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BIOPHYSICAL RESEARCH

THE EFFECTS OF ACIDIC DEPOSITION ON ALBERTA AGRICULTURE A REVIEW

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EXECUTIVE SUMMARY

The current scientific literature on the effects of acidic precipitation, SO_2, NOx, O_3 and H_2S on agricultural production was reviewed for this publication.

Literature was acquired through computer-assisted searches (e.g., of the DIALOG data bases AGRICOLA (USDA, ENVIROLINE, and BIOSIS), library searches, and correspondence with government, information, and research organizations in the United States, Canada, and England.

The focus of this review was on crops, pollutants, and processes particularly relevant to Alberta, Canada. Data used quantitatively were selected on the basis of sound experimental design and reporting.

In Alberta, sources for the pollutants covered in this review are the petroleum industry and fossil fuel combustion for commercial industry, transportation, urban centres, and power generation. Twenty-five to 50% of the sulphur deposition in Alberta is in the form of wet acidic deposition.

Agricultural production is a significant component of Alberta's economy. Total agricultural receipts reached 3.9 billion dollars in 1984, with over 19 million hectares (47 million acres) utilized by the agricultural sector. The highest grossing crops were the grains, i.e., barley, wheat, rye, and mixed grains. The highest grossing non-grain crops were sugar beets, potatoes, field beans, and field peas.

The effects of these pollutants on agriculture were reviewed in five sections: the effects of acidic precipitation, the effects of gaseous air pollution, the effects of mixtures of pollutants, the effects of acidic deposition on plant-soil interactions, and the effects of acidic deposition on plant-symbiont interactions.

Changes in growth and yield of crops are of greater economic importance than are other potential effects of acidic deposition. For seed, grain, oil, fruit, and bean crops, marketable yield is determined by the development and maturation of reproductive organs. For both economic and environmental concerns, the effects on plant growth, yield, and reproduction due to acidic deposition are the most important responses.

Acidic Precipitation

Exposure to simulated strongly acidic precipitation resulted in reduced yields in 14 out of 19 species reviewed in this report. There were no field surveys found that documented a reduction in yield due to ambient acidic wet deposition. The mechanisms by which acidic precipitation inhibits plant growth, or alters plant form, are not known; foliar injury has not been directly correlated, nor have short-term changes in soil conditions been identified. Root growth tended to be inhibited more than did shoot growth, i.e., there tended to be an increase in the shoot to root ratio.

In general, dicots were more likely to show inhibited growth than were monocots. No experiments reported an inhibition of growth, for any species, above pH 4.0. The groups of crops most susceptible to reductions in yield were root, cole, leafy, tuber, legume, fruit, grain, seed forage, and leafy forage crops, arranged in descending order of sensitivity.

There is little evidence for a linear dose response function because frequently no change in effect occurred at doses greater than those producing a positive or negative response. This suggests that acidic wet deposition may have a combination of competing (inhibitory or stimulatory) effects on plant growth. However, the below pH 3.5 dose-response approaches linearity, with a yield loss of about 5% per drop in pH unit below pH 3.5.

The formation, development, and survival of pods, flowers and fruits are sensitive to acid rain at moderately low pH's (below pH 4.0). Pollen viability appears to be more sensitive in herbaceous species than in woody species, but data are inconclusive. Acidic wet deposition may interfere with anthesis, fertilization, and fruit set, development and maturation, as well as seed germination and seedling emergence. In perennial species, acidic wet deposition may have cumulative effects on fruiting. For flowering plants, the brief bloom period is very vulnerable to external influences, and may coincide with seasons of high acidity rainfall.

Foliar damage resulting from exposure to simulated acidic wet deposition has been experimentally shown to lower marketable yield of truck crops, lower plant resistance to pathogens, and has been linked with reduced plant productivity.

The threshold for foliar injury from simulated acidic wet deposition was between pH 3.0 and 3.5 for the 36 crop species reviewed. The groups of crops most susceptible to visible injury were, from most to least susceptible, root, leafy, cole, legume, fruit, grain, and leafy and seed forage crops, respectively. The potential for economic loss was greatest for leafy, cole, and fruit crops. Monocots, such as wheat, barley, and timothy, were resistant to foliar injury above pH 2.5. There is a low risk of foliar injury to field grown vegetation from exposure to current ambient levels of acidity; however, increased emissions may pose a risk to sensitive plants and plant communities.

It is unlikely that the S or N in acidic wet deposition could be a significant source of foliar fertilizer to crops, or pose a risk of salt damage. Soil mediated effects are discussed below.

Most nutrients are leached from foliage faster as the acidity of precipitation increases, as are some organic compounds. Changes in carbohydrate and protein content of feed crops are of widespread economic concern, as well as indications of significant physiological responses of plants to acidic wet deposition.

Gaseous Pollution

Gaseous air pollutants may cause either increases or decreases in growth and yield. The effects of gaseous pollutants on growth and yield are of primary concern in agricultural systems. They can have more of an economic impact on the agricultural industry than any of the effects of other pollutants.

Low concentration SO_2 exposures can cause an increase in growth and yield in plants growing in sulphur deficient soils. Several studies, however, have shown significant decreases in growth and yield due to SO_2. To avoid deleterious effects on growth and yield in agricultural crops, average annual concentrations of ambient SO_2 should not exceed 0.01 ppm and 24-hour averages should not exceed 0.06 ppm according to present standards. The literature shows that, with a safety margin for sensitive species, these standards are adequate.

The relative ranking of plant sensitivities to SO_2 was analyzed for forages and grains because they occupy approximately 75% of the acreage of improved land in Alberta. Red clover was calculated as the most sensitive species followed by the winter grains, wheat, and rye; next in sensitivity are other grains, barley, spring wheat, and oats; at the less sensitive end of the scale is alfalfa; the least sensitive of the species studied is canola. Alfalfa has been determined by other investigators to be very sensitive to SO_2. Perennial grasses are more sensitive to SO_2 than alfalfa. Annual grasses seem to be significantly less sensitive to SO_2 than alfalfa.

Forage, grain, and grass species can be ranked for relative sensitivities as follows:

clover > winter grains > spring grains > alfalfa > canola

and

winter grasses > alfalfa > other grasses

The position of alfalfa in the first ranking is not definite.

Nitrogen dioxide in low concentrations can assume the role of a fertilizer and be a source of necessary nitrogen for the plant. Increases in plant growth and yield have been reported with low concentration NO_2 exposures, when plants were grown in both nitrogen deficient soils and those with optimum nitrogen nutrition. Small reductions in growth and yield for sensitive agricultural species can occur at continuous NO_2 concentrations of 0.05 ppm. Nitrogen oxide has not been shown to cause decreases in growth and yield at or near ambient levels.

Most of the studies conducted on the effect of NO_2 on growth and yield have been at high concentrations (more than 1.0 ppm). This is in part because many agricultural species may have only slight changes in growth and yield at concentrations as high as 1.0 ppm when plants are exposed to NO_2 alone. Acute exposures appear to be more injurious.

The relative sensitivity of many agricultural crops to NO_2 is as follows: Of the field crops and grasses, the leguminous forage crops, barley, and oats are the most sensitive. Also sensitive are leek, carrot, lettuce, and celery. Of intermediate sensitivity are tomato and celery. Also of intermediate sensitivity are an annual grass (bluegrass), wheat, corn, rye, and potato. Considered least sensitive are a perennial grass (Kentucky bluegrass), two cole crops (cabbage and kohlrabi), the same root crop (carrot), and asparagus.

Ozone has been proven to reduce growth and yield of many agricultural species. For O_3, the lowest limit for injury follows several hours of exposure to a concentration range of 0.02 to 0.05 ppm for most species under general conditions.

