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EFFECTS OF SULFUR OXIDES IN THE ATMOSPHERE ON VEGETATION;

Revised Chapter 5 for Air Quality Criteria for Sulfur Oxides

Task 16
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NATIONAL ENVIRONMENTAL RESEARCH CENTER
OFFICE OF RESEARCH AND DEVELOPMENT
U.S. ENVIRONMENTAL PROTECTION AGENCY
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RESEARCH REPORTING SERIES

Research reports of the Office of Research and Development, Environmental Protection Agency, have been grouped into five series. These five broad categories were established to facilitate further development and application of environmental technology. Elimination of traditional grouping was consciously planned to foster technology transfer and a maximum interface in related fields. The five series are:

1. Environmental Health Effects Research
2. Environmental Protection Technology
3. Ecological Research
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This report has been assigned to the ECOLOGICAL RESEARCH series. This series describes research on the effects of pollution on humans, plant and animal species, and materials. Problems are assessed for their long- and short-term influences. Investigations include formation, transport, and pathway studies to determine the fate of pollutants and their effects. This work provides the technical basis for setting standards to minimize undesirable changes in living organisms in the aquatic, terrestrial, and atmospheric environments.

PREFACE

Air quality criteria state what science has thus far been able to measure of the obvious as well as the insidious effects of air pollution on man and his environment. Criteria provide the most useful basis presently available for determining the levels of air pollutants that will protect the public health and welfare. The Clean Air Act states: "Air quality criteria for an air pollutant shall accurately reflect the latest scientific knowledge useful in indicating the kind and extent of all identifiable effects on public health or welfare which may be expected from the presence of such pollutant in the ambient air, in varying quantities."

*Air Quality Criteria for Sulfur Oxides** was issued under the 1967 amendments to the Clean Air Act. National ambient air quality standards were proposed, based on these criteria, and were promulgated under the 1970 amendments to the Clean Air Act.

The Clean Air Act states that the Administrator of the Environmental Protection Agency (EPA) "shall from time to time review, and, as appropriate, modify, and reissue any criteria . . ." Limitations in the criteria for secondary standards in *Air Quality Criteria for Sulfur Oxides,** which became apparent since the adoption of Air Quality Standards, prompted review and revision of Chapter 5, "Effects of Sulfur Oxides in the Atmosphere on Vegetation." This document presents the revision to Chapter 5, and also includes revised portions of Chapter 10, "Summary and Conclusions," that relate to effects on vegetation.

This revision includes a number of studies completed since initial publication in 1969. All data expressed in micrograms per cubic meter are referenced to 25° C and a pressure of 1013.2 mb (760 mm Hg) unless stated otherwise.

Following the initial revision by EPA personnel, there was a sequence of review and revision by (1) the National Air Quality Criteria Advisory Committee, which has a membership broadly representative of industry, universities, conservation interests, and all levels of government, and by (2) individuals specially selected for their competence, expertise, or special interest in the effects of air pollutants on vegetation. The efforts of these reviewers, without which this document could not have been completed successfully, are acknowledged individually on the following pages.

As required by the Clean Air Act, appropriate Federal departments and agencies were consulted prior to issuing this criteria document. A Federal consultation committee, comprised of members designated by the heads of departments and agencies, reviewed the document and met with EPA staff members to discuss their comments. These representatives are also listed following this discussion.

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*Air Quality Criteria for Sulfur Oxides. U.S. Department of Health Education and Welfare, National Air Pollution Control Administration. Washington, D.C. Publication No. AP-50. January 1969. 178 p.

The EPA is pleased to acknowledge the efforts of each of the persons specifically named, as well as the many not named, who contributed to producing this document. Their participation does not necessarily imply complete endorsement of all the conclusions presented herein; in the last analysis, the Environmental Protection Agency alone retains full responsibility for its contents.

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INTRODUCTION

Pursuant to authority delegated to the Administrator of the Environmental Protection Agency, Revised Chapter 5 of *Air Quality Criteria for Sulfur Oxides, Effects of Sulfur Oxides in the Atmosphere on Vegetation,* including revisions to related parts of Chapter 10, "Summary and Conclusions," is issued in accordance with Section 108 of the Clean Air Act (42 U.S.C. 1857 *et seq.).*

Air quality *criteria* are an expression of the scientific knowledge of the relationship between various concentrations of pollutants in the air and their adverse effects on man and his environment. Air quality criteria are descriptive; that is, they describe the effects that have been observed to occur when the ambient air level of a pollutant has reached or exceeded a specific figure for a specific time period. In developing and using criteria, many factors have to be considered. The chemical and physical characteristics of the pollutants and the techniques available for measuring these characteristics must be considered, along with exposure time, relative humidity, and other conditions of the environment. The criteria must consider the contribution of all such variables to the effects of air pollution. Further, the individual characteristics of the receptor must be taken into account.

The criteria in this document serve as the bases for National Secondary Ambient Air Quality Standards. National Secondary Ambient Air Quality Standards specify a level of air quality, the attainment and maintenance of which in the judgment of the Administrator, based on criteria, are requisite to protect the public welfare from any known or anticipated adverse effects associated with the presence of such air pollutant in the ambient air.

Upon promulgation of the standards, each State must prepare implementation plans that describe how these standards will be met. The Clean Air Act has provisions ensuring that a plan is prepared and carried out by each State or by EPA where States default or otherwise are judged incapable of meeting the standards.

CONTENTS

Page

LIST OF TABLES

EFFECTS OF SULFUR OXIDES IN THE ATMOSPHERE ON VEGETATION;

Revised Chapter 5 for Air Quality Criteria for Sulfur Oxides

A. GENERAL

The sulfur oxides represent one category of pollutants that affect plant life. Within this category of pollutants, sulfur dioxide (SO_2) appears to be the major causal agent of plant injury, although plants may respond to other compounds of sulfur such as sulfuric acid aerosols. In one of the earliest reports concerning SO_2 injury to plants, Stoeckhardt,[1] in 1871, discussed smoke damage to forest trees in Germany. Since this early report, extensive experiments and observations of the effects of SO_2 on vegetation have been made by investigators in all parts of the world. Thomas,[2,3] Brandt and Heck,[4] Katz and McCallum,[5] and Daines,[6] have written reviews of these studies. Studies of the effects of sulfur oxides upon vegetation need to be continued if the manner in which sulfur oxides cause plant injury is to be understood.

Plants vary greatly in their response to SO_2. This variation in response by plants is due to their genetic composition, to their response to environmental factors, individually and in combination, and to the time-concentration relationship of SO_2 by itself and in combination with other atmospheric pollutants. Variation in any one of the complex of interacting factors will result in a variation in plant response.

This document is not intended as a complete, detailed literature review, and it does not cite every published article relating to effects of sulfur oxides in the ambient atmosphere upon vegetation. However, the literature, comprising more than 700 articles, has been reviewed thoroughly for information related to the development of criteria. The document, based on both professional and scientific judgment, not only summarizes the current scientific knowledge of air pollution effects by sulfur oxides upon vegetation, but also points up the major deficiencies in that knowledge.

B. SYMPTOMS OF THE EFFECTS OF SULFUR DIOXIDE ON VEGETATION

The effects of SO_2 upon plants can be classified into two general categories: *visible effects* and *subtle effects. Visible effects* are identifiable pigmented or necrotic foliar patterns that result from major physiological disturbances to plant cells. *Subtle effects* are those that are not visibly identifiable but result in measurable growth or physiological changes in the plant. *Subtle effects* are not visibly identifiable and can be identified only when measurable growth or physiological changes occur in the plant. Both visible and subtle effects are *physiological effects* and result from the disturbance of biochemical processes at the molecular level. Whether or not the biochemical disturbances give rise to visible symptoms determines the category to which they are assigned.

1. Visible Effects

Visible effects to plants can be further classified into *acute* and *chronic injury. Acute injury* is severe injury that occurs within a few hours after exposure and is characterized by the collapse of cells with the subsequent development of necrotic patterns. It is associated with high, short-term SO_2 concentrations, although severe injury, similar to acute injury, may develop from chronic exposures. *Chronic injury* is light to severe injury that developes from exposure over an extended time period. It is associated with long-term exposures where the pollutant concentration is sufficiently high to produce some cell destruction or disruption. It is identifiable by chlorotic or other pigmented patterns and in some instances is associated with necrotic markings. Acute injury symptoms are generally more characteristic of a specific pollutant than those of chronic injury, which are not necessarily specific for a particular toxic agent. Insects, nutrition, microbiotic diseases, and other factors can produce leaf injury patterns similar to those induced by SO_2.

Foliar symptoms in plants have often provided the first indication of a pollution problem; however, since SO_2 type symptoms may result from other abiotic and/or biotic influences, related evidence must be considered before attributing injury to SO_2. The related evidence should include a knowledge of SO_2 sources and observations showing decreased injury levels with increasing distance from the source. Monitoring of pollution concentrations, consideration of meteorological conditions, and observation of several plant species, especially when symptoms are not characteristic, can also aid in the diagnosis of injury. The use of field chambers from which pollution has been removed may also contribute to identifying the cause of injury.

Descriptions of SO_2 injury are found in numerous publications.[2,3,6-9] These reports also consider symptoms caused by other pollutants and various biotic and environmental stresses that may produce symptoms resembling those caused by SO_2. Summaries of effects on a large number of plant species susceptible to SO_2 are given by Wood[10] and by Middleton and Taylor.[11] Three pictorial atlases document visual SO_2 symptoms[12-14] and include detailed descriptions of injury with a listing of SO_2 susceptible species.

a. Acute Injury[12,13]

Acute symptoms of SO_2 injury result from the rapid absorption of toxic concentrations of the gas. In broad-leaved plants, tissues in sharply defined marginal and interveinal areas take on a dull water-soaked appearance immediately after exposure. These areas subsequently dry and may bleach to ivory or become brown to reddish-brown in color. The separation of injured areas from surrounding, apparently healthy, tissue is usually distinct. Injury seldom extends across leaf veins unless the injury is severe.

The basic bleached and collapsed blotches described on broad-leaved plants are, however, also typical of grass foliage. The final bleached pattern between the parallel veins of grass leaves gives a streaked effect.

Acute injury of conifers usually occurs in bands on needle tips, with injured areas taking on a red-brown color. Injured areas change from the usual dark green color to a lighter green, and lesions develop yellow-brown and finally red-brown coloration. In severe cases, discoloration may involve the whole needle. The affected trees usually cast their needles prematurely.

b. Chronic Injury[12,13]

Low concentrations of sulfur dioxide require several days or weeks to cause the development of the yellowing or chlorotic symptoms of chronic injury. The chlorotic effect, with varied color patterns, often resembles premature senescence. Necrosis may develop in some plants, resulting in white bleached areas or red to brown coloration, which may resemble acute injury. Chronic injury may be followed by leaf abscission. A large amount of sulfate is found in leaves with chronic symptoms, whereas leaves that are acutely injured show only a small increase in sulfate content. However, large quantities of sulfate may accumulate in leaf tissue without visible leaf symptoms.[15,16] Both acute and chronic injury symptoms may develop upon the same plant. The period of development and the sensitivity of the plant to particular sulfur dioxide concentrations are important in differentiating the type of injury.

Chronic injury, when exhibited on plants exposed to SO_2, is due to either short-term peaks or long-term average concentrations. The general consensus of most investigators is that short-term peaks are more important than long-term averages.

2. Subtle Effects

Subtle effects, as a concept, implies that SO_2 can interfere with physiological and biochemical processes and with plant growth and yield without attendant development of visible symptoms. The processes are microscopic or molecular in nature. Therefore, in order to determine their existence, studies have to be conducted that can detect whether measureable changes in the rate of photosynthesis, in stomatal behavior, and in growth or yield have occurred.

3. Physiological Effects

Physiological effects include both visible and subtle effects. Both types of effects result from the disturbance of physiological processes at the molecular level. Whether or not the physiological changes give rise to visible symptoms determines to which category they are assigned.

a. *Photosynthesis*

Wislicenus[17] indirectly related SO_2 to photosynthesis in demonstrating that the sensitivity of spruce to SO_2 was proportional to light intensity. Thomas and Hill[18] and Katz[9] reported that exposures of alfalfa to high concentrations of SO_2 for short time periods resulted in a transitory reduction in carbon dioxide (CO_2) assimilation; recovery began within an hour after treatment. In the latter experiments,[9] the CO_2 suppression response was recorded for about 2 days. Katz and Lathe[8] and Katz[9] reported that SO_2 concentrations of 262 to 524 $\mu g/m^3$ (0.1 to 0.2 ppm) did not affect photosynthesis, respiration, stomatal behavior, or growth but that concentrations above 1048 $\mu g/m^3$ (0.4 ppm) did affect sensitive plants, if the stomata were open.

