications. This study investigated the relationship between exposure concentrations of SO_2, and the response of five crops growing under ambient conditions in the field. It showed that, although navy beans and maize showed a slight increase or no change in yield when exposed to SO_2 concentrations up to 285 $\mu g\ m^{-3}$, yield of peanuts was reduced by about 5 and 10% at 140 and 280 $\mu g\ m^{-3}$, respectively and yield of wheat and soybean were reduced by about 5 and 25% at 135 and 275 $\mu g\ m^{-3}$ respectively, when these concentrations were maintained for eight hours per day.

Further work with shorter daily exposure durations and a wider range of species will help establish the SO_2 concentrations likely to damage the crops and native vegetation of Australia.

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