The relative sensitivity of many agricultural crops to O_3 is as follows: Leafy vegetables are the most sensitive in all cases, while perennials and woody species are the most resistant. For the sensitive and resistant plant types, grasses and legumes are more sensitive than oats (a grain); but for intermediate plant types, wheat (a grain) is more sensitive than the grasses, which in turn are more sensitive than legumes and clover.

Hydrogen sulphide is the most phytotoxic of the gases reviewed. However, at concentrations commonly found in the ambient air, the actual risk posed to plants by H_2S is much lower than the risk from the other gases. For most species investigated in this review there were either no effects on, or increases in, yield with long-term exposures at a concentration of 0.10 ppm; but with a concentration of 0.30 ppm, decreases in yield were quite evident. For more sensitive species (eg., alfalfa, grapes) yields were reduced at concentrations as low as 0.03 ppm.

Interactions between Pollutant Types

The increased phytotoxicity of a given gaseous pollutant in the presence of another has become an important consideration when assessing the impact of pollutants on vegetation. Frequently, elevated concentrations of more than one pollutant exist as a result of atmospheric mixing: the emissions of a pollutant into already polluted air; the simultaneous emission of more than one pollutant; or, the chemical conversion of different pollutants. Most pollution sources emit more than one pollutant. These mixed emissions may be simultaneous or sequential over time.

Interactive effects of pollutants in combination can be described as follows: (1) The plant response to the pollutant mixtures is additive, and is similar to the summed effects of the individual pollutants. (2) The plant response may be antagonistic (less than additive). (3) The plant response may be synergistic (greater than additive). In addition, in sequential exposures, plants may become sensitized or hardened to a pollutant by a previous exposure to a different pollutant. Changes in injury type may also occur in plants exposed to pollutant mixtures compared to single pollutants. Plant responses to pollutant combinations depend not only on the components of the mixtures and their temporal succession, but also on the same factors that influence plant response to single pollutant exposure.

Synergistic, additive, and antagonistic interactions for decreases in growth and yield have been observed with exposures to mixtures of SO_2 and O_3, of SO_2 and NO_2, and of NO_2 and O_3. In addition, researchers have found that in nearly every instance, exposure to a mixture of SO_2, NO_2, and O_3 causes a greater loss in plant growth and yield than the single gases or the two-pollutant mixtures. Studies conducted thus far have been important because they have shown that growth and yield responses to NO_2-pollutant-mixtures occur in the NO_2 concentration range of 0.05 to 0.30 ppm, well below the air quality standard for NO_2 and within ambient elevated NO_2 concentrations. The decrease in growth and yield caused by NO_2 in the presence of SO_2 and/or O_3 ranges from 5% to 20% at concentrations of NO_2 that cause little or no injury when the pollutant is present singly.

Studies on the effects of combined exposures of wet acidic deposition and gaseous pollutants on plants are only in their initiation. These studies thus far generally show synergistic and additive interactions. The interaction between gaseous pollutants and wet acidic deposition is significant because these two pollutant types usually occur concurrently.

Plant Response

The extent and nature of injury caused by contact with acidic deposition (both acidic precipitation and dry gaseous pollution) is a function of the characteristics of the species, the cultivar, the pollutant, and the method of exposure.

Acidic deposition varies in ways that may influence plant response. Acidic precipitation exposure characteristics which influence plant response include the instantaneous dose (i.e., concentration) and the cumulative dose (i.e., total deposition), the peak or constancy of pH (over multiple treatments), the sulphate to nitrate ratio and total ion composition, the chemical form (e.g., wet or particulate), and temporal factors such as the length of time during and between rain events. Gaseous pollution exposure characteristics which influence plant response include concentration, the length of time of exposure, the peak or constancy of concentration (for multiple or long-term treatments), the pollutant species or combination of pollutant species, and temporal sequence.

Crops grown in a controlled environment, such as a greenhouse or a growth chamber, consistently displayed a lower tolerance for acidic wet deposition than did field grown crops. Other growth conditions that influence plant dose-response include irrigation, plant nutrition, edaphic factors, climate, location, and season.

The relationship between crop yields in experiments and crop yields under standard agronomic conditions is an important concern for future research.

Plant-Soil Interactions

Among species prominent in Alberta, oats are the most tolerant of acidic soils, while alfalfa, barley, and canola are the most sensitive. Although most of the grasslands of Alberta have rich, well-buffered soils, foliar exposure to acidic deposition may influence plant reproduction, productivity, or partitioning of photosynthate. The secondary effects can be lower tolerance to some environmental stresses (e.g. drought) and changes in species viability.

Fertilization and other soil management practices have a much greater impact on soil acidity than do current or projected levels of acidic deposition in Alberta. On unmanaged soils, long-term deposition may have deleterious effects on soil. Aluminum toxicity is the most common cause of crop failure on acidic soils. Manganese toxicity and calcium deficiency are other common problems. Soil acidity is not directly toxic until the pH is below 3.0. Under some conditions (e.g., sulphur-poor soils) plant growth may be stimulated by deposition of nitrates and sulphates.

Plant-Symbiont Interactions

Acidic deposition may affect plant-symbiont interactions through impact on the plant, the symbiont, or both. Acidic deposition can alter the plant's quality as a host organism or decrease plant resistance to infection. Symbiotic organisms may be affected at different stages of their life cycle (e.g., reproductive phases). Wet deposition is of greater significance than is dry deposition in affecting interactions between plants and their pathogens.

Conclusions

Agricultural production contributed 10.2% of Alberta's gross domestic product in 1981, with grain crops such as wheat and barley accounting for over 75% of Alberta's total farm cash receipts (Alberta Agriculture Statistics Branch, letter 1985). Almost 30% of Alberta's land area is used for farming, with 12% being cultivated at a given time (Alberta Agriculture 1982). The estimated farm cash receipts and acreage under cultivation are detailed in Table 38. Ecologically, agriculture and grazing are dominant in four ecoregions of Alberta: Short Grass, Mixed Grass, Fescue Grass, and Aspen Parkland Regions, which cover about 25% of Alberta (Strong and Leggat 1981). Thus, the effect of air pollutants on agriculture is of both economic and ecological concern.

The Clean Air Act of Alberta establishes maximum permissible levels of gaseous air pollutants in the ambient air. These regulations are summarized in Table 39. Comparable air quality standards, however, have not been set with respect to acidic precipitation. The average annual pH of precipitation in Alberta, determined from eleven precipitation monitoring stations in two networks between 1978 and 1984, was 5.5 with a range from 5.2 to 6.1 while the median pH for this period was 6.0 (Lau and Das 1985). These data indicate that little or no acidic wet deposition has been recorded for Alberta and indicate that there is currently no risk to agricultural crops in Alberta from regional scale acidic wet deposition.

If the air quality standards for SO_2 are met, there should be no adverse effects on agriculture due to SO_2 under most conditions and with most agricultural plants. However, some studies suggest that the most sensitive agricultural species exposed to concentrations of SO_2, at or slightly higher than permissible allowances under environmental conditions conducive to gas exchange, may be injured by SO_2 exposure. To injure the most sensitive species, concentrations of between 0.05 and 0.5 ppm for several hours are usually required.

Nitrogen dioxide concentrations of 0.25 to 0.50 ppm for long periods of time are generally required to induce injury in sensitive agricultural plants. However, a few studies have shown injury to plants at concentrations at or below the maximum permissible concentrations. No reports of injury are available for acute exposures lower than the maximum permissible concentration. For this reason we believe that if the Government of Alberta standards are adhered to for acute NO_2 exposures, no injury should occur in agricultural species. In light of the few experiments showing injury at chronic exposures at or above the maximum permissible concentrations of NO_2, there is some question as to whether the standards for chronic exposure are enough to protect sensitive agricultural species.