These results and the research of others[19,20] indicate that the rate of photosynthesis is reduced soon after sensitive plants are exposed to SO_2. If visible injury does not occur, the photosynthetic rate returns to normal after exposure terminates, but if injury results, complete recovery is not attained. The magnitude of the photosynthetic response varies with respect to pollutant concentrations, environmental influences, and plant sensitivity.[21-24]

Recent information indicated that SO_2 was reduced to hydrogen sulfide (H_2S) by several plant species during and after fumigation.[25-27] This reaction may be associated with photosynthesis, since the response was obtained only in the presence of light.[27]

b. *Stomatal Relationships*

Stomata are the principal avenue of SO_2 entrance into plant leaves. Conditions that favor open stomata result in increased SO_2 assimilation and increased plant sensitivity.[3,9,28] Majernik and Mansfield[29,30] demonstrated a stimulation of stomatal opening in bean plants when they were exposed to SO_2 at relative humidities above 40 percent but a suppression of stomatal opening at a relative humidity of 32 percent.

Katz[9] found a slight reduction in the number of open stomata after exposing alfalfa to 2358 $\mu g/m^3$ (0.9 ppm) of SO_2 and a significant reduction after exposure to 2620 $\mu g/m^3$ (1 ppm). Continuous fumigation at an average concentration of 1050 $\mu g/m^3$ (0.4 ppm) did not influence stomatal opening until acute injury symptoms developed. Vogl[19] reported that stomata of pine remained open after plants were injured. Neither of these reports included humidity conditions.

Spedding[31] presented information that suggested that humidity influenced the assimilation of SO_2 when stomata were closed and that SO_2 also entered plant tissues through the cuticle.

c. *Changes in Chemical Composition*

Sulfur dioxide exposures may result in changes in the chemical composition of plants. Materna[32] found increases in sulfur and potassium levels when spruce needles were exposed in spring, but calcium and magnesium levels were not affected. For citrus leaves, calcium and potassium levels decreased during winter exposures; however, in the summer, calcium levels were not affected and potassium content increased.[33] Materna[34] reported increases in the silicic acid content of spruce needles injured by SO_2.

Arndt[35] demonstrated increases in amino acid concentrations of herbaceous plants after exposure to 660 $\mu g/m^3$ (0.25 ppm) SO_2. The amount of increase depended on specific amino acids and plant species. In exposures producing chronic injury, Boertitz[21] reported no significant change in pH, carbohydrate, or amino acid content of extracts from spruce needles; however, in more recent field studies of the Ore Mountain area, he found increases in the carbohydrate levels and pH values of needle extracts.[36]

Injury resulting from chronic SO_2 exposure can usually be confirmed by the presence of high sulfur content in leaves, although variation in normal sulfur content must be considered.[7,37] In Japan,[38] sulfur content of citrus leaves correlated with atmospheric SO_2 concentrations. Katz[9] demonstrated that sulfur content increased with time of exposure. Under natural conditions, analysis can reflect the degree of pollution to which vegetation has been exposed. In some industrial areas, McCool and Johnson[39] found a decrease in sulfur content of vegetation with an increase in distance from the SO_2 source.

d. Growth and Yield Reductions

Growth and yield reductions may result in the absence of visible injury. Tingey *et al.*[40] demonstrated reduced root weights of radish when exposed to SO_2 concentrations of 131 to 160 $\mu g/m^3$ (0.05 to 0.06 ppm) for 40 hr/week for 5 weeks in greenhouse exposure chambers; however, the second run of the experiment did not produce the same plant response. Other studies by Reinert *et al.*[41] showed reductions in several growth parameters for Bel W_3 tobacco when exposed to 262 $\mu g/m^3$ (0.1 ppm) SO_2, 8 hr/day, 5 days/week, for 4 weeks in greenhouse exposure chambers. Bel W_3 is a variety of tobacco extremely sensitive to injury by SO_2 and has been used as a plant monitor. Both of the above studies were conducted under conditions which would seldom, if ever, be found in the ambient air. More studies are needed to verify the results.

In ambient air studies, Bleasdale[42] reported that growth of rye grass was reduced when the maximum average SO_2 concentrations for 24 hours were between 262 and 524 $\mu g/m^3$ (0.1 and 0.2 ppm) for 2 and 3 days during experiments of 63 and 73 days. In this study, interactions with pollutants other than SO_2 were not considered and may have contributed to the observed growth response.

C. MECHANISM OF ACTION

The mechanism by which plants are injured by SO_2 is not understood. Transient physiological effects, subtle growth reductions, and acute injury symptoms may result from the formation of sulfite ions and their effect on membrane integrity. Acute injury does not occur if the rate of SO_2 absorption does not exceed the capacity of the plant to oxidize the sulfite to sulfate ions. Under long-term SO_2 stress, sulfates thus formed may accumulate with the subsequent development of chronic injury symptoms.[33]

D. FACTORS AFFECTING RESPONSE OF VEGETATION TO SULFUR DIOXIDE

The response of a given variety or species of plants to a specific air pollutant cannot be predetermined on the basis of the known response of related plants to the same pollutant. Neither can the response be predetermined by a given response of a plant to similar doses of different pollutants. The interplay of genetic susceptibility, growth stage, and environmental influences must be considered for each plant and pollutant. No one factor may be considered independently of the other factors.

1. Environmental Factors

a. Temperature

Plants are more resistant to SO_2 at temperatures below 40° F.[43-47] Setterstrom and Zimmerman[43] reported that buckwheat was equally susceptible to injury at 65° and 105°F. Several investigators[9,48] have reported greater resistance in conifers during the winter and have related this to lower physiological activity of plants. Resistance may increase during winter dormancy with low gas exchange rates; however, even at low levels of physiological activity, conifers may be injured, especially in areas with higher SO_2 concentration during winter months. In addition, temperatures are often near 40° F during winter seasons in many areas. Van Haut and Stratmann[13] indicated that conifers remain sensitive during the winter when water is available to them. In the spring, with increases in physiological activity, sensitivity to SO_2 also increases. On the basis of studies with Douglas fir and yellow pine, Katz[9] reported that in the spring, with increases in physiological activity, sensitivity to SO_2 also increases. Exposures to SO_2 at concentrations of 1965 $\mu g/m^3$ (0.75 ppm) for 147 hours near the end of the winter dormancy period resulted in foliar injury of 55 percent; however, in early autumn this concentration was applied for 334 hours without the development of injury. For spruce, experiments have demonstrated increased sensitivity in the spring and autumn when compared with summer and winter seasons.[49]

b. Humidity

Sensitivity to SO_2 tends to increase with increasing humidity.[43-45] Wells[45] noted that in the Salt Lake Valley 70 percent appeared to be the critical humidity level. Above 70 percent, plants were much more susceptible to injury by sulfur dioxide than below. Swain[44] concurred but stated that increases in relative humidity (RH) from 70 to 100 percent did not result in much increase in sensitivity. In 1-hour exposures at an average concentration of 3537 $\mu g/m^3$ (1.35 ppm) SO_2, Zimmerman and Crocker[50] found that variations between 50 and 75 percent RH had little effect on plant sensitivity. Setterstrom and Zimmerman[43] concluded that for RH values above 40 percent, differences of 20 percent RH are required to produce detectable differences in sensitivity; however, they mention that O'Gara in an address before the American Institute of Chemical Engineers stated that plants were three times as sensitive at an RH of 100 percent as at 30 percent. Thomas and Hendricks[28] reported a 90 percent loss in sensitivity when RH was reduced from 100 to 0 percent. Generally, resistance to injury by sulfur dioxide seems to be associated with decreasing relative humidity; however, variations associated with a particular plant species or with environmental conditions do exist.

Under conditions of high humidity, a sulfuric acid mist may form. In fog,[51,52] this acid mist may cause leaf spotting on several plant species.

c. Light

Setterstrom and Zimmerman[43] reported that buckwheat was more susceptible to injury from SO_2 when grown under conditions of reduced light intensity. A 65 percent reduction in light intensity (to approximately 3000 foot-candles) resulted in greater susceptibility than that for plants grown in full sunlight (approximately 10,000 to 12,000 foot-candles) or under conditions of 25 and 35 percent reduction in light intensity. Light received prior to treatment affected sensitivity, since plants kept in the dark for 2 hours preceding SO_2 exposure were more resistant than comparable plants kept in the light.[50] Plants are 5 to 6 times as resistant to SO_2 in the dark as in the light.[13,45] Since stomata of most plants are closed during darkness, plants are more tolerant of SO_2 in the absence of light. In studies conducted at night with exposure to 2227 $\mu g/m^3$ (0.85 ppm) for 4 hours, foliar injury of alfalfa, tomato, buckwheat, sweet clover, oats, rye, and barley was not observed; however, injury resulted during daylight exposures of 2096 $\mu g/m^3$ (0.8 ppm) of SO_2 for periods of 1 or 2 hours.[50] In experiments with bush beans, SO_2 exposures that produced moderate injury during the day had no effect at night.[13,53] However, when plants were exposed during the day following a night exposure, injury was greater than the single day exposure. The reverse order also resulted in increased injury, as did exposure under continuous light for 24 hours.

d. Edaphic Factors

Plants are more sensitive to SO_2 when adequate soil moisture is available for normal plant growth. Minor variations in soil moisture have no detectable effect on sensitivity; however, when moisture content approaches the wilting point or if wilting occurs, plant resistance increases.[9,43,50,54] Brandt and Heck[4] recommended withholding water from greenhouse and irrigated crops during periods of high pollution potential as a preventative measure for reducing damage.

Investigations of the effect of soil nutrient levels in relation to plant sensitivity have involved comparisons of plants growing under various nutritional or fertilization levels. Such studies indicate an increased resistance with increased fertilization in rape, spinach, and radish.[54] Varied results have been recorded for pine.[55-57] In the Ore Mountains of Czechoslovakia,[34] nutrient applications resulted in an increase in resistance to SO_2 for several tree species. In field and laboratory experiments, Cotrufo and Berry[58] found a reduction in SO_2 induced needle necrosis of several white pine clones after fertilizer applications. In contrast, deficiencies of nitrogen and sulfur were correlated with increased resistance for tobacco and tomato.[59] With alfalfa,[43] nutrient deficient conditions increased sensitivity, but with oats, increases in nitrogen and other nutrients were associated with increased sensitivity.[54]

Few studies have considered the influence of soil structure, soil temperature, aeration, and the biotic complex on plant sensitivity. Brandt and Heck[4] state that sensitivity is reduced when plants are grown in heavy soils. This may be the result of lower oxygen tensions. In studies involving three plant species and four soil types, Guderian[60] found that plant injury varied in respect to soil type, nitrogen application, and species of plant.

e. Diurnal Changes

The sensitivity of plants to SO_2 may vary during the day. Factors that favor open stomata and photosynthesis also favor SO_2 assimilation. Under these conditions, plants are more sensitive during the morning than during the afternoon. Thomas and Hendricks[28] concluded that on a cloudless day exposure of alfalfa early in the morning resulted in only slight injury, while exposure later in the morning resulted in increased injury; plants exposed between late morning and mid-afternoon had decreased injury, with the most rapid decrease later in the day. Although climatic conditions and stomatal movements are important factors in diurnal injury patterns, decreases in sensitivity during afternoon periods may be related to the accumulation of carbohydrates in leaves[13,28] or to an increase in buffering capacity of plant tissues.[54]

f. Interactions with Other Pollutants

Ambient air is composed of many different pollutants. A few studies have considered this fact, but most studies deal with single pollutant effects. The interaction of ozone (O_3) with SO_2 was first reported on Bel W_3 tobacco by Menser and Heggestad.[61] The interaction of these air pollutants affecting injury and growth in several other species has been reported.[62-64] Injury to six plant species from the interaction of nitrogen dioxide (NO_2) and SO_2 has recently been reported.[65] Growth and injury results are further discussed in Section J.2. The interactions shown between SO_2 and other pollutants offers a partial explanation for occasional inconsistencies between results obtained in laboratory studies in which only single pollutants were used and the results obtained in the natural environment. For example, growth reductions of radish occurring after exposures to mixtures of SO_2/O_3 were greater than reductions from SO_2 alone.