Ozone concentrations of 0.03 ppm (for very sensitive species) and 0.10 ppm (for species of intermediate sensitivity) are required to induce injury in agricultural plants when exposed to O_3 for several hours. Research indicates that the maximum permissible concentrations of O_3 specified for acute injury are sufficient to protect agricultural plants. Although the maximum permissible concentration is not specified as an annual mean, if this concentration follows the same relative patterns as those for the other pollutants, it should also be adequate to protect plants. Damage to agricultural species of intermediate sensitivity due to chronic exposures is generally not seen at concentrations below 0.05 ppm.

From the most recent research on the effects of H_2S on agricultural crops, these standards appear adequate for the maintenance of plant health.

Because injury to sensitive agricultural species has been observed during chronic exposures at or near maximum permissible levels of gaseous pollutants when present singly, there is concern over the possible synergistic effects of these pollutants at the same concentrations when present together. If these pollutants react synergistically for injury induction, then they are more phytotoxic than those for which government standards allow.

The annual mean values of SO_2, NOx, and O_3 concentrations in Edmonton and Calgary for downtown, industrial, and residential areas for the years 1977 to 1984 are well below the maximum permissible concentrations and are apparently at safe (nonphytotoxic) levels. In any agricultural area, or area being considered for agricultural use, monitoring data for various pollutants should be taken into account assuming at least additive interactions among pollutants.

Recommendations

Broadly defined, the recommended objectives for future research are as follows: (1) to enable estimation of present crop losses due to all atmospheric pollution; (2) to enable prediction of crop damage from changes in total atmospheric deposition; (3) to determine causative agents in crop loss, and safe thresholds of those agents, when occurring singly or in combination.

More specific research recommendations are detailed in the following paragraphs. These include recommendations for research emphasis, preferred experimental design, ecosystem studies, field surveys, and pollutant mixture studies.

Data indicate that more experiments, under standard agronomic conditions, are warranted for perennial crops, for crops that have demonstrated sensitivity to acidic deposition, or for crops of significant economic or ecological importance. With regard to acidic precipitation these crops include fruit trees, root crops (especially sugarbeet), canola, soybeans, ryegrass, alfalfa, and leafy crops. With regard to gaseous pollutants they include leguminous forage crops (including alfalfa and clover), leafy vegetables, and some grains.

Because dry deposition accounts for over one-half of the sulphur deposition in Central Alberta, research on short- and long-term effects of dry deposition on plant yield is recommended. More research is needed using several different concentrations of a gaseous pollutant on important agricultural species and cultivars in order to assess their relative sensitivities. Such experiments will allow comparisons with existing data. The research should incorporate the pollution monitoring data for a particular region and should be conducted on sensitive species exposed to supplemental additions of pollution. Pollution mixture studies should be conducted using ratios of pollutants reflecting ambient mixtures. In addition to the pollutant species investigated, average concentrations, peak concentrations (which are often not taken into account), the duration of each of these concentrations, and ambient temporal patterns of pollutant types should be considered. When possible, experimental analysis should include both changes in partitioning of photosynthetic assimilates and growth analysis. This information would support modelling.

Whole-ecosystem studies are needed to investigate the individual and interactive effects of acidic deposition on plant reproduction and growth. Long-term (i.e., two-three years) field research is especially recommended for perennial forages such as perennial ryegrass and alfalfa. The effects of acidifying atmospheric substances on continuous plant propagation should be assessed. Short-term experiments are needed to empirically determine if the effects of pollutants on seed and fruit production are a result of direct action on sexual organs or indirect action by injury to other plant parts or processes.

The thresholds for reduction in plant growth and visible injury are sufficiently high that present acidity levels of ambient precipitation in Alberta do not currently pose a risk to agricultural plants. To establish a baseline of both crop yield data and atmospheric quality data, field surveys, ideally in the same location as the precipitation and the air quality monitoring network, should be carried out over multiple seasons in districts rich in canola, leguminous forage, perennial forage, forage seed, sugar beet, fruit crops, or winter grains. Field surveys should also encompass a natural grassland area with poorly buffered soil.

Research in the area of pollutant mixtures, and pollutant and CO_2 (carbon dioxide) mixtures demands more attention. Experiments with pollutant mixtures should be conducted on agricultural species of economic importance in Alberta and on species shown to be particularly sensitive to either or both acidic precipitation and gaseous air pollutants. In order to assess the relative effect of pollutant mixtures, ambient, and single pollutant controls must be established.

TABLE OF CONTENTS

TABLE OF CONTENTS (continued)

TABLE OF CONTENTS (continued)

TABLE OF CONTENTS (concluded)

LIST OF TABLES

LIST OF TABLES (concluded)

LIST OF FIGURES

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This review was funded by the Acid Deposition Research Program of Alberta. We would like to thank them for their interest in and support of environmental protection. Our appreciation is extended to those at the Kananaskis Centre for Environmental Research for their continuous guidance throughout the project. We would like to extend our sincere thanks to Stan Martins of Lawrence Livermore National Laboratory for his support with the computer backup including the establishment of the database that brought all this information together. We gratefully acknowledge the assistance of many coworkers at Lawrence Livermore National Laboratory for their invaluable input and suggestions in this review. They include Kris Surano, Paul Daley, John Koranda, Mike Novo, Jeremy Fried, and Scott Patton. The extra hours they put in are greatly appreciated.

A number of publications used in this review are secondary references because the original paper was not available. Because the content of the original paper was viewed as essential, when references of this type are used, both the document in which they were cited and the original paper are referenced. For the convenience of the reader, both documents are listed in the "References Cited" section of this review.

Several of the summary tables in this review were modified from the work of other authors. All of the literature used in the creation of these tables are also listed in the "References Cited" section of this review for the convenience of the reader.

1. INTRODUCTION

This review outlines the current knowledge of the effects of acidic deposition on agriculture, including plant response to pollutants, plant response to soil changes due to pollutants, and effects on interactions between plants and symbionts. Acidic deposition may trigger changes in crops, soils, and crop-symbiont interactions. The effects of wet and dry deposition on agricultural plants are discussed in Sections 2 and 3, respectively. Wet acidic deposition generally refers to the deposition of aqueous hydrogen, sulphate, and nitrate ions on plants or soil (Lee 1981). In the discussions of dry deposition, the gaseous air pollutants considered are: the acidic gases SO_2 (sulphur dioxide) and NOx (oxides of nitrogen), the oxidant O_3 (ozone), and H_2S (hydrogen sulphide). In the discussion of the effects on agricultural plants attention is paid to: direct effects on plant physiology; foliar responses such as visible injury, fertilization, buffering, and leaching; crop growth; and, reproduction. Relative species sensitivity to foliar injury and changes in growth and yield have been analyzed from available dose-response data. Because experimental conditions vary considerably and may have a significant influence on plant response, a review of experiment design factors was made to aid in data interpretation. Species important to Alberta agriculture are emphasized except where there is a limited amount of data on these species or where comparisons to other species increase understanding. In Section 4 the effects of pollutant combinations on agricultural plants are considered. The effects of acidic deposition on plant response to pollution-induced changes of the soil environment are detailed in Section 5. The effects of acidic deposition on plant-symbiont interactions are reviewed in Section 6. In Section 7 we give conclusions on the impact that atmospheric pollutants may have on Alberta agriculture. Section 8 indicates specific areas covered in this review that need further research. Section 9 provides a summary of the review.