2. Genetic Factors

Plant sensitivity to SO_2 can be considered as a function of morphological and biochemical characteristics controlled by the genetic plasticity of the plants within a population. Thus, some plants are more sensitive than others to pollution stress. Both inter- and intraspecific differences in sensitivity occur. For example, sensitivity variations within species have been demonstrated with spruce[66] and white pine.[67] In this regard, SO_2 acts as a selection pressure mechanism. The more resistant variants within a species continue normal growth and existence, but under this SO_2 pressure, the more sensitive types weaken and may not survive within the polluted area.

Shapiro, Servis, and Welcher,[68] based on experiments conducted with isolated DNA and bacteria, using sodium bisulfite, have suggested that SO_2 in the atmosphere may constitute a genetic hazard. At present, however, there is no basis for extrapolating from such experiments to living organisms that are structurally and functionally more complex.

3. Stage of Development

The growth stage or phase of development at which plants are exposed to SO_2 affects their susceptibility and the yield losses associated with injury. Wells[69] reported that barley yields were slightly reduced by SO_2 exposures when plants were from 10 to 60 cm high, but that yields were reduced by 20 to 30 percent if plants were exposed during early grain development. For wheat, Brisley and Jones[70] demonstrated greater yield reductions with exposure in the early stages of growth than in later stages. Thomas[71] demonstrated that injury to cereals at tillering could be sustained with little loss in yield, but that yield was reduced much more by injury after culms had formed. In several plant species, van Haut[53] reported a "critical development stage" in which there was a high probability that leaf injury would result in reduced yield. This critical stage occurred with bean shortly before flowering and during pod growth; with radish, at the young seedling stage and again as the roots began to increase in size; and with oats just before panicle emergence, at flowering, and during flower opening.

The leaves of most plants are more sensitive to SO_2 just after maximum expansion has occurred. Developing and older leaves tend to be more resistant.[7,43,53] Variation in susceptibility between species has been observed. Van Haut[53] found that needles of pine and larch are very sensitive to SO_2 before growth has been completed.

E. PROBLEMS OF DIAGNOSIS AND ASSESSMENT OF THE ECONOMIC IMPACT OF SULFUR DIOXIDE

The plant is a product of its environment. Every environmental factor, favorable or unfavorable, produces a response in the plant. Sulfur dioxide interacts with other environmental factors such as the climate, soil, biota (insects, man, and microorganisms), and the genetic constitution of the plant to produce responses within the plant. Injury produced by SO_2 may not only be modified or obscured by these other environmental factors, but the plant may develop injuries from these other factors that are difficult or impossible to distinguish from those caused by SO_2. Ornamental and agronomic crops grown under special management practices must be carefully examined before attributing poor growth to SO_2. Many bacterial, viral, and fungal diseases, as well as insect infestation, can produce symptoms in plants that are quite similar to those produced by SO_2. To aid in making definitive diagnoses of SO_2 effects upon vegetation, injuries must be observed in the field and supported by laboratory studies using different levels of the pollutant. Laboratory and field chamber studies are essential if qualitative and quantitative models of pollutant effects upon vegetation are to be developed. Since it is impossible to include all parameters, laboratory and field chamber studies do not simulate ambient field conditions.

The question that must be answered in the assessment of SO_2 damage to plants is whether or not the plant has been so altered by the pollutant as to significantly influence its growth, survival, yield, or use. In cases where leaf injury impairs the use of the plant for food, as in the case of cabbage or lettuce, or for ornamental purposes, assessment is relatively straightforward. However, where the marketable product is not influenced by appearance, assessment of economic damage is more difficult. Hill and Thomas[72] showed that the yield of alfalfa was reduced in proportion to the area of the leaf destroyed. The economic impact of leaf injury to fruit trees is extremely difficult to assess because the effect upon the fruit is not known.

In discussing the effect of air pollution on vegetation, Guderian, van Haut, and Stratmann[73] have suggested a method of making the distinction between the terms *injury* and *damage* in cases where the effects of air pollution on vegetation is concerned. Accordingly, *injury* is defined as any identifiable and measurable response of a plant to air pollution. *Damage* resulting from air pollution injury is defined as any identifiable and measureable adverse effect upon the desired or intended use of a plant or of a product derived from the plant. Thus, in using these terms, *leaf necrosis of alfalfa is a symptom of* injury; however, any assessment of damage requires a judgment that the injury affects the yield or use of the plant.

There are instances, also, where the esthetic or sentimental value of the plants is impaired by SO_2. Examples of these are the vegetation growing on a hillside and a tree planted by a particular college or university class as a memoir of their college days. In the first instance, leaf damage or the death of the plants detracts from the view. In the second, the tree is largely of sentimental value, and its demise is extremely difficult to assess in dollars and cents.

F. EFFECTS OF LOWER ORGANISMS

The effects of SO_2 on nonvascular plants and on plant pathogens have been studied by many investigators. The majority of these studies have considered the incidence of specific organisms within areas influenced by SO_2 emissions. The absence of species of lichens and bryophytes has been correlated with the presence of low concentrations of SO_2.[74-79] Lichens have been used in the recognition and monitoring of SO_2,[80-82] and qualitative scales for estimating SO_2 concentrations have been developed on the basis of sensitivity differences among species. Skye[83] found that the diversity of species was reduced in areas with an annual SO_2 concentration of approximately 39.3 $\mu g/m^3$ (0.015 ppm) (determinations were averaged over 4-week periods). Gilbert[74] found that several species of bryophytes and lichens disappeared when winter averages (October-April) exceeded 52 $\mu g/m^3$ (0.02 ppm). In a lichen transplant study, death of the test species occurred within 29 days at locations with the highest average SO_2 concentrations. The SO_2 concentration, determined intermittently, averaged 230 $\mu g/m^3$ (0.087 ppm).[84]

The extreme sensitivity of lichens to SO_2 appears to be due to the breakdown of the algal component. Rao and LeBlanc[85] have shown that SO_2 absorption by lichens causes the decomposition of chlorophyll *a* to phaeophytin *a*. Experimentally, chlorophyll breakdown occurred when the lichens were exposed to concentrations of 13,100 $\mu g/m^3$ (5 ppm) for 24 hours.

The importance of long-term average concentrations versus many shorter terms of higher concentrations on the reaction in lichen populations awaits critical study.

The effects of SO_2 have also been investigated in relation to the occurrence of various biotic plant diseases. Koeck[86] observed the absence of mildew on oak in areas near SO_2 sources, while the disease was widespread in areas distant from these sources. Scheffer and Hedgcock[87] observed that the incidence of several rust and other fungal diseases was low in areas influenced by SO_2, but root rot caused by *Armillaria mellea* and bark beetle infestations were more prevalent on declining trees affected by SO_2. This relationship is characteristic of these secondary pathogens. For soil pathogens, population increases may be related to increases in soil acidity in addition to the presence of more susceptible hosts.[88] Saunders[89] demonstrated that SO_2 reduced the incidence and severity of the fungus *Diplocarpon rosae*, causing blackspot of roses. Results from field studies suggested that average daily concentrations above 105 $\mu g/m^3$ (0.04 ppm) SO_2 nearly eliminated the blackspot disease.

In sample areas near a Sudbury, Ontario, smelter complex, Linzon[90] noted that fewer white pine trees were affected by blister rust, heart rot, and insect infestation. In contrast, the occurrence of bark abnormalities was higher on white pine near the smelter complex than in other research areas. These abnormalities consisted of a rough bark or canker condition and a purple bark condition that appeared as an unnaturally purplish color.

In southern Poland,[91] acidification of tree bark was correlated with air pollution by SO_2. The relationship of this phenomenon to the growth and development of bark organisms has not been studied.

In severely injured conifer stands, Boesener[92] found higher populations of bark breeding insects than in stands that exhibited lower amounts of injury. Boesener indicated that the high insect populations accelerated tree decline. In another insect population study, Przybylski[93] observed increases in aphid populations in areas near an SO_2 source. He concluded that this increase may be related to reductions in aphid predators.

G. ACID PRECIPITATION

The oxidation and the solution of SO_2 in water has increased the acidity of precipitation in several areas of the world. Based on pH values dating from 1955, Oden[94] reported an increase in acidity of precipitation over a 12-year period in Sweden. The lowest single value, a pH of 2.8, was recorded in 1967. A similar trend has been reported in the northeastern United States. Within this region, the lowest annual average pH of 4.03 was recorded at the Hubbard Brook Experimental Forest, New Hampshire.[95] At Hubbard Brook, the lowest single pH was 3.0. Such trends have been related to SO_2 and to some extent to oxides of nitrogen (NO_X) emissions from industrial complexes within these areas. In addition, particulate matter emitted from combustion processes also contributes to increased acidity.[96,97]

Values associated with nonindustrialized areas are also lower than the neutral pH of 7.0, but these values are related to the conversion of normal atmospheric CO_2 to carbonic acid rather than to the stronger acids resulting from reactions with SO_2. In these nonindustrial areas, pH values between 4.9 and 6.8[98-101] have been recorded.

The acidic precipitation has resulted in increased acidity of soils, rivers, and lakes.[7,71,94,102] Several researchers have related increased soil and water acidification to ground level concentrations of SO_2.[7,102,103] Increases in soil acidity can affect the availability of plant nutrients and change the species composition of soil microorganisms, with possible concomitant reductions in the rates of mineralization and decomposition processes.[94,104,105] Changes in these processes can affect the growth and development of higher plants. Although soil acidification did not appear to affect decomposition processes in an arid industrialized region of Czechoslovakia, the number of aerobic bacteria and actinomycetes was reduced in research plots near the pollutant source, while increases in fungal populations were recorded.[79] Fungi are more tolerant of acidic conditions.

Oden[94] indicated that effects on plant growth are related to the content of basic compounds in the soil. In this regard, soils of basic composition, such as arable soils, are more resistant to pH change. Calculations have revealed that acidification of these soils will require a time period of 125 to 1000 years. This period could increase with weathering and application of lime to soils. For forest soils, which tend to be more acidic, this time period is only 30 to 50 years. Sandy soils are affected most by the acidification reaction; whereas, soils of limestone and basalts are affected least because weathering of these materials effectively neutralizes the acidic effect.

Conclusive evidence involving the effect of soil acidification on forest productivity has not been presented; however, several reports have described possible influences.[105] In Norway and Sweden, the amount of calcium in upper soil zones was related to forest productivity. This relation was based on the conversion of calcium carbonate ($CaCO_3$) to a more soluble calcium sulfate ($CaSO_4$) compound by the action of sulfuric acid (H_2SO_4) from precipitation. Compounds of calcium were then removed from the soil by leaching and run-off. Growth effects were estimated from the relationships of acid deposition to calcium removal and the effect of reduced quantities of calcium on forest growth. Based on this information, an annual decrease in growth of about 1 percent per year was determined.

Other investigations in Sweden have compared tree growth in areas affected by acidification with relatively unaffected regions. Comparisons of the two areas indicated that tree growth was reduced in affected areas. In this case, the annual growth reduction amounted to approximately 0.3 percent per year. If the 1965 to 1970 levels of sulfur emissions remain constant, a reduction in forest growth of between 10 and 15 percent has been estimated for the year 2000.[105]

The effect of acidic precipitation on herbaceous plants has also been studied. Cohen and Ruston[106] demonstrated reductions in the growth of timothy grown in pots when plants were irrigated with acid rain and H_2SO_4 solutions at concentrations between 10 and 320 ppm. This was within the range of normal acidity levels of 5 to 100 ppm H_2SO_4.

Leaching of nutrients from plant foliage has also been associated with the increased acidity of precipitation. In the Ore Mountains, Materna[107] found that sulfur in precipitation contributed 39 kg sulfur per hectare (ha) per year to soil of an open area, whereas soil under a forest canopy received 133 kg/ha-yr. With leaf fall, an additional 10 to 20 kg/ha-yr was supplied. In addition to increases in soil acidity, leaching from plant foilage may contribute to reductions in plant nutrients, decreases in growth, and changes in foliar microflora.

The effect of increasing acidic precipitation in the northeastern United States on vegetation, streams, and the soil has not been adequately studied.

H. MISCELLANEOUS ASPECTS OF SULFUR DIOXIDE EFFECTS ON VEGETATION

Although the aspects discussed in this section do not impinge directly on air quality standards, they should be considered in any control activity. These include possible usage of vegetation as a sink for SO_2 and the effects of sulfuric acid aerosols.