Agriculture in Alberta is extensive, comprising more than 19 million hectares (47 million acres) and grossing almost 3.9 billion dollars in total receipts in 1984 (Alberta Agriculture 1982; Alberta Agriculture Statistics Branch, letter 1985). Receipts for grain alone amounted to 1.7 billion dollars. Roughly half of Alberta's 12.5 million hectares (31 million acres) of improved land is utilized for grain crops, which include barley, wheat, rye, and mixed grains. In the last agricultural census, forages (including grasses and legumes) were farmed on approximately 1.8 million hectares (4.4 million acres), and oil-seed crops occupied 0.6 million hectares (1.5 million acres). After grains, the highest grossing crops were sugar beets, potatoes, field beans, and field peas. Given the economic contribution of agriculture to Alberta, one can see why there is concern over the possibility of crop losses due to air pollution.

It is the deposition of SO_2, NOx, O_3, and H_2S (referred to as gaseous air pollutants in this review) and wet acidic deposition that are of major importance in Alberta. The total annual emissions of SO_2 and NOx in the province of Alberta in 1982 were approximately 488,297 tonnes and 353,511 tonnes, respectively (Sandhu and Blower 1986). The majority of the SO_2 emissions in Alberta are emitted by the petroleum industry and the coal fired power plants of the electric utilities. The majority of the NOx emissions in Alberta are emitted by the petroleum industry, the coal fired power plants of the electric utilities, urban centres, and motor vehicles on highways. Although the petroleum industry is the principal source of H_2S emissions, the pulp and paper industry is also a contributor. It is estimated that between 25 to 50% of the sulphur deposited in Alberta is in the form of wet deposition (Nyborg and Crepin 1977; Kociuba et al. 1984; Sandhu and Blower 1986).

1.1 POLLUTANTS

Atmospheric pollution may be categorized as wet deposition and dry deposition. Dry deposition includes deposition of both gases and particulates. Gases can be acidic, such as SO_2 and NOx or non-acidic such as the oxidant O_3. These gases may return to the earth's surface by two pathways: (1) as dry deposition by absorption and adsorption by vegetation, litter, and soil; or, (2) by oxidation in the atmosphere to sulphates and nitrates, including the acids sulphuric acid (H_2SO_4) and nitric acid (HNO_3), which are deposited in precipitation, in dew, by dry deposition of particulate matter, or by interception of fog by vegetation or the ground. When these acids are deposited by precipitation, it is referred to as wet acidic deposition, or more commonly, as "acid rain." Table 1 illustrates different types of acidic deposition. The measured acidity of precipitation at locations isolated from pollution is due to the presence of weak organic acids and strong mineral acids. The pH at such remote sites has been found in the range of pH 4.8 to 5.6 (Lefohn and Brocksen 1984). Precipitation with a higher concentration of free hydrogen is termed wet acidic deposition. Most of the research reviewed employed acidic pollution in the form of acidic gases, acidic mists, or simulated acidic "rain" to study plant response to acids in the atmosphere. Acidic precipitation and mists are considered together in this review. There are no dose-response data available from experiments using acid fog. Acid fogs are characterized by very low pH with low total H^+ due to water density content. Rainfall acidity has increased by 2 to 3 orders of magnitude over much of eastern North America during the past 30 years (Likens et al. 1979). With the continued use of fossil fuels and smelting of metals it is unlikely that these acidity levels will decrease (Johnston et al. 1981).

Atmospheric quality varies regionally as well as within a given region, and thus with experimental location. Eleven precipitation minitoring stations in two networks were in operation in Alberta during the period between 1978-1984. Alberta Environment operated the Precipitation Quality Monitoring Network (PQMN) which consisted of six stations, while Environment Canada operated five stations in Alberta as part of the Canadian Network for Sampling Precipitation (CANSAP). The average annual pH of precipitation from these eleven stations during the 1978-1984 period was 5.5 with a range from 5.2 to 6.1, while the median pH was 6.0 (Lau and Das 1985). The average annual wet deposition of hydrogen ion for the same period was 1.5 m mole m^{-2} y^{-1} with a range from 0.4-3.2 m mole m^{-2} y^{-1} (Lau and Das 1985). These data indicate that little acidic wet deposition has been recorded for Alberta. In contrast to Alberta, rain of pH 3.0 to pH 3.5 occurs for 2% of the rain events in Southern Ontario (Adams and Hutchinson 1984). In the Eastern US rainfall ranges from pH 3.0 to 6.0 with half the summer events at pH 4.0 or lower, and with volume-weighted means as low as pH 3.9 in some regions (Lee et al. 1981; Jacobson 1984). At Brookhaven National Laboratory in New York, 58% of the rainfall in 1979 was between pH 3.5 and pH 4.5 (Evans et al. 1981b). The median pH of rainfall for the period 1978 through 1984 in the northeastern US ranged between 4.2 and 4.7 (Knapp et al. 1987).

Table 1. Some physical and chemical properties of components of acidic deposition.

Physical Form	Common Chemical Components	Particle Diameter (μm)	Concentration (μg m^{-3})	Deposition Process	Deposition Velocity (cm s^{-1})
Gas	SO_2	--	1300	diffusion, chemabsorption	0.2-0.6
Aerosol	H_2SO_4, $(NH_4)HSO_4$	.01-10	40	diffusion, impaction	less than 0.2
Fog Clouds	H_2SO_4 $(NH_4)HSO_4$	.1-3		impaction	1-3
Mist	H_2SO_4, HNO_3 $(NH_4)HSO_4$	30-300		impaction, sedimentation	3-50
Rain	H_2SO_4, HNO_3	300-3000		sedimentation	50-800

Source: Jacobson (1984)

The atmospheric quality data for Alberta are not complete because of the paucity of permanent monitoring stations at rural sites. Urban sites (such as Edmonton and Calgary) are monitored more closely. The annual mean values of SO_2, NOx, and O_3 concentrations in Edmonton and Calgary for downtown, industrial, and residential areas for the years 1977 to 1984 are well below the maximum permissible concentrations (Alberta Environment 1984a) and are apparently at safe (non-phytotoxic) levels. In any agricultural area, or area being considered for agricultural use, monitoring data for various pollutants should be taken into account with at least additive responses among the pollutants on crops considered.

The maximum permissible concentrations of SO_2 as set by the Government of Alberta are 0.01 ppm as an annual mean concentration, 0.06 ppm as a 24-hour concentration, and 0.17 ppm as a one-hour concentration. The maximum permissible concentrations of NO_2 are approximately 0.03 ppm as an annual mean concentration, 0.10 ppm as a 24-hour concentration, and 0.20 ppm as a one-hour concentration. The maximum permissible concentrations of O_3 are approximately 0.025 ppm as a 24-hour concentration and 0.08 ppm as a one hour concentration. The maximum permissible concentrations of H_2S are approximately 0.003 ppm as a 24-hour concentration and 0.01 ppm as a one-hour concentration. This is further discussed in the "Conclusions" section of this report (Section 7).

1.2 PLANT RESPONSE

The extent and nature of plant response to atmospheric pollutants are a function of plant, pollutant, and environmental characteristics. Plant response may be mitigated or intensified by these different factors, and these factors often vary among experiments. In addition, the relationship between crop yields in experiments versus crop yields under standard agronomic conditions must be considered. The sensitivity of species and the threshold for deleterious effects on productivity depend on these factors.

Susceptibility to both wet acidic deposition and dry gaseous deposition varies among species, and among cultivars within species. No established way exists to relate sensitivities among species without conducting experiments with each species in question. The age of the plant and the stage of plant development at the time of pollutant exposure influence the nature of plant response including the plant's threshold for injury and reduction in productivity. Plant parts may also be affected preferentially according to their age and the stage of development.

Leaf surface characteristics may influence plant response to pollutant exposure. These characteristics may vary among species or cultivars and within stages of plant development for individual plants. Important to a plant's response to wet acidic deposition are leaf surface characteristics that affect or determine wettability, water retention, permeability, and penetration, as well as rates of exchange of water and dissolved substances. Shape and ability to retain water droplets affect the placement, nature, and degree of injury (Keever and Jacobson 1983a; Bockheim 1984). The differences in leaf characteristics among species may contribute to the variation in sensitivity among species. Growth conditions, such as regional meteorology, affect the leaf surface (Neufeld et al. 1985a) and also affect plant sensitivity to wet acidic deposition and dry deposition of gases.

Changes in exposure frequency, duration, number, or pattern of exposure may affect plant response as well as length of time between exposures, magnitude of fluctuations in pH or concentrations, and diurnal patterns of exposure. More frequent events allow less time for leaf recovery and in the case of wet acidic deposition, may prevent drying. In addition, for exposures to wet acidic deposition, increased acidity will increase the extent and degree of foliar injury (Evans and Curry 1979; Jacobson 1984). For acid aerosols and fogs, droplet size can be important in plant response (Jacobson 1984).

Both the instantaneous dose (i.e., concentration) and the cumulative dose (i.e., total deposition) are significant in influencing plant response (Irving 1983). The constancy of pH for wet acidic deposition and of concentration for dry gaseous deposition can influence plant response. Researchers have found that the pH (of acidic precipitation) and the concentration (of gaseous air pollutants) influence the extent of injury more than does the duration of exposure for a given dose (Johnston et al. 1981; Godzik and Krupa 1982; Lefohn and Brocksen 1984; and Guderian 1985). Plants exposed to the same dose (concentration • time) at various concentrations will, in all probability, exhibit more injury at the higher concentrations (Taylor et al. 1975).

The growth conditions of the plant are comprised of a wide variety of factors including location, environmental conditions, structural environment, and agricultural practice. General responses to atmospheric pollutants of plants grown under different growth conditions may be similar, but quantitative relationships between dose and response clearly are affected by environmental conditions (Jacobson 1982). Environmental conditions that favour rapid growth, including high light intensity, high relative humidity, adequate soil moisture, and moderate temperature, may increase the susceptibility of plants to gaseous pollutant injury by promoting wide stomatal aperture, and therefore rapid absorption of pollutant gases.

The experimental setting is generally quite different from the natural or standard agronomic environment. Most experiments reviewed followed standard agronomic practice. Experimental practice can be more favourable than natural environments and/or standard agronomic environments (e.g., the use of commercial potting mixes, fertilization, or irrigation) or less favourable (e.g., root stress due to the limited size of plant pots).

A plant's response to wet and dry deposition may be influenced by the nutrient composition of soils. Generally, plants that are given an adequate supply of nutrients are less sensitive to injury than plants with a deficient or an excess supply (Leone and Brennan 1972; Guderian 1977; and Cowling and Koziol 1982); but there are exceptions to this which seem to depend on the pollutant in question, the dosage of this pollutant, and the nutrient composition of the soil (Cowling and Koziol 1982). Plants grown in sulphur and nitrogen deficient soils will often respond with increased growth and yield when exposed to low concentrations of SO_2 and NO_x, respectively. The same plants will show no change in growth and yield when exposed to the same fumigations in soils with sufficient sulphur.

The effects of external, environmental factors on plant response to atmospheric pollutants have been observed repeatedly when comparing field experiments to those conducted in greenhouses and chambers. Plants grown in controlled environments, such as greenhouses, glasshouses, or growth chambers show greater susceptibility to foliar injury and a lower threshold for yield reductions (National Academy of Sciences 1977a; Beckerson et al. 1979; Evans et al. 1981b; Irving and Miller 1981; Evans 1982; Troiano et al. 1982; Cohen et al. 1982; Keever and Jacobson 1983c; and Reinert 1984). Thus, results from controlled environment experiments can overestimate plant response to acidic deposition. Plants insensitive to a given dose in a greenhouse will probably not be adversely affected by a similar dose under ambient conditions (Evans et al. 1982c; Jacobson 1984). Water stress, relative humidity, and temperature are important factors that vary significantly among experimental environments (Neufeld et al. 1985a).

2. EFFECTS OF ACIDIC PRECIPITATION ON AGRICULTURAL PLANTS

For plants grown under standard management, the most important pathway for acidic precipitation effects is through contact with foliage rather than through acid-induced changes in the soil environment (Johnston et al. 1981; Amthor and Bormann 1983). The potential effects of acidic precipitation on vegetation are shown in Table 2. Direct effects of foliar contact with simulated acidic rain, such as visible injury, foliar leaching, and buffering, and changes in plant nutrient content from contact with acidic solutions, are considered in this section, as well as effects on plant growth and reproduction. It is important to note that in reality the chemical composition and pH of precipitation varies within and between individual rain events at any given geographical location. Vegetation exposure studies, therefore, conducted with simulated precipitation of constant chemical composition and pH and the resultant responses must be viewed with caution.

2.1 VISIBLE FOLIAR INJURY

2.1.1 Introduction

Visible foliar injury (VFI) is the most often reported symptom of plant response to acidic precipitation. Simulated acid rain has induced visible injury on the foliage, fruit, and flowers of agricultural and horticultural crop species. Foliar damage may result in lower productivity, lower economic yield, and/or lower resistance to pathogens. An understanding of visible foliar injury enhances our ability to assess and predict ecological and economic damage from acid deposition in agricultural regions. This report will consider the processes associated with, and the consequences of, foliar injury. The extent and nature of injury caused by contact with acidic precipitation are functions of the characteristics of the species, the cultivar, the pollutant, and the method of exposure. Experimental data on VFI dose-response relationships for agronomic species were used to develop a ranking of relative sensitivity among crop species.

2.1.2 Foliar Injury and Productivity

A direct correlation between visible foliar injury and yield has yet to be established (Evans et al. 1981a, 1982c; Johnston et al. 1981; Lee 1981; and Proctor 1983;), and there is no known index of VFI correlated with growth or yield. Acid rain studies have found cases where growth is stimulated in plants with VFI, as well as cases where growth is inhibited in the absence of VFI (Hindawi et al. 1980; Evans et al. 1981a). Foliar injury may reduce productivity through structural changes, such as inducing necrotic lesions or curling and wilting of the leaf, and/or through physiological changes, such as altering diffusion resistance or reducing intercellular spaces. Where macroscopic foliar injury occurs, the reduction of photosynthetic leaf area may reduce plant productivity. Direct foliar contact with acid rain can influence rates of photosynthesis and respiration; research results are inconclusive as to the net effect on productivity (Hindawi et al. 1980). Acid rain can also inhibit the initiation or development of plant structures, thereby reducing their contribution to total plant biomass. Pod formation inhibited by acid rain reduced seed yields of snap bean in experiments by Johnston et al. (1981). While the precise mechanisms of injury and resistance are not known, the literature does contain descriptions of the associated processes and symptomology.

Table 2. Potential effects of acidic precipitation on vegetation.

DIRECT EFFECTS

1. Damage to protective surface structures such as cuticle.
2. Interference with normal functioning of guard cells.
3. Poisoning of plant cells after diffusion of acidic substances through stomata or cuticle.
4. Disturbances of normal metabolism or growth processes without necrosis of plant cells.
5. Alteration of leaf- and root exudation processes.
6. Interference with reproductive processes.
7. Synergistic interaction with other environmental stress factors.