1. Vegetation as a Sulfur Dioxide Sink

The maintenance of protective vegetational areas, or *green belts,* near industrial complexes has been a recent topic in urban and regional planning.[108,109] The concept of SO_2 removal by vegetation results from assimilation of SO_2 by plant foliage and the deflection of polluted air masses above vegetational areas.[108-110] Martin and Barber's[110] studies demonstrated a maximum SO_2 reduction of 157 $\mu g/m^3$-hr (0.06 ppm/hr) by hawthorne hedge. Variations in uptake were associated with the physiological activity of the plants and the environmental conditions affecting the plants. In areas containing a large number of emission sources, Wentzel[109] indicated that vegetation belts offered only limited protection. Lampadius[111] found only slight differences in SO_2 concentrations within forest stands, forest edges, and clearings. He concluded that removal of SO_2 by forest vegetation was of minor importance. Although vegetation may reduce the level of SO_2 in some instances, there is no evidence that it will have a major impact on ambient SO_2 concentrations.

2. Effects of Sulfuric Acid Mist on Vegetation

Thomas, Hendricks, and Hill[52] discussed experiments in which plants were treated with sulfuric acid aerosols at concentrations of 78,600 to 170,300 $\mu g/m^3$ (30 to 65 ppm). Sulfuric acid droplets settled on dry leaves without causing injury, but when the leaf surface was wet, a spotted type of injury developed. Middleton, Darley, and Brewer[51] and Thomas, Hendricks, and Hill[52] reported that this type of injury occurred in the Los Angeles area during periods of heavy air pollution accompanied by fog when the surface of the leaf may be wet. Injury may also occur in the absence of fog near combustion effluents containing sulfur oxides when the dew point of the gas effluent results in acid droplet formation.

The sequence of symptom development is one in which the exposed surface, usually the upper surface, shows the initial necrosis. The pH of moisture on the leaf surface may be less than 3.0. Cellular collapse and many small spots develop progressively through the upper epidermis, mesophyll, and lower epidermis of the leaf, leaving scorched areas. No glazing or bleaching accompanies this injury, and leaf areas covered by exposed leaves show no marking. In the Los Angeles area, injury of Swiss chard and beets was more nearly typical of all plant species examined. Alfalfa also developed a spotted injury pattern. Spinach, being more uniformly wetted by fog, developed a more diffuse type of injury.

I. EFFECTS ON BIOMASS AND YIELD

Although evidence has been presented (Section B.3.d) that shows a growth reduction in the absence of visible injury, the early literature supports the view that visible injury is closely correlated with yield and/or growth reductions. Thomas[3] and Katz[9] concluded that growth effects do not occur until at least

5 percent of the foliage is visibly injured. Yield reduction from acute SO_2 injury was found to be equivalent to the removal of the same amount of leaf tissue. Light to moderate defoliation of cotton from SO_2 exposure had no detrimental effect on fiber grade, staple length, or ginning percentage.[112] Guderian[113] found that the order of sensitivity, as determined by leaf necrosis and yield, was often different when comparing several grass and forage species and native plants common to open fields. For example, based on leaf necrosis, alfalfa ranked high with regard to sensitivity; however, when yield was considered, this plant ranked in the resistant category. Guderian and Stratmann[114,115] found that growth and yield of potato were progressively reduced with increased pollution intensity. In addition, seed tubers obtained from heavily polluted areas gave significantly lower yields in the following year than tubers of the same weight obtained from crops grown in control areas. *Guderian[113] reported changes in the composition of plant societies after exposure to* SO_2.

Many studies have shown that the reduction in crop yield from exposure to SO_2 is proportional to the percentage of leaf area destroyed.[8,69,70,72,116] This relationship is adequately expressed in the equation:

$$y = a - bx \tag{5-1}$$

where: y = yield expressed as percentage of control
a = a constant, approximately 100 percent
b = slope of yield/leaf-destruction curve
x = percentage of leaf area destroyed

Hill and Thomas[72] exposed field alfalfa plots to 2620 to 13,100 μg/m^3 (1 to 5 ppm) of SO_2 for a single exposure or multiple exposures of 1 to 2 hours during the growth of the crop. The equations developed show:

1. Single fumigation at early, medium, or late stage, representing either 25, 50, or 80 percent of the growth period of crop:

$$\begin{aligned} y &= 99.5 - 0.30x \\ n &= 96 \\ r &= 0.64 \pm 0.06 \\ S_y &= 7.4 \text{ percent} \end{aligned} \tag{5-2}$$

2. Double fumigation at early and medium, early and late, or medium and late stages in the growth of the crop:

$$\begin{aligned} y &= 95.5 - 0.49x \\ n &= 34 \\ r &= 0.79 \pm 0.07 \\ S_y &= 8.2 \text{ percent} \end{aligned} \tag{5-3}$$

3. Triple fumigation at early, medium, and late stages in the growth of the crop:

$$\begin{aligned} y &= 96.6 - 0.75x \\ n &= 12 \\ r &= 0.98 \pm 0.014 \\ S_y &= 4.1 \text{ percent} \end{aligned} \tag{5-4}$$

where: n = number of plots fumigated
r = correlation coefficient
S_y = standard deviation of individual yields from the regression line

Similar results were obtained by clipping a percentage of leaf tissue equal to that damaged by SO_2 from a group of test plants.[72] An equation similar to that above was developed for alfalfa using exposures of 1 to 600 hours and from 262 to 7860 μg/m^3 (0.1 to 3 ppm) of SO_2.[28]

$$\begin{aligned} y &= 99 - 0.37x \\ n &= 103 \\ r &= 0.48 \\ S_y &= 8.8 \text{ percent} \end{aligned} \tag{5-5}$$

Results from barley,[69] wheat,[70] and cotton[116] studies differ from alfalfa in that the production of grain and cotton is a measure of the yield and not of the vegetative growth. The stage of development of the plant when leaf destruction occurs is very important, with the most important stage of growth being near the time of blossom and fruit development. Examples for barley,[69] using Equation 5-1, show:

1. Early stage, less than 25 cm in height:

$$y = 98 - 0.06x \quad n = 18 \quad r = 0.13 \quad S_y = 12.2 \text{ percent} \qquad (5\text{-}6)$$

2. Heading out stage:

$$y = 98 - 0.40x \quad n = 60 \quad r = 0.74 \quad S_y = 10.2 \text{ percent} \qquad (5\text{-}7)$$

Data from experiments dealing with other crops were used in the same basic equation (5-1). Controlled additions of SO_2 in these field experiments have shown correlations between visible leaf injury and the ultimate crop yield.

The most comprehensive growth-yield experiments conducted in the vicinity of an SO_2 source were carried out in Biersdorf, Germany.[114,115,117,118] A wide variety of plants, including cereals, vegetables, trees, forage and fruit crops, were studied at five locations at differing distances from a single pollution source (Table 5-1).[114,115,118] The tests were run over the 7-month growing seasons of 1959 to 1960. Foliar symptoms were observed at all locations, and growth and yield reductions were determined by comparison with a control site free of SO_2. A review of maximum SO_2 concentrations and the percent of time that measureable SO_2 levels existed suggests that many short-term high-concentration episodes were responsible for the injury and growth reductions that occurred. The 30-minute averages are indicative of the highest values that might produce an effect in the time period used.

Growth suppression and injury development of white pines were reported by Linzon[90,119] based on data from field plots that were located up to a distance of 25 miles from a smelter complex near Sudbury, Ontario, Canada. Results from this forest ecosystem study are shown in Table 5-2.[119,120] Average SO_2 concentrations over a 10-year period for 6-month growing seasons are shown for each of three experimental locations. The frequency of 30-minute average concentrations above three values are shown to provide an indication of the maximum concentrations that might produce injury and growth effects. The net change in tree volume is used as the measure of growth.

Linzon[90] noted that persistent high concentrations of SO_2 produced certain well defined growth effects on white pine. However, there was a sharp improvement in the growth of white pine when SO_2 levels dropped below 655 $\mu g/m^3$ (0.25 ppm).

In a comprehensive study of the smelter at Trail, British Columbia, the growth of Douglas fir, yellow pine, and lodgepole pine was adversely affected for a distance of 12 to 18 miles from the smelter.[9] Daessler, Kaestner, and Ranft[121] have presented evidence showing growth reductions for several conifer and deciduous tree species growing near a zinc smelter. Chlorotic dwarf of white pine has been studied in the United States,[122] but few investigators have considered growth effect on other tree species. In Germany, the growth of European beech and larch was reduced in areas influenced by SO_2 emissions.[13]

Growth suppression in the absence of foliar injury (Section B.3.d) for ambient air exposures[42] and for controlled greenhouse exposures[40,41] are presented in Table 5-3. Reduced growth of several plants exposed in field chambers to known concentrations of SO_2 over specific time periods are also shown in Table 5-3.[113]

The results from tobacco at 262 $\mu g/m^3$ (0.1 ppm) SO_2 and radish at 131 $\mu g/m^3$ (0.05 ppm) SO_2 showed a reduction in certain growth parameters for these two species when grown under conditions of maximum sensitivity to SO_2. The conditions under which these results were obtained would probably never be duplicated under ambient conditions. These controlled studies were well conceived and reflect the best growth data available from more recent studies.

J. DOSE-INJURY RELATIONSHIP OF SULFUR DIOXIDE TO VEGETATION RESPONSE

The interrelations of time and concentration (dose) as they affect injury to plants are

Table 5-1. SULFUR DIOXIDE CONCENTRATIONS AND ASSOCIATED VEGETATIONAL EFFECTS IN RESEARCH AREAS AT BIERSDORF, GERMANY

Average concentration,[a] μg/m³ (ppm)		Maximum concentration,[b] μg/m³ (ppm)		Species	Effects[c]
1959	*1960*	*1959*	*1960*		
338 (0.129)	388 (0.145)	14,148 (5.4)	17,292 (6.6)	Wheat, rye, oats	1
				Rape, alfalfa, red clover	1,2
				Potato, beet, spinach	1,2
				Tomato, carrot	1
183 (0.070)	272 (0.104)	9432 (3.6)	17,030 (6.5)	Wheat, rye, oats	1
				Rape	2
				Alfalfa, red clover	1,2
				Potato, beets, spinach	1,2
				Carrot	1
				Apple, sweet cherry, plum, current, gooseberry	1,2,3
				Pedunculate oak, red beech, larch	3
123 (0.047)	134 (0.051)	6288 (2.4)	5764 (2.2)	Wheat, rye, oats	1
				Rape	2
				Potato, beet	1
				Alfalfa, red clover	1,2
				Spinach	2
				Apple, current, gooseberry	1,2,3
				Sweet cherry, plum	3
				Current	1,3
				Pedunculate oak, red beech, spruce, larch	3
45 (0.017)	66 (0.025)	3406 (1.3)	4978 (1.9)	Winter wheat	1
				Potato	1
				Spinach	2
				Apple	2
				Current	1,3
				Gooseberry	1,2,3
				Pedunculate oak, red beech, spruce, larch	3
37 (0.014)	26 (0.010)	2096 (0.8)	4454 (1.7)	Spinach	2
				Gooseberry	1,3

[a]Average concentrations for 7-month growing season (4/1-10/31) determined by multiplying the percent of time that measurable concentrations were found by average concentrations during this time period Values reflect results from five stations radiating from a single source.

[b]Maximum concentrations based on 30-minute averages

[c]Plant responses based on 1959 and 1960 growing season
1 = Reduction in yield
2 = Reduction in quality
3 = Reduction in growth (shoot height, diameter of stem, and/or foliage dry weight).

Table 5-2. CHANGES IN NET TREE VOLUME OF EASTERN WHITE PINE ASSOCIATED WITH SULFUR DIOXIDE CONCENTRATIONS NEAR A SMELTER COMPLEX IN SUDBURY, CANADA

Average concentration,[a] μg/m³ (ppm)	Concentration frequencies, percent[b]			Net average annual gain or loss in total tree volume[c]
	655 μg/m³ (0.25 ppm)	1310 μg/m³ (0.50 ppm)	2620 μg/m³ (1.0 ppm)	
118 (0.045)	5.92	2.36	0.38	Tree volume reduced 1.3% over 10-yr period.
45 (0.017)	0.98	0.11	0.01	Tree volume reduced 0.6% over 10-yr period.
21 (0.008)	0.33	0.01	0.00	Tree volume increased 1.6% over 10-yr period[d]

[a]Average concentrations for 6-month growing season (5/1-10/31) over a 10-year period (1954-1963). Values are from three stations radiating from a group of three major SO_2 sources.

[b]Concentration frequencies based on the percentage of 1/2-hour average concentrations above the respective SO_2 values over the 10-year period.

[c]White pine sampling areas were located several miles from the air monitoring sites, but were within the same concentration isopleths.