INDIRECT EFFECTS

1. Accelerated leaching of substances from foliar organs.
2. Increased susceptibility to drought and other environmental stress factors.
3. Alteration of symbiotic associations.
4. Alteration of host/parasite interactions.

Adapted from Morrison (1984) and Tamm and Cowling (1976)

Foliar injury is not easily correlated with reduction in growth or yield because the response of the plant involves many processes that are not well understood. For example, the plant may alter its partitioning of photosynthate depending on the nature of injury sustained, or the stage in its development when exposed (Jacobson 1984). Plant adjustment, recovery, and compensation after exposure to simulated acidic wet deposition are suggested areas of research (Jacobson 1984).

2.1.3 Foliar Injury and Market Yield

Visible damage to foliage or fruit can lower the market value or market yield of some crops (Lee 1981; Evans et al. 1981a; and Plocher et al. 1985). The direct economic impact, i.e., lowering market value through blemishes or wilting, is restricted to fresh, market fruits and vegetables, and has a direct relationship to the extent and degree of injury. Produce sold for canning or juicing will be less affected, or unaffected. The indirect economic impact of foliar injury, i.e., the reduction of market yield due to reduced productivity, is much harder to quantify. There are insufficient published data to establish a link between ambient acidic precipitation and visible injury that would reduce the marketability of fruits or leaves (Evans et al. 1981a).

2.1.4 Foliar Injury and Pathogens

Exposure of foliage to acidic wet deposition may alter plant-pathogen relationships. Perturbations of the leaf surface may make the plant more vulnerable to penetration by pathogens. For example, infection courts, where penetration is easier, form in lesions induced by acid rain or gaseous pollutants (Shriner and Cowling 1980). Changes in the leaf chemistry or exudates will alter their ability to support fungus, and may alter the biochemistry of pathogens eating the foliage. Invertebrate pests may also be directly or indirectly affected by foliar response to acidic precipitation. For example, simulated acid rain applied to foliage reduced slug infestations of radish (*Raphanus sativus*) and onion (*Allium cepa*) plants compared with control plants grown in the same location. The role of acid precipitation and gaseous pollutants in plant-pathogen interactions is discussed in detail in Section 6.

2.1.5 Characteristics of Foliar Injury

Acidic precipitation has many effects on leaf tissue. The most commonly reported foliar injury from wet acidic deposition is brown necrotic lesions. Chlorosis, changes in the cuticular waxes, and gall formation have also been reported. At the cellular level, reduction in mesophyll conductance, decreased intracellular space, and a reduction in the size of starch granules have been observed (Ferenbaugh 1976; Neufeld et al. 1985a). The types of foliar response detected in an experiment depend on whether the observations were made visually, with a hand lens, or with a microscope (Jacobson 1984). Histological examination of plant tissue provides information about the effects of acidic deposition on plant physiology and on the possible mechanisms of plant response. Visual inspection is the easiest to conduct and thus allows for greater replication. The macroscopic symptoms observed in statistically significant numbers elucidate trends in foliar damage likely to affect leafy and fruit crop market values. This degree of replication also allows investigation of the relationship between pollutant treatments and foliar response.

2.1.5.1 Leaf surface response: lesions. There are no established correlations between the frequency of occurrence of the types of lesions discussed above and the density of trichomes or stomata. In beans (*Phaseolus vulgaris*) and sunflower (*Helianthus annuus*), lesion density increased as a function of total leaf area (Evans et al. 1977). The frequency of lesions was not found to correlate with the densities of trichomes and stomata, which decrease as leaf area increases. Nevertheless, it appears that lesions preferentially form near trichomes and stomata (Evans et al. 1977, Evans 1984b). Evans and Curry (1979) observed that in soybeans (*Glycine max*), the vascular tissue and cells at the base of trichomes formed natural depressions where acidic droplets collected, and where lesions tended to form. Crafts (1961) postulated that there were micropores around the bases of trichomes and glandular hairs that allowed for more rapid penetration in these specialized areas.

2.1.5.1.1 Lesion development. In contrast to stomata-conducted gaseous pollutants, which injure the mesophyll cells initially, wet acidic deposition affects the leaf surface tissue initially (Evans et al. 1977; Evans and Curry 1979). Damage progresses from the epidermal cells to the internal cells, except where more rapid diffusion through the stomata allows internal injury. Lesions develop by adaxial epidermal cell collapse followed by plasmolysis of palisade cells and eventual damage of the spongy mesophyll cells (Evans et al. 1977; Hindawi et al. 1980). Necrotic lesions form where entire cell strata are dead and there is no metabolic activity. Bleached cells of chlorotic lesions exhibit a reduced level of metabolic activity. Depending on the type of foliage and the degree of injury, lesions may or may not be bound by veins (Jacobson and Hill 1970). Thus, the size and shape of lesions vary.

2.1.5.1.2 Galls. Galls that elevated the leaf surface formed on the leaves of bush bean and sunflower (Evans et al. 1977), on wormwood (*Artemesia* sp.), and on wax bean and spinach (*Spinacea oleracea*) (Adams and Hutchinson 1984) after contact with simulated acid rain. The elevation prevented acidic droplets of subsequent doses from collecting in the damaged areas and the total area of injury was reduced (Evans et al. 1977). The galls are formed by abnormal cell division (hyperplasia) and enlargement (hypertrophy) in the spongy mesophyll layer when overlying palisade cells collapse. In comparing the response of tree leaf tissue to acidic deposition, Evans and Curry (1979) noted that the hypertrophic and hyperplastic reactions were weakest in the most sensitive species.

2.1.5.2 Leaf response. Morphological changes in the leaf tissue occurring after exposure to wet acidic deposition can modify leaf response to subsequent exposures. As noted, galls are a protective reaction. Alterations in the epicuticular waxes and indumentum hairs are predominant, rather than changes in the cuticle itself (Hindawi et al. 1980). The formation of surface irregularities or depressions, e.g., through acid-induced erosion of waxes or cell collapse, can increase water holding capacity of the leaf thereby increasing the probability of injury by lengthening the time of contact (Evans et al. 1977; Jacobson and Van Lueken 1977; and Evans and Curry 1979). The main route for internal damage is penetration through the stomata, which is mitigated by negative feedback within the tissue because stomata tend to close in the presence of acids. When acid solutions surround the guard cell, water diffuses from the cell due to osmotic pressure. Loss of water lowers guard cell turgor and closes the stomata (Plocher et al. 1985). In other experiments, simulated acidic precipitation raised guard cell turgor, thus reducing the diffusion resistance for gas exchange by the stomata. Foliage affected in this manner by acid rain may be prone to increased wilting and water stress. Since lower diffusion resistance can also result in higher photosynthetic uptake, the net effect of plant response on productivity or market yield is not clear. The impact of free hydrogen ions on internal cell functions is only qualitatively understood. There is potential for reduction in ATP activity if proton concentration gradients across membranes are altered (Evans 1984b). Exposure to simulated acidic precipitation has decreased the total chlorophyll concentration (Johnston et al. 1981; Hindawi et al. 1980; and Ferenbaugh 1976), with an equal reduction in chlorophyll a and chlorophyll b noted in leaf tissue of bush beans (Hindawi et al. 1980).

2.1.6 Factors That Influence Plant Response

The extent and nature of injury caused by contact with acidic precipitation are functions of the characteristics of the species, the cultivar, the pollutant, and the nature of exposure.

2.1.6.1 Characteristics of plants that influence plant response. Many plant factors can influence responses to acidic deposition. These include plant age and stage of development of leaf, area of leaf in contact with acid solution, and rate of absorption. Leaf shape and ability to retain water droplets can affect the placement, nature, and degree of injury (Bockheim 1984; Keever and Jacobson 1983a).

2.1.6.1.1 Plant development. For a given species, the stage of plant development at the time of exposure can influence the nature of plant response. Foliar injury is most pronounced on some species just prior to full leaf expansion (Evans 1984b). More commonly, however, newly expanded (Evans and Curry 1979; Evans et al. 1981a; Keever and Jacobson 1983a; and Neufeld et al. 1985a) and older, pre-senescent (Evans et al. 1977; Keever and Jacobson 1983a) leaves are the most susceptible to visible foliar injury. In addition, increased acidity resulted in increased rates of senescence in *P. vulgaris* (Plocher et al. 1985). The leaf was least sensitive before expansion in experiments using soybeans (Evans et al. 1977). Some experiments suggest that not only are older leaves less vulnerable to visible injury, they also repair damage suffered when in the newly expanding stage. For example, foliar injury was only visible until soybean plants were 20 days old (Evans et al. 1981b), and although the young expanding leaves were damaged, injury was not visible at harvest in green peppers (*Capsicum annuum*) (Lee et al. 1981).

Changes in the cuticle and cuticular waxes with age offer a partial explanation of these results. Rapidly expanding leaves have incomplete wax coverage, leaving portions of the cuticle exposed (Neufeld et al. 1985b). The cuticular waxes may act as a barrier, preventing aqueous ions from penetrating the leaf's surface. In addition, the cuticle is more hydrophilic than are the surface waxes; thus, the expanding leaves (which have more of the cuticle exposed) have higher wettability and water retention than do unexpanded or fully expanded leaves. The shape of young leaves can also contribute to their higher wettability (Neufeld et al. 1985a,b).

Wettability is a general term describing the amount of leaf surface area in contact with a water droplet. Wettability is positively correlated with the degree of foliar damage (Keever and Jacobson 1983c), although it is not necessarily correlated with threshold. Susceptibility threshold and resistance to foliar injury are not directly linked (Neufeld et al. 1985b). Threshold is defined as the exposure quantity (it may be in terms of concentration of acidity or total free hydrogen deposition, for example) that is sufficiently high such that any higher dose will result in deleterious effects.

2.1.6.1.2 Variation in sensitivity among species. Leaf surface characteristics determine wettability, water retention, permeability, and penetration, as well as rates of exchange of water and dissolved substances. These leaf characteristics vary by species, cultivar, and stage of plant development and may be factors in the variation in sensitivity among species. Growth conditions affect the leaf surface (Neufeld et al. 1985b) and also affect plant sensitivity to acidic precipitation. Agricultural plants in general have a lower resistance to foliar damage when grown in controlled environments when compared to field-grown (Irving and Miller 1981; Evans et al. 1981a; Cohen et al. 1982; Troiano et al. 1982; Evans et al. 1982b; and Keever and Jacobson 1983b).

2.1.6.2 Pollutant and pollutant exposure. The acidity (concentration of free hydrogen ions) of the pollutant and the method of exposure are directly correlated with plant response. An increase in acidity, frequency, duration, and/or number of simulated acidic rain events increases the extent and degree of foliar injury (Evans and Curry 1979; Jacobson 1984). The duration of precipitation events and water retention by the leaf (determined by leaf characteristics and micrometeorology) determine the length of acid-leaf contact time. More frequent events allow less time for leaf recovery, and may prevent the leaf from drying. The occurrence of injury is positively correlated with the length of time that the leaf is wet, and negatively correlated with the number of days between exposures (Irving 1983). By contrast, for gaseous pollutants the occurrence of injury increases as the rate of exposure increases (dose applied in shorter time).

In most cases, foliar injury is observed only after repeated exposures to acidic solutions. Whether this is due primarily to the increase in total hydrogen ions in contact with the leaf or related to the temporal factors outlined above is not known. The data are ambiguous regarding the relative impact of temporal variations in the delivery of a fixed hydrogen deposition. It appears that pH extremes are important; rain events with a varying pH giving a volume-weighted mean of 3.0 will tend to induce more foliar damage than will the same number of events with rain at constant pH 3.0 (Johnston et al. 1981; Irving and Miller 1981; and Lefohn and Brocksen 1984). No experiments were found that compared the plant response to a fixed hydrogen dose applied in one highly acidic, low volume dose, to one dilute, large volume dose, or to many dilute doses.

2.2 SENSITIVITY OF PLANTS TO FOLIAR INJURY

2.2.1 Introduction

Susceptibility to foliar damage from acidic wet deposition varies among species, and among cultivars within species. The relative sensitivity and characteristics of injury for each of the following crops are based on data from 13 field and 14 controlled environment experiments exposing growing plants to simulated wet acidic deposition.

The highest pH resulting in visible foliar injury and the lowest pH applied without resulting in visible foliar injury are listed for 37 crop species in Table 3. The range between the two pH values approximates a threshold for foliar injury, for each cultivar, under specific environmental conditions. Crops grown in a controlled environment, such as greenhouse or growth chamber, consistently displayed a lower tolerance for acidic wet deposition than did field grown crops.

2.2.2 Dicotyledons

2.2.2.1 Root crops. Root crops were the most sensitive agronomic group reviewed. The approximate threshold for foliar injury is pH 2.8 to pH 3.0 in field studies, and pH 3.5 to pH 4.0 in controlled environment studies. Radishes have suffered VFI from simulated acidic rain with pH as high as 4.2 (Evans et al. 1982c). Beet (*Beta vulgaris*) is the only crop documented to have sustained visible foliar injury from ambient rainfall alone (Evans et al. 1982a). Marketable yield of beets, radishes, and carrots (*Daucus carota*) was reduced by increasing acidity in most studies. Root crops experienced the greatest reduction in yield among all crop groups studied by Oregon State University (OSU) (Cohen et al. 1981; Lee et al. 1981; Cohen et al. 1982; and Plocher et al. 1985).

2.2.2.2 Leafy crops. Leafy crops show slightly less susceptibility to foliar injury than root crops. However, the threat to economic yield is greater with the leafy crops, which may lose value if blemished (Lee 1981). Pot-grown spinach, mustard greens (*Brassica japonica*), and Swiss chard (*Beta vulgaris*) showed VFI in the OSU experiments. The wrapper leaves of lettuce (*Lactuca sativa*) were damaged in another controlled environment study (Evans et al. 1982b).

2.2.2.3 Cole crops. Cole crops also lose market value when blemished. The threshold for damage to cole foliage is pH 3.0-3.5, higher than for leafy crops. Foliar injury was not correlated with reductions in market yield (Lee et al. 1981). While no data are available for canola or rapeseed (*Brassica napus*), other brassicas appear moderately resistant to foliar damage from acid rain.

2.2.2.4 Tuber crops. The only tuber species reviewed was the potato (*Solanum tuberosum*), which showed no foliar injury in growth chambers and only moderate foliar injury at pH 3.5 when grown in a greenhouse (Cohen et al. 1982).

2.2.2.5 Legume crops. Legumes include two kinds of crops: those grown for forage hays, such as alfalfa (*Medicago sativa*) and clover (*Trifolium* sp.), and those grown for oil

Table 3. Visible foliar injury: pH threshold.