[d]Increases in tree volume were measured at white pine sampling areas located near the SO_2 monitoring station farthest from the three sources.

essential elements of air quality criteria. There are insufficient data in the literature to develop equations capable of defining effects of chronic injury, or the reduction of growth, yield, or quality of plant material. There have been several attempts to develop rational models to express time-concentration-response results of plants to acute exposures from SO_2. Several empirical relationships have been proposed that give some insight as to what may happen under a given set of circumstances.

1. Mathematical Equations

The first dose-response relationship for SO_2 was developed by O'Gara[123] under growth conditions that produced maximum sensitivity in the plant studied. The equation was developed from exposures of alfalfa over a relatively short period of time with the production of acute injury. Thomas and Hill[124] modified the O'Gara equation for alfalfa, but the generalized equation can be shown as:

$$t(c - a) = b \qquad (5\text{-}8)$$

where:
- t = time, hours
- c = concentration of pollutant when it is above the threshold, ppm
- a = threshold concentration below which no injury occurs regardless of length of exposures, ppm
- b = constant

The parameters a and b are dependent on the species and variety of plant and the degree of injury. The equation can be rearranged to:

$$c = \frac{b}{t} + a \qquad (5\text{-}9)$$

The plot of c versus $1/t$ is a straight line. The parameter a is the intercept for $1/t = 0$, or

Table 5-3. GROWTH REDUCTION IN VEGETATION EXPOSED TO SULFUR DIOXIDE FOR LONG AND SHORT TIME PERIODS

Species	Concentration[a] μg/m³	(ppm)	Exposure time	Effect	Conditions	Reference
Tobacco (*Nicotiana tabacum* L. "Bel W_3")	262	(0.1)	8 hr/day, 5 days/wk, (4 wks)	Reduced growth	Greenhouse exposure chambers	41
Radish (*Raphanus sativus* L. "Cherry Bell")	131	(0.05)	8 hr/day, 5 days/wk, (5 wks)	Reduced growth	Greenhouse exposure chambers	40
Ryegrass (*Lolium perenne* L. "Aberystwyth S23")	<262	(<0.1)[b]	63 days	Reduced growth	Ambient air greenhouse	42
	<262	(<0.1)[c]	77 days	Reduced growth		42
Timothy (*Phleum pratense* L.)	2489	(0.95)	8 hr	Reduced growth	Field exposure chambers	113
Alsike clover (*Trifolium hybridum* L.)	2489	(0.95)	8 hr	Reduced growth	Field exposure chambers	113
Crimson clover (*Trifolium incarnatum* L.)	2489	(0.95)	8 hr	Reduced growth	Field exposure chambers	113
Red clover (*Trifolium pratense* L.)	2489	(0.95)	12 hr	Reduced growth	Field exposure chambers	113
Italian rye (*Lolium multiflorum* Lmk.)	2489	(0.95)	12 hr	Reduced growth	Field exposure chambers	113
Mixtures of: *T. pratense* and *L. multiflorum*	2489	(0.95)	12 hr	Reduced growth Growth not affected	Field exposure chambers	113
Vetch (*Vicia sativa* L. and *V.faba* L.), pea (*Pisum arvense* L.) and lupine (*Lupinus lentens* L.)	996	(0.38)	48 hr	Reduced growth for all species	Field exposure chambers	113

[a] Average concentrations over the reported time periods. Inaccuracies associated with instrumentation result in deviations as great as ±10 percent.
[b] Except 2 days at concentrations of 262 to 524 μg/m³ (0.1 to 0.2 ppm).
[c] Except 3 days at concentrations of 262 to 524 μg/m³ (0.1 to 0.2 ppm).

when t is infinitely large. Thus a could be considered the threshold concentration for injury.

The O'Gara equation (5-8) could also be written:

$$t = b\left(\frac{1}{c - a}\right) \qquad (5\text{-}10)$$

Zahn[125] proposed a function that he suggested would fit experimental data over longer time periods better than the O'Gara equation. The equation expressed in the same form as Equation 5-10 above is:

$$t = b\ \frac{1 + 0.5c}{c\ (c - a)} \qquad (5\text{-}11)$$

The threshold value a was given as 0.1 for alfalfa; b was called a dimensional resistance factor that incorporates the influence of environmental conditions. Comparing the three equations (5-8, 5-10, 5-11), the time required for threshold injury for alfalfa at an SO_2 concentration of 1048 $\mu g/m^3$ (0.4 ppm) would be 13, 6, or 10 hours. At higher concentrations of SO_2, there are only minor differences of time.

Guderian, van Haut, and Stratmann[73] recognized that the O'Gara equation did not give the best fit to their observations for either short- or long-term exposures. This led to the development of an exponential equation of the form:

$$t = Ke^{-b(c-a)} \qquad (5\text{-}12)$$

where:
- t = time, hours
- K = vegetation lifetime, hours
- e = base of the natural logarithm
- b = biological complex factor (which includes the influences of environmental factors)
- c = concentration of pollutant when it is above the threshold, ppm
- a = injury threshold, ppm

These parameters vary with species, environmental conditions, and degree of injury.

In the midtime ranges of 0.5 to 12 hours, all of the equations fit the available data reasonably well; however, the exponential form (Equation 5-12) fits over a wider range of time. These equations relate a given time and concentration to a specific percentage of injury. They have been developed using experimental data from a limited number of plant species.

These two-dimensional models are limited in their application since they do not incorporate the relationships of the many factors that affect plant response to SO_2. A multivariate model is needed if these relationships are to be considered. Wolozin and Landau[126] proposed a nonlinear function incorporating all relevant factors that affect a plant's response. They suggest that in any multivariate analysis the following factors be considered: differing SO_2 levels, duration and frequency of such levels, relative humidity, temperature, diurnal pattern of SO_2 concentrations, species of plant, and stage of plant growth.

2. Dose-Injury Data

Since useful mathematical models are not available, an extensive summary of time-concentration-response data found in the literature is necessary. A discussion of growth effects was presented in Section I, and the data were summarized in Tables 5-1, 5-2, and 5-3. This section will be limited to a discussion of acute effects that occur over a relatively short time span, results of field exposures where identifiable injury is present, and results of experiments utilizing mixtures of pollutants. In most cases (except Table 5-7, which shows the response of white pine and radish to low mixture concentrations over a period of several weeks), the responses noted are the result of acute exposures to the toxicant in question.

A study comparing spruce forests in a high and in a medium pollution area was conducted in Czechoslovakia.[46] Results are in terms of a relative determination of foliar injury to spruce. Four-month growing season averages and 30-minute maximum concentrations of SO_2 are reported. Although the injury results, presented in Table 5-4, are not easily quantified, the injury observed was of the acute type. Materna, Jirgle, and Kucera[46]

Table 5-4. SEASONAL AVERAGE SULFUR DIOXIDE CONCENTRATIONS ASSOCIATED WITH FOLIAR INJURY TO SPRUCE IN TWO LOCATIONS IN CZECHOSLOVAKIA

Average concentrations,[a,b] $\mu g/m^3$ (ppm)	Maximum concentrations,[b,c] $\mu g/m^3$ (ppm)	Foliar injury
68 (0.026)	943 (0.36)	Severe
47 (0.018)	812 (0.31)	Moderate

[a] Average concentrations for 4 months of the growing season (6/1/66 - 9/30/66) determined from day and night monthly averages.

[b] Monitoring instruments functioned with an error less than 10 percent only when concentrations were above 150 $\mu g/m^3$.

[c] Maximum concentrations based on highest 30-minute average.

state that their monitoring instruments functioned with an error less than 10 percent only when concentrations were above 150 $\mu g/m^3$.

Many experiments have related time and concentration to a response in plants sensitive to SO_2. It is reasonable that experiments and field observations relating to short-time acute threshold responses be reviewed for inclusion in a table of plant responses. Results from three investigations are shown in Table 5-5.[70,127,128] The results of the white pine study[127] are included because they report effects at much lower concentrations than noted before. It should be noted that the procedures followed in making the plant grafts and the measurement techniques used make the results in the reference of questionable value.[127]

Table 5-6 lists agricultural and forest species growing in the area of Sudbury, Ontario, Canada.[129] Shown are the minimal average concentrations for which injury was observed after exposures of 1, 2, 4, and 8 hours. These field observations relate to the total pollution load over the 8-hour averaging period. The average injury was 10 percent on the leaves affected.[129]

The interaction of SO_2 with other pollutants was briefly discussed in Section D.1.f. Only interactions between SO_2 and 0_3 and SO_2 and NO_2 have been studied. These results, presented in Table 5-7,[40,61-65] are not based on extensive studies but are preliminary. They point out some conflicting reports, which need in-depth study. It is apparent that, under certain conditions and with given levels of gases in the gas mixtures, some plants can be more severely affected than by individual pollutants. However, there are cases where plants are apparently protected by pollutant mixtures. Nevertheless, the potential for damage at low concentrations of pollutant mixtures exists.

Using the threshold concentrations from Tables 5-5, 5-6, and 5-7 and information involving effects that relate time and concentration over short time periods, projected SO_2 concentrations causing injury to three susceptible groupings of plants were developed (Table 5-8). This table was taken with minor changes from Heggestad and Heck.[130] Table 5-9 gives a complete list of plants that have been studied in relation to SO_2. The plants in Table 5-9 are categorized using the sensitivity scale used in Table 5-8. Within each susceptibility grouping, the plants are listed alphabetically by family.

Table 5-5. CONCENTRATIONS OF SULFUR DIOXIDE CAUSING INJURY TO SENSITIVE VEGETATION[a]

Species	Concentration[b] µg/m³	(ppm)	Exposure time, hr	Effect[c]	Conditions	Reference
White pine (*Pinus strobus* L.)	131	(0.05)	1	Needle injury rating of *3*	Branch exposure chamber in greenhouse	127
	131	(0.05)	2	Needle injury rating of *5*		
	131	(0.05)	3	Needle injury rating of *8*		
	262	(0.10)	1	Needle injury rating of *5*		
	262	(0.10)	2.5	Needle injury rating of *8*		
Alfalfa (*Medicago sativa* L.)	1310	(0.5)	4	5% leaf injury	Greenhouse exposure chambers	70
	1310	(0.5)	4	19% leaf injury		
Broccoli (*Brassica oleracea* var. *botrytis* L.)	655	(0.25)	4	6% leaf injury	Same	70
	1310	(0.5)	4	4% leaf injury		
	1310	(0.5)	4	None		
Apple (*Malus* sp. "Manks Codlin")	1258	(0.48)	6	Leaf injury rating of *6*	Branch exposure chambers in natural stands	128
Pear *Prunus* sp, "Legipont"	1258	(0.48)	6	Leaf injury rating of *4*	Same	128
"Conference"	1336	(0.51)	6	Leaf injury rating of *5*		
Mountain ash (*Sorbus aucuparia* L.)	1415	(0.54)	3	Leaf injury rating of *3*	Same	128
	2175	(0.83)	3	Leaf injury rating of *7*		

[a]The vegetation was observed or exposed when growing under environmental conditions that made it most sensitive to SO_2.

[b]Average concentrations over the reported time periods. Inaccuracies associated with instrumentation result in deviations as great as ±10 percent.

[c]The effects are reported differently in each reference. Their definition is briefly described.

1. Reference 127 The needle injury rating is based on a *1* to *8* scale with *1* as no injury and *8* as 2 to 3 cm of tip necrosis.
2. Reference 70: The values reflect the average percentage foliar injury on the three most severely injured leaves.
3. Reference 128: The leaf injury rating is based on a *0* to *10* scale with *0* as no injury and *10* as the entire leaf surface injured.

Table 5-6. SULFUR DIOXIDE CONCENTRATIONS CAUSING INJURY TO AGRICULTURAL AND FOREST SPECIES[a]

Species	Maximum average concentrations[b]							
	1 hr,		2 hr,		4 hr,		8 hr,	
	$\mu g/m^3$	(ppm)	$\mu g/m^3$	(ppm)	$\mu g/m^3$	(ppm)	$\mu g/m^3$	(ppm)
	Agricultural							
Buckwheat (*Fagopyrum* sp.)	1467	(0.56)	1022	(0.39)	681	(0.26)	393	(0.15)
Barley (*Hordeum vulgare* L.)	1651	(0.63)	1153	(0.44)	629	(0.24)	314	(0.12)
Red clover (*Trifolium pratense*, L.)	1834	(0.70)	1205	(0.46)	707	(0.27)	367	(0.14)
Radish (*Raphanus sativus*, L.)	1991	(0.76)	1415	(0.54)	760	(0.29)	367	(0.14)
Oats (*Avena sativa*, L.)	1651	(0.63)	1546	(0.59)	891	(0.34)	445	(0.17)
Peas (*Pisum sativum*, L.)	1651	(0.63)	1546	(0.59)	891	(0.34)	445	(0.17)
Rhubarb (*Rheum rhaponticum*, L.)	1651	(0.63)	1546	(0.59)	891	(0.34)	445	(0.17)
Timothy (*Phleum pratense*, L.)	1729	(0.66)	1415	(0.54)	1048	(0.40)	550	(0.21)
Swiss chard (*Beta vulgaris* var. *cicla*, L.)	2306	(0.88)	1677	(0.64)	1074	(0.42)	707	(0.27)
Beans (*Phaseolus* sp.)	1205	(0.46)	1179	(0.45)	1127	(0.43)	550	(0.21)
Beets (*Beta vulgaris*, L.)	3432	(1.31)	2017	(0.77)	1179	(0.45)	603	(0.23)
Turnips (*Brassica rapa*, L.)	3432	(1.31)	2017	(0.77)	1179	(0.45)	603	(0.23)
Carrots (*Daucus carota*, L.)	2830	(1.08)	2070	(0.79)	1310	(0.50)	655	(0.25)
Cucumbers (*Cucumis sativa*, L.)	2830	(1.08)	2070	(0.79)	1310	(0.50)	655	(0.25)
Lettuce (*Lactuca sativa*, L.)	1677	(0.64)	1467	(0.56)	1126	(0.43)	996	(0.38)
Tomatoes (*Lycopersicon esculentum*, Mill.)	1677	(0.64)	1467	(0.56)	1126	(0.43)	996	(0.38)
Potatoes (*Solanum tuberosum*, L.)	1677	(0.64)	1467	(0.56)	1126	(0.43)	996	(0.38)
Raspberry (*Rubus idaeus*, L.)	1939	(0.74)	1651	(0.63)	1389	(0.53)	1022	(0.39)
Celery (*Apium graveolens*, L.)	2279	(0.87)	1939	(0.74)	1441	(0.55)	760	(0.29)
Spinach (*Spinacea oleracea*, L.)	3511	(1.34)	2384	(0.91)	1310	(0.50)	891	(0.34)

Table 5-6. SULFUR DIOXIDE CONCENTRATIONS CAUSING INJURY TO AGRICULTURAL AND FOREST SPECIES[a] (Continued)

Species	Maximum average concentrations[b]							
	1 hr, μg/m³	(ppm)	2 hr, μg/m³	(ppm)	4 hr, μg/m³	(ppm)	8 hr, μg/m³	(ppm)
	Forest							
Cabbage (*Brassica oleracea,* L.)	2463	(0.94)	2332	(0.89)	1834	(0.70)	1179	(0.45)
Corn (*Zea mays,* L.)[c]	--	--	--	--	--	--	--	--
Bracken fern (*Pteridium aquilinum,* L.)	1179	(0.45)	891	(0.34)	625	(0.25)	550	(0.21)
Large tooth aspen (*Populus grandidentata* Michx)	1729	(0.66)	1126	(0.43)	969	(0.37)	524	(0.20)
Willow (*Salix* sp.)	1074	(0.41)	996	(0.38)	865	(0.33)	786	(0.30)
Trembling aspen (*Populus tremuloides* Michx)	1100	(0.42)	1022	(0.39)	681	(0.26)	341	(0.13)
Jack pine (*Pinus banksiana* Lamb.)	1362	(0.52)	1153	(0.44)	760	(0.29)	524	(0.20)
White pine (*Pinus strobus* L.)	1179	(0.45)	917	(0.35)	655	(0.25)	550	(0.21)
Alder (*Alnus* sp.)	1205	(0.46)	1126	(0.43)	1126	(0.43)	550	(0.21)
Red pine (*Pinus resinosa* Ait)	2043	(0.78)	1809	(0.69)	1153	(0.44)	786	(0.30)
Balsam poplar (*Populus balsamifera* L.)	2149	(0.82)	1703	(0.65)	1179	(0.45)	681	(0.26)
Austrian pine (*Pinus nigra* Arnold)	1729	(0.66)	1179	(0.45)	1153	(0.44)	865	(0.33)
Witch hazel (*Hamamelis virginiana,* L.)	2987	(1.14)	1965	(0.75)	1179	(0.45)	603	(0.23)
Red oak (*Quercus* sp.)	2332	(0.89)	2149	(0.82)	1598	(0.61)	1074	(0.41)
Sugar maple (*Acer saccharum* Marsh.)	2149	(0.82)	1703	(0.65)	1624	(0.62)	1205	(0.46)
White spruce (*Picea glauca* (Moench) (Voss)	2279	(0.87)	2070	(0.79)	1834	(0.70)	1310	(0.50)
Cedar (*Thuja occidentalis,* L.)[c]	--	--	--	--	--	--	--	--

[a]The vegetation was observed when growing under environmental conditions that made it most sensitive to SO_2.

[b]Average concentrations over the reported time periods. Inaccuracies associated with instrumentation result in deviations as great as ±10 percent.

[c]Never injured near recorder stations.

Table 5-7. **VEGETATIONAL RESPONSE TO SULFUR DIOXIDE IN COMBINATION WITH EITHER OZONE OR NITROGEN DIOXIDE**[a]

Species	Concentration ratio,[b] µg/m³ (ppm)	Exposure time	Effect,[c] percent foliar injury	Reference
	Sulfur dioxide/ozone			
Tomato				
(*Lycopersicon esculentum* Mill.)	262/196 (0.1/0.1)	4 hr	–25[d]	70
	655/490 (0.25/0.1)	4 hr	– 3	
	1310/980 (0.5/0.1)	4 hr	4	
	2620/1960 (1.0/0.1)	4 hr	–33[d]	
Alfalfa				
(*Medicago sativa* L.)	1310/98 (0.5/0.05)	4 hr	–17	70
	262/196 (0.1/0.1)	4 hr	19[d]	
	655/196 (0.25/0.1)	4 hr	21[d]	
	1310/196 (0.5/0.1)	4 hr	55[d]	
Broccoli				
(*Brassica oleracea* var. *botrytis* L.)	1310/98 (0.5/0.05)	4 hr	17[d]	70
	262/196 (0.1/0.1)	4 hr	34[d]	
	655/196 (0.25/0.1)	4 hr	11	
	1310/196 (0.5/0.1)	4 hr	14	
Cabbage				
(*Brassica oleracea* var. *capitata* L.)	1310/98 (0.5/0.05)	4 hr	4	70
	262/196 (0.1/0.1)	4 hr	12	
	655/196 (0.25/0.1)	4 hr	14	
	1310/196 (0.5/0.1)	4 hr	47[d]	
	2620/196 (1.0/0.1)	4 hr	–42[d]	
Spinach				
(*Spinacia oleracea* L.)	2620/196 (1.0/0.1)	4 hr	–48[d]	70
Tobacco				
(*Nicotiana tabacum* L.)				
Bel W_3	655/59 (0.25/0.03)	2 hr	15[d]	67
Bel W_3	655/98 (0.25/0.05)	4 hr	16[d]	70
	1310/98 (0.5/0.05)	4 hr	55[d]	
	262/196 (0.1/0.1)	4 hr	8	
	685/196 (0.25/0.1)	4 hr	75[d]	
	1310/196 (0.5/0.1)	4 hr	73[d]	
Bel B	655/59 (0.25/0.03)	2 hr	9[d]	67
Bel B	655/98 (0.25/0.05)	4 hr	3[d]	70

Table 5-7. VEGETATIONAL RESPONSE TO SULFUR DIOXIDE IN COMBINATION WITH EITHER OZONE OR NITROGEN DIOXIDE[a] (Continued)

Species	Concentration ratio,[b] μg/m³	(ppm)	Exposure time	Effect,[c] percent foliar injury	Reference
Bromegrass (*Bromus inermis* L.)	2620/196	(1.0/0.1)	4 hr	−61[d]	70
Radish (*Raphanus sativus* L.)	1310/98	(0.5/0.05)	4 hr	6	70
	262/196	(0.1/0.1)	4 hr	31[d]	
	655/196	(0.25/0.1)	4 hr	22[d]	
	1310/196	(0.5/0.1)	4 hr	45[d]	
White pine (*Pinus strobus* L.)	262/196	(0.1/0.1)	4 to 8 wk, 5 days/wk, 4 to 8 hr/day	9	68
	131/98	(0.05/0.05)	10 to 30 days, 12 hr/day	Trace-extensive necrosis	69
Radish (*Raphanus sativus* L.)	131/98	(0.05/0.05)	5 wk, 5 days/wk, 8 hr/day	Reduced growth	40
	Sulfur dioxide/nitrogen dioxide				
Bean (*Phaseolus vulgaris* L.)	131/188	(0.05/0.1)	4 hr	0	71
	262/188	(0.1/0.1)	4 hr	11	
	262/282	(0.1/0.15)	4 hr	24	
	655/282	(0.25/0.15)	4 hr	4	
	524/376	(0.2/0.2)	4 hr	16	
Oats (*Avena sativa* L.)	655/94	(0.25/0.05)	4 hr	3	71
	131/188	(0.05/0.1)	4 hr	0	
	262/188	(0.1/0.1)	4 hr	27	
	262/282	(0.1/0.15)	4 hr	12	
	655/282	(0.25/0.15)	4 hr	0	
	524/376	(0.2/0.2)	4 hr	10	

Table 5-7. VEGETATIONAL RESPONSE TO SULFUR DIOXIDE IN COMBINATION WITH EITHER OZONE OR NITROGEN DIOXIDE[a] (Continued)

Species	Concentration ratio,[b] μg/m³	(ppm)	Exposure time	Effect,[c] percent foliar injury	Reference
Radish					
(*Raphanus sativus* L.)	262/188	(0 1/0.1)	4 hr	27	71
	262/282	(0.1/0.15)	4 hr	24	
	655/282	(0.25/0.15)	4 hr	4	
	131/470	(0.05/0.25)	4 hr	13	
Soybean					
(*Glycine max* L.)	131/94	(0.05/0.05)	4 hr	2	71
	524/94	(0.2/0.05)	4 hr	6	
	655/94	(0.25/0.05)	4 hr	7	
	262/188	(0.1/0.1)	4 hr	35	
	262/282	(0.1/0.15)	4 hr	20	
	655/282	(0.25/0.15)	4 hr	1	
	524/376	(0.2/0.2)	4 hr	9	
	131/470	(0.05/0.25)	4 hr	2	
Tomato					
(*Lycopersicon esculentum* Mill.)	655/94	(0.25/0.05)	4 hr	1	71
	131/188	(0.05/0.1)	4 hr	0	
	262/188	(0.1/0.1)	4 hr	1	
	262/282	(0.1/0.15)	4 hr	17	
	655/282	(0.25/0.15)	4 hr	0	
	131/470	(0.05/0.25)	4 hr	0	

[a] The vegetation was grown under greenhouse conditions such that the plants were most sensitive to the pollutants and pollutant mixtures.

[b] Average concentration of pollutants. Inaccuracies associated with instrumentation result in deviations as great as ±10 percent.

[c] The effects are reported differently in each reference. Their definition is briefly described:

1. References 67, 68, and 70: Percentages are expressed as the difference between the percent of foliar injury from the SO_2/O_3 mixture and the additive percent injury of the single gas exposures. Minus signs indicate that injury from the mixture was less than the additive injury from single gas treatments.
2. Reference 69: Descriptive only.
3. Reference 40: Growth reductions from the mixture were either less than additive or equal to the additive effects of single gas treatments.
4. Reference 71: Foliar injury from the SO_2/NO_2 mixtures occurred at pollution levels below the threshold injury concentration for SO_2 (0.5 ppm) or NO_2 (2.0 ppm) when used alone.

[d] Percentage differences are significant at the 0.05 level.