Species	Highest pH with Foliar Injury	Lowest pH with No Injury	Growth Conditions[1]	Reference
ROOT				
Beet cv. Detroit Dark Red	4.0	5.6	C.E.	1
Beet	4.0		F	2
Carrot cv. Danvers	3.0	3.5	C.E.	1
Radish	4.2	5.6	C.E.	3
Radish	2.7		F	4
Radish	2.8		F	5
Radish cv. Cherry Belle	3.5	4.0	C.E.	1
LEAFY				
Lettuce	3.1	4.0	C.E.	3
Lettuce, Bibb cv. Limestone	3.5	4.0	C.E.	1
Lettuce, head cv. Great Lakes	3.5	4.0	C.E.	1
Mustard green cv. Southern Giant	3.5	4.0	C.E.	1
Spinach cv. improved thick leaf	3.5	4.0	C.E.	1
Swiss chard cv. Lucullus	4.0	5.6	C.E.	1
Tobacco cv. Burley 21	3.5	4.0	C.E.	1
COLE				
Broccoli cv. Italian green	3.5	4.0	C.E.	1
Cabbage	3.0	3.5	C.E.	1
Cauliflower cv. Early Snowball	3.5	4.0	C.E.	1
TUBER				
Potato cv. White Rose	3.5	4.0	C.E.	1
LEGUME				
Alfalfa cv. Honeoye	3.1	4.0	C.E.	3
Alfalfa cv. Honeoye		2.7	F	5
Alfalfa cv. Vernal	3.5	4.0	C.E.	1
Bean, bush	2.5	3.0	C.E.	6
Bean, bush	3.0		C.E.	7
Bean, bush	3.2	4.0	C.E.	8
Bean, kidney	3.2		C.E.	9
Bean, kidney		2.8	C.E.	10
Bean, kidney		2.7	F	5
Bean, pinto	3.0	4.0	C.E.	11
Bean, snap		2.6	F	12
Greenpea cv. Marvel	3.5	4.0	C.E.	1
Peanut cv. Tennessee Red	3.5	4.0	C.E.	1
Red clover cv. Kenland	3.5	4.0	C.E.	1
Soybean	2.9		C.E.	13
Soybean cv. Evans (G-0)	3.5	4.0	C.E.	1
Soybean cv. Hark(G-1)	3.5	4.0	C.E.	1
Soybean cv. Norman	3.5	4.0	C.E.	1
Soybean cv. OR-10	4.0	5.6	C.E.	1
Soybean cv. Amsoy 71	3.3	4.1	F	14

continued...

Table 3 (Continued).

Species	Highest pH with Foliar Injury	Lowest pH with No Injury	Growth Conditions[1]	Reference
LEGUMES (continued)				
Soybean cv. Amsoy 71	2.7	3.1	F	15
Soybean cv. Davis	3.4	4.2	C.E.	16
Soybean cv. Davis	3.2	4.0	F	17
Soybean cv. Wells		3.0	C.E.	18
Soybean cv. Wells		2.8	F	19
Soybean cv. Wells		3.0	F	18
FRUIT				
Apple blossom, Golden Delicious	3.0	4.0	F	20
Apple blossom, McIntosh	3.5		F	21
Apple foliage		2.5	F	21
Apple foliage, Empire		2.5	F	21
Apple foliage, Golden Delicious	3.0	4.0	F	20
Apple foliage, Golden Delicious		2.5	F	21
Apple foliage, McIntosh		2.5	F	21
Cucumber cv. 5116 Cresta	3.5	4.0	C.E.	1
Grape leaves	2.5		F	22
Green pepper cv. Calif. Wonder	4.0	5.6	C.E.	1
Strawberry cv. Quinalt	3.0	3.5	C.E.	1
Tomato cv. Patio	3.5	4.0	C.E.	1
FLOWER				
Sunflower	3.2		C.E.	23
Zinnia flower petals	2.8		C.E.	24
Zinnia foliage	2.8		C.E.	24
GRAIN				
Barley cv. Steptoe		3.0	C.E.	1
Corn cv. Golden Midget	3.0	3.5	C.E.	1
Corn cv. Pioneer 3992		3.0	F	25
Oats cv. Cayuse		3.0	C.E.	1
Wheat		2.7	C.E.	3
Wheat cv. Fieldwin		3.0	C.E.	1
BULB				
Onion cv. Sweet Spanish		3.0	C.E.	1
FORAGE				
Bluegrass cv. Newport	4.0	5.6	C.E.	1
Fescue cv. Alta Tall	3.5	4.0	C.E.	1
Orchardgrass cv. Potomac	3.5	4.0	C.E.	1
Ryegrass cv. Linn	3.5	4.0	C.E.	1
Ryegrass, perennial		3.0	C.E.	
Timothy cv. Climax	3.5	4.0	C.E.	1

[1] C.E. = Controlled Environment
F = Field Grown

continued...

Table 3 (Concluded).

References:
1. Lee et al. (1981)
2. Evans et al. (1982a)
3. Evans et al. (1982c)
4. Troiano et al. (1982)
5. Evans et al. (1982b)
6. Ferenbaugh (1976)
7. Hindawi et al. (1980)
8. Johnston et al. (1981)
9. Shriner (1974)
10. Paparozzi (1981)
11. Evans et al. (1980)
12. Troiano et al. (1984)
13. Evans and Curry (1979)
14. Evans et al. (1983)
15. Evans et al. (1981c)
16. Norby and Luxmoore (1983)
17. Brewer and Heagle (1983)
18. Irving and Miller (1981)
19. Troiano et al. (1983)
20. Proctor (1983)
21. Forsline et al. (1983b)
22. Forsline et al. (1983a)
23. Jacobson and Van Leuken (1977)
24. Keever and Jacobson (1983a)
25. Plocher et al. (1985)

and seed, such as soybean, bush bean and peanut (Arachis hypogaea). Susceptibility varies among the leguminous species, depending in part on their leaf characteristics (e.g., leafy varieties may have higher wettability). With the exception of a kidney bean study (Paparozzi 1981), all legumes in controlled environment studies experienced foliar injury in response to pH values below 3.1. Plants were consistently less sensitive in field trials. Of eight field experiments with legumes, only one reported foliar injury from acid rain above pH 2.7 (Evans et al. 1983). An experiment performed on field grown and chamber-grown soybeans in the same season, with the same cultural practices and the same pollutant exposure regime, found a significant increase in susceptibility in the chamber plants (Irving and Miller 1981). A similar result was seen with alfalfa (Plocher et al. 1985). Soybeans and alfalfa were the only field grown legumes reviewed that showed visible foliar injury from acid precipitation. The soybean cultivar 'Amsoy 71' appears to be more sensitive than does the cultivar 'Wells'.

2.2.2.6 Fruit crops. Although foliar injury is common (Plocher et al. 1985), growth of annual fruit crops is in general stimulated by simulated acidic precipitation. With tomato (Lycopersicon esculentum), foliar injury may be sufficiently widespread to lower market yield despite higher biomass production (Lee et al. 1981). Of the fruit crops investigated by Lee et al. (1981), strawberry (Fragaria x ananassa) showed the most tolerance and green pepper showed the least tolerance of exposure to acidic precipitation. Green pepper foliage was injured at pH 4.0 when plants were young but no damage was visible at harvest (Lee et al. 1981).

Perennial fruit trees normally exhibit only long-term foliar responses to acid rain; foliar injury from a single season of simulated acid rain treatments was observed in only one study, with apple trees (Malus sp.) (Proctor 1983). The data from Proctor are difficult to compare with those from other studies because the volume of acid rain applied was not constant, and was not specified. Another experiment with apple trees in the same treatment pH range resulted in no accounts of visible damage to foliage (Forsline et al. 1983b). Numerous studies have concluded that deciduous broad-leafed trees are less sensitive than herbaceous plants to foliar injury (Jacobson and Van Leuken 1977; Evans and Curry 1979; Haines et al. 1980; Proctor 