Table 5-8. PROJECTED SULFUR DIOXIDE CONCENTRATIONS THAT WILL PRODUCE THRESHOLD INJURY TO VEGETATION FOR SHORT-TERM EXPOSURES[a]

	Concentration producing injury in three susceptibility groups of plants					
	Sensitive,		Intermediate,		Resistant,	
Time, hours	μg/m³	(ppm)	μg/m³	(ppm)	μg/m³	(ppm)
0.5	2620 to 10,480	(1.0 to 4.0)	9170 to 31,440	(3.5 to 12)	≥26,200	(≥10)
1.0	1310 to 7860	(0.5 to 3.0)	6550 to 26,200	(2.5 to 10)	≥20,960	(≥ 8)
2.0	655 to 5240	(0.25 to 2.0)	3930 to 19,650	(1.5 to 7.5)	≥15,720	(≥ 6)
4.0	262 to 2620	(0.1 to 1.0)	1310 to 13,100	(0.5 to 5)	≥10,480	(≥ 4)
8.0	131 to 1310	(0.05 to 0.5)	524 to 6550	(0.2 to 2.5)	≥ 5240	(≥ 2)

[a] Values were developed from subjective evaluations of injury reported in the literature where both time and concentration were considered. The concentrations and times shown for each susceptibility grouping are reasonable only when the plants are growing under the most sensitive environmental conditions and stage of plant maturity.

Table 5-9. LISTS OF PLANTS IN THREE SUSCEPTIBILITY GROUPS BY SENSITIVITY TO SULFUR DIOXIDE[a]

Species	Reference
Sensitive	
Aceraceae	
Maple (*Acer pseudoplatanus* L.)	128
Amaranthaceae	
Pigweed (*Amaranthus retroflexus* L.)	131
Begoniaceae	
Begonia (*Begonia* sp.)	28
Bignoniaceae	
Catalpa (*Catalpa* sp.)	28
Carophyllaceae	
Bouncing bet (*Saponaria officinalis* L.)	28
Sweet William (*Dianthus baratus* L.)	28
Chenopodiaceae	
Beet (*Beta vulgaris* L.)	28
Lamb's quarters (*Chenopodium album* L.)	131
Spinach (*Spinacia oleracea* L.)	28,50
Swiss chard (*Beta vulgaris* var. *cicla* L.)	28,50
Convolvulaceae	
Sweet potato (*Ipomea batata* L.)	28,47
Compositae	
Aster (*Aster* sp.)	28
Bachelor's buttons (*Centaurea cyanus* L.)	28
Cocklebur (*Xanthium* sp.)	28,131
Cosmos (*Bidens* sp.)	28,132,50
Dandelion (*Taraxacum officinale* Weber)	28,131
Endive (*Cichorium endivia* L.)	50,47
Marigold (*Tagetes* sp.)	28
Prickly lettuce (*Lactuca scariola* L.)	28
Ragweed (*Ambrosia* sp.)	28
Zinnia (*Zinnia* sp.)	28
Cruciferae	
Broccoli (*Brassica oleracea* var. *botrytis* L.)	70
Brussels sprouts (*Brassica oleracea* var. *gemmifera* L.)	28
Cabbage (*Brassica oleracea* var. *capitata* L.)	70
Kale (*Brassica oleracea* var. *acephala* DC.)	28
Mustard, black (*Brassica* sp.)	28
Mustard, hedge (*Sisymbrium* sp.)	28
Nasturtium (*Nasturtium* sp.)	28

Table 5-9. LISTS OF PLANTS IN THREE SUSCEPTIBILITY GROUPS BY SENSITIVITY TO SULFUR DIOXIDE[a] (Continued)

Species	Reference
Cruciferae (continued)	
Radish (*Raphanus sativus* L.)	70,50
Turnip (*Brassica rapa* L.)	28
Curcurbitaceae	
Cucumber (*Cucumis sativus* L.)	131
Pumpkin (*Cucurbita pepo* L.)	28
Squash (*Cucurbita maxima* Duchesne)	28
Euphorbiaceae	
Rubber (*Hevea brasiliensis* Muell.)	133
Fagaceae	
Beech (*Fagus silvatica* L.)	131
Gramineae	
Barley (*Hordeum vulgare* L.)	28,47
Bentgrass (*Agrostis palustris* Huds.)	132
Bluegrass (*Poa annua.* L.)	132
Bromegrass (*Bromus* sp.)	70
Fescue, red (*Festuca rubra* L.)	132
Junegrass (*Poa pratensis* L.)	28
Oats (*Avena sativa* L.)	9,50,47
Orchardgrass (*Dactylis glomerata* L.)	28
Rye (*Secale cereale* L.)	28,50,47
Ryegrass (*Lolium* sp.)	28
Wheat (*Triticum aestivum* L.)	28
Iridaceae	
Gladiolus (*Gladiolus* sp.)	131
Iris (*Iris* sp.)	131,28
Labiatae	
Coleus (*Coleus blumei* Benth.)	131
Leguminosae	
Alfalfa (*Medicago sativa* L.)	70,89,50,47
Bean (*Phaseolus vulgaris* L.)	51,134
Bean, lima (*Phaseolus lunatus* L.)	70,28
Pea (*Pisum sativum* L.)	28
Sweet clover (*Meliotus* sp.)	28,47
Sweet pea (*Lathyrus odoratus* L.)	28,50
Soybean (*Glycine max.* Merr.)	70
Vetch (*Vicia* sp.)	131

Table 5-9. LISTS OF PLANTS IN THREE SUSCEPTIBILITY GROUPS BY SENSITIVITY TO SULFUR DIOXIDE[a] (Continued)

Species	Reference
Liliaceae	
Leek (*Allium porrum* L.)	28
Onion (*Allium cepa* L.)	70
Malvaceae	
Cotton (*Gossypium hirsutum* L.)	28,131
Hollyhock (*Althaea* sp.)	28
Mallow (*Malva* sp.)	28
Nyctaginaceae	
Four o'clock (*Mirabilis jalapa* L.)	28
Pinaceae	
Larch (*Larix* sp.)	89,129
White pine (*Pinus strobus* L.)	129
Plantaginaceae	
Plantain (*Plantago* sp.)	28
Polygonaceae	
Buckwheat (*Fagopyrum* sp.)	129,131, 50,47
Rhubarb (*Rheum rhaponticum* L.)	28
Smartweed (*Polygonum* sp.)	28,47
Sorrel (*Rumex* sp.)	
Rosaceae	
Apple (*Malus* sp.)	128,28,131
Apricot (*Prunus* sp.)	131,128
European cherry (*Prunus padus* L.)	128
Mountain ash (*Sorbus aucuparia* L.)	87
Pacific ninebark (*Physocarpus capitatus* (Pursh) Ktze.)	28
Peach (*Prunus* sp.)	128
Pear (*Pyrus* sp.)	128
Prune (*Prunus* sp.)	131
Saskatton serviceberry (*Ameliancheir alnifolia* Nutt.)	87
Saxifragaceae	
Gooseberry (*Ribes* sp.)	28
Hydrangea (*Hydrangea* sp.)	28
Solanaceae	
Eggplant (*Solanum melongena* L.)	28,47
Nightshade (*Solanum* sp.)	28
Petunia (*Petunia* sp.)	135
Tobacco (*Nicotiana tabacum* L.)	70,136

Table 5-9. LISTS OF PLANTS IN THREE SUSCEPTIBILITY GROUPS BY SENSITIVITY TO SULFUR DIOXIDE[a] (Continued)

Species	Reference
Ulmaceae	
Chinese elm (*Ulmus parvifolia* Jacq.)	137
Elm (*Ulmus* sp.)	28
Umbellifereae	
Carrot (*Daucus carota* L.)	28
Celery (*Apium graveolens* L.)	131
Parsley (*Petroselinum crispum* Nym.)	28
Parsnip (*Pastinaca* sp.)	28
Vitaceae	
Wild grape (*Vitis labrusca* L.)	131
Intermediate	
Aceraceae	
Box elder (*Acer negundo* L.)	28
Maple (*Acer* sp.)	28
Norway maple (*Acer platanoides* L.)	137
Anacardiaceae	
Sumac (*Rhus* sp.)	28
Asclepiadaceae	
Milkweed (*Asclepias* sp.)	28
Begoniaceae	
Begonia (*Begonia* sp.)	138
Betulaceae	
California hazel (*Corylus californica* (A.D.C.) Rose.)	87
Cannaceae	
Canna (*Canna* sp.)	28
Caprifoliaceae	
Columbia snowberry (*Symphoricarpos rivularis* Suks.)	87
Honeysuckle (*Lonicera* sp.)	28
Snowball (*Viburnum* sp.)	28
Compositae	
Chrysanthemum (*Chrysanthemum* sp.)	28
Cruciferae	
Horse-radish (*Armoracia rusticana* Gaertn., B Bay. and Scherb)	28
Shepherd's purse (*Capsella bursa-pastora* L.)	28

Table 5-9. LISTS OF PLANTS IN THREE SUSCEPTIBILITY GROUPS BY SENSITIVITY TO SULFUR DIOXIDE[a] (Continued)

Species	Reference
Cucurbitaceae	
Cucumber (*Cucumis sativa* L.)	28
Euphoribiaceae	
Castor bean (*Ricinus communis* L.)	47,28
Fagaceae	
Pin oak (*Quercus palustris* L.)	137
Ginkgoaceae	
Ginkgo (*Ginkgo* sp.)	137
Gramineae	
Kentucky bluegrass (*Poa pratensis* L.)	137
Salt grass (*Spartina* sp.)	28
Iridaceae	
Gladiolus (*Gladiolus* sp.)	28
Labiatae	
Salvia (*Salvia* sp.)	47
Leguminosae	
Wisteria (*Wisteria* sp.)	28
Liliaceae	
Onion (*Allium cepa* L.)	28
Malvaceae	
Hibiscus (*Hibiscus* sp.)	28
Oleaceae	
Lilac (*Syringa vulgaris* L.)	28
Pinaceae	
Douglas fir (*Pseudotsuga taxifolia* Brit.)	87
Fir (*Abies* sp.)	9
Pine, lodgepole (*Pinus contorta* Dougl.)	87
Pine, ponderosa (*Pinus ponderosa* Law)	9
Pine, western white (*Pinus monticola* Dougl.)	87
Portulacaceae	
Purslane (*Portulaca* sp.)	28

Table 5-9. LISTS OF PLANTS IN THREE SUSCEPTIBILITY GROUPS BY SENSITIVITY TO SULFUR DIOXIDE[a] (Continued)

Species	Reference
Roseaceae	
Plum (*Prunus* sp.)	28
Rose (*Rosa* sp.)	28
Sweet cherry (*Prunus avium* L.)	28
Salicaceae	
Poplar (*Populus* sp.)	28
Saxifragaceae	
Mock-orange (*Philadelphus* sp.)	28
Mock-orange, Lewis (*Philadelphus lewisii* Pursh.)	87
Scrophulariaceae	
Snapdragon (*Antirrhinum* sp.)	139
Solanoceae	
Potato, Irish (*Solanum tuberosum* L.)	28
Tobacco (*Nicotiana tabacum* L.)	140
Vitaceae	
Virginia creeper (*Parthenocissus quinquefolia* Planch.)	28
Resistant	
Caryophyllaceae	
Dianthus (*Dianthus* sp.)	139
Cucurbitaceae	
Cantaloupe (*Cucumis melo* L.)	28
Ericaceae	
Rhododendron (*Rhododendron* sp.)	139
Fagaceae	
Oak (*Quercus* sp.)	141
Oak, live (*Quercus virginiana* Mill.)	28
Oak, pin (*Quercus palustris* L.)	137
Oak, white (*Quercus alba* L.)	141
Gramineae	
Corn (*Zea mays* L.)	129

Table 5-9. LISTS OF PLANTS IN THREE SUSCEPTIBILITY GROUPS BY SENSITIVITY TO SULFUR DIOXIDE[a] (Continued)

Species	Reference
Liliaceae	
Lily (*Lilium speciosum* Thunb.)	47
Oleaceae	
Privet (*Ligustrum* sp.)	28
Orchidaceae	
Orchid (*Cattleya* sp.)	50,139,47
(*Cymbidium* sp.)	50,141,47
(*Odontoglossum* sp.)	50,141,47
(*Oncidium* sp.)	50,141,47
Pinaceae	
Arbor-vitae (*Thuja* sp.)	28
Cedar (*Thuja occidentalis* L.)	129
Rubiaceae	
Gardenia (*Gardenia* sp.)	139
Rutaceae	
Citrus (*Citrus* sp.)	28
Umbellifereae	
Celery (*Apium graveolens* L.)	28

[a] Plants were placed into the three susceptibility groups as defined in Table 5-7. The time-concentration data were obtained for each plant by checking the appropriate reference.

K. SUMMARY

Plant species and varieties vary in sensitivity to SO_2. This is the result of the interaction of environmental and genetic factors that influence plant response. Temperature, humidity, light, other air pollutants, edaphic conditions, the stage of plant growth and the selective pressures between and within species all interact in affecting the sensitivity of plants to injury from sulfur dioxide. (Section D.1, 2, and 3.) Since ambient air is composed of many pollutants, interaction with other pollutants must be considered in analyzing the effects of SO_2 on vegetation. In this regard, adverse foliar and growth effects from pollutant mixtures may be of a larger magnitude than effects from exposures to SO_2 alone. (Section D.1.e.)

The response of a given variety or species of plants to a specific air pollutant cannot be predetermined on the basis of the known response of related plants to the same pollutant. Neither can the response be predetermined by a given response of a plant to similar doses of different pollutants. The interplay of genetic susceptibility and environmental influences must be considered for each plant and pollutant. (Section D.)

The responses of vegetation to sulfur dioxide may be classified into two general categories – *visible effects* and *subtle effects. Visible effects* are visually identifiable pigmented or necrotic foliar patterns that result from major physiological disturbances to plant cells. *Subtle effects* are those that produce measurable growth or physiological changes in plants but do not cause visible injury. (Section B.)

Visible effects can be subdivided into *acute* and *chronic* injury. *Acute injury* is severe injury that occurs within a few hours after exposure to SO_2 and is characterized by the collapse of cells with the subsequent development of necrotic patterns. It is associated with high, short-term SO_2 concentrations. In broad-leaved plants, it is characterized by white or brown interveinal and marginal necrosis of the leaf. Red to brown colored necrotic lesions occur in conifers. This necrotic response usually involves the needle tip, but other portions of the needle may also be affected. Acute injury patterns are generally more characteristic of a specific pollutant than chronic injury patterns. (Section B.1.a.)

Chronic injury results in light to severe injury that develops from exposure over an extended time period. It is associated with long-term exposures where the pollutant concentration is sufficiently high to produce some cell destruction or disruption. Symptoms are usually in the form of leaf chlorisis, but necrotic areas may also develop. Foliar injury is followed by leaf abscission, and the response may resemble normal senescence. Acute and chronic injuries may develop on the same leaves. (Section B.1.b.)

Subtle effects implies that SO_2 can interfere with physiological and/or biochemical processes, and with plant growth and yield without attendant development of visible symptoms. Processes that have been studied include photosynthesis, stomatal behavior, chemical composition, and reductions in growth and yield. (Section B.2)

The term *physiological effects* includes both subtle and visible effects. Physiological changes in plants precede the visible expressions of injury; however, visible injury may not occur at all. Changes in the plant processes, enzyme systems, and chemical composition may result in growth and yield reductions in the absence of visible injury. (Section B.3.)

The mechanism by which plants are injured by SO_2 is not understood. Acute injury does not occur if the rate of SO_2 absorption does not exceed the capacity of the plant to oxidize sulfite to sulfate ions. Under long-term SO_2 stress, sulfate thus formed may accumulate, with the subsequent development of chronic injury symptoms. (Section C.)

In assessing SO_2 damage to plants, the most significant question is whether or not the plant has been so altered by the pollutant that its growth, survival, yield, or use has been impaired.

Except in those instances where damage to the plant foliage results in decrease in the value of the product, economic damage is extremely difficult to assess. (Section E.)

Growth and/or yield reductions may occur without visible injury to plants. (Section B.3.d) Laboratory studies demonstrated that reduced root weights of radishes occurred with exposure to SO_2 at concentrations of 131 to 160 $\mu g/m^3$ (0.05 to 0.06 ppm), 40 hr/week for 5 weeks. Reduction in the growth of tobacco occurred with exposure to SO_2 concentrations of 262 $\mu g/m^3$ (0.1 ppm), 40 hr/week for 4 weeks. (Section B.3.d., Table 5-3) The conditions under which the studies were conducted, however, would probably seldom, if ever, be reached in the ambient air. More studies are needed before a definitive statement can be made.

Most reports, however, have considered that visible injury is required for reductions in growth and yield. Many studies have shown that the reduction in crop yield from exposure to SO_2 is proportional to the percentage of leaf area destroyed. The relationship between the percentage of leaf destroyed and reduction in crop yield has been expressed in the equation $y = a - bx$, where y = the yield expressed as the percentage of the control and x = the percentage of leaf area destroyed. The constant a is about 100 percent, and b is the slope of the yield/leaf-destruction curve. (Section I, Equation 5-1.)

Foliar injury of agronomic crops and trees was reported at SO_2 concentrations of 1074 to 1650 $\mu g/m^3$ (0.41 to 0.63 ppm) for 1-hour exposure periods when these exposure periods were within 8-hour time periods with average concentrations of 314 to 786 $\mu g/m^3$ (0.12 to 0.30 ppm). Concentrations of 314 $\mu g/m^3$ (0.12 ppm) injured barley after 8-hour periods. (Tables 5-5 and 5-6.) In Germany, growth reductions of several forage plants were demonstrated after field exposures of 2489 $\mu g/m^3$ (0.95 ppm) SO_2 for 8 hours. (Table 5-3.) For Italian rye, growth was also affected at this concentration in exposure periods of 12 hours, but when this species was grown in combination with red clover, growth was not affected by SO_2 exposure. (Table 5-3.) In contrast, reduced growth of rye grass occurred when average daily SO_2 concentrations were less than 262 $\mu g/m^3$ (0.1 ppm) for about 96 percent of the experimental periods and no greater than 524 $\mu g/m^3$ (0.2 ppm) during the remaining periods of time. (Section B.3.d, Table 5-3.)

Growth, yield, and quality effects have also been related to growing season average emissions from single sources. In Germany, reductions in these parameters were demonstrated for spinach and gooseberry at growing season averages of 26 to 37 $\mu g/m^3$ (0.010 to 0.014 ppm) SO_2. A larger number of agronomic species were affected at averages of 45 to 66 $\mu g/m^3$ (0.017 to 0.025 ppm) SO_2. In this study, the effects were associated with maximum 30-minute values of 2096 to 4978 $\mu g/m^3$ (0.8 to 1.9 ppm) SO_2. (Table 5-1.)

Laboratory and field chamber studies are essential if qualitative and quantitative models of pollutant effects upon vegetation are to be developed. Since it is impossible to include all parameters, laboratory and field chamber studies do not simulate ambient field conditions. The following results were obtained through field chamber studies. Several forage plants exhibited growth reductions after field exposures of 2489 $\mu g/m^3$ (0.95 ppm) SO_2 for 8 hours. (Table 5-3.) Injury to the foliage of varieties of apple and pear trees occurred after 6-hour exposures to 1258 $\mu g/m^3$ (0.48 ppm) SO_2; however, foliar injury of mountain ash occurred after exposure to 1415 $\mu g/m^3$ (0.54 ppm) SO_2 for 3 hours. (Table 5-5.)

The interrelations of time and the concentration of a pollutant are extremely important in determining the amount of injury that will be produced by a given pollutant. Several attempts have been made to develop rational models that express time-concentration-response results of plants to acute exposures of SO_2. (Section J.1.)

Since ambient air contains many pollutants, interaction with other pollutants must be considered in analyzing the effects of SO_2 on vegetation. In this regard, adverse foliar and growth effects from pollutant mixtures may be of a larger magnitude than effects from single SO_2 exposures. (Section J.2.) Foliar injury of three of six agronomic crops (alfalfa, broccoli, and radish) was greater after 4-hour exposures involving SO_2/O_3 mixtures of 262/196 $\mu g/m^3$ (0.1/0.1 ppm) for each pollutant than for ozone alone. No injury was observed after exposure to SO_2

alone. (Table 5-7.) In addition, growth reductions of radish, occurring after exposures to SO_2/O_3 mixtures of 131/94 $\mu g/m^3$ (0.05/0.05 ppm) 8 hr/day, 5 days/week for 5 weeks, were greater than reductions from single SO_2 exposures. (Section B.1.f.)

Foliar injury to four of five agronomic crops (beans, oats, radish, and soybeans) developed after 4-hour exposures to SO_2/NO_2 mixtures of 262/188 $\mu g/m^3$ (0.1/0.1 ppm) of each pollutant. The concentration used was below the injury threshold for each of the gases. (Table 5-7.)

Lichens and bryophytes are very sensitive to the presence of SO_2. Lichens have been used in the recognition and monitoring of SO_2. The presence of several fungal pathogens has been reduced in SO_2 polluted areas. (Section F.)

Another effect of SO_2 involves the acidification of precipitation. The oxidation and solution of SO_2 in precipitation has increased the acidity of soil and water in many parts of the world. This increase in acidity may reduce populations of microorganisms and affect the process of decomposition and mineralization. Acid precipitation may also contribute to the leaching of nutrients from plant foliage and from the soil. (Section G.) Further studies of the effects of acid rainfall in the United States are needed.

Sulfuric acid mists may occur when heavy air pollution is accompanied by fog. These mists result in necrotic spots, usually on the upper surface, which may then develop progressively through to the lower epidermis. (Section H.2.)

Reduced growth of white pine occurred with average SO_2 concentrations of 45 $\mu g/m^3$ (0.017 ppm) associated with peak 30-minute maximums of 3249 $\mu g/m^3$ (1.24 ppm) during growing seasons over a 10-year period. (Table 5-2.)

Since short-term concentrations are probably more important than long-term averages in the development of vegetational injury, growing season or annual averages as well as the maximum concentrations must be shown if they are to have any value in determining causal relationships. In this regard, there is a need for the development of mathematical equations to express relationships between short-term concentrations, long-term averages, and vegetational response to sulfur dioxide. (Section J.1.)

L. CONCLUSIONS

The final chapter of *Air Quality Criteria for Sulfur Oxides* includes summaries of the preceding chapters of that document and conclusions based upon them. The summary of vegetation effects presented in that chapter (Chapter 10, Section A.6) no longer represents the best information currently available, and the reader is referred instead to the preceding section of this report. The conclusions related to vegetation in that document (Chapter 10, Section B.4) also are superseded by those presented in this section, as is the brief statement in the "Resume" (Chapter 10, Section C).

The conclusions that follow are derived from a careful evaluation by the Environmental Protection Agency of the foreign and American studies cited herein. They represent the Agency's best judgment of the effects that may occur when various levels of pollution are reached in the atmosphere. The data from which the conclusions were derived, and the qualifications that should be considered in using the data, are identified by section or table reference in each case.

In applying the guidelines presented in the following paragraphs, factors other than pollutant concentration that affect a plant's response to pollution, including the sensitivity of the given variety or species to the pollutant, duration of exposure, temperature, humidity, interaction with other pollutants, edaphic conditions, and state of plant development, should be kept in mind. Since short-term concentrations are probably more important than long-term averages in the development of vegetational injury, maximum concentrations as well as growing season or annual averages must be specified in evaluation of long-term exposures. In this regard, there is a need for the development of mathematical equations that express relationships between short-term concentrations, long-term averages, and vegetation response to sulfur dioxide.

For plants such as maple trees, spinach, and sweet potatoes that are sensitive to sulfur dioxide, damage or reduction in growth or yield may result from short-term exposures as low as 131 to 1316 $\mu g/m^3$ (0.05 to 0.5 ppm) over periods of 8 hours or 2620 to 10,480 $\mu g/m^3$ (1.0 to 4.0 ppm) over periods of ½ hour. More resistant plants such as oak trees and corn may require exposures of over 5240 $\mu g/m^3$ (2 ppm) for the 8-hour period or over 26,000 $\mu g/m^3$ (10 ppm) for the ½-hour period. (Section J.2, Tables 5-8 and 5-9.)

Growing season average concentrations as low as 26 to 66 $\mu g/m^3$ (0.010 to 0.025 ppm) have been reported to affect a large number of agronomic species. These averages were associated with maximum 30-minute values of 2096 to 4978 $\mu g/m^3$ (0.8 to 1.9 ppm). (Section I, Table 5-1.)

Foliar and growth affects of mixtures of SO_2 with other pollutants may be greater than the effects of SO_2 alone. Mixtures of both SO_2 and ozone and SO_2 and nitrogen dioxide have been found to produce greater effects than either pollutant alone.

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15. Supplementary Notes

16. Abstracts

Limitations in the criteria for secondary standards in the publication "Air Quality Criteria for Sulfur Oxides," which became apparent since the adoption of Air Quality Standards, prompted review and revision of Chapter 5, "Effects of Sulfur Oxides in the Atmosphere on Vegetation." This document presents the revision to Chapter 5, and also includes revised portions of Chapter 10,"Summary and Conclusions," that relate to effects on vegetation. The document, based primarily on a thorough review of available literature, summarizes current scientific knowledge of air pollution effects by sulfur oxides upon vegetation and also points up the major deficiencies in that knowledge.

17. Key Words and Document Analysis. 17a. Descriptors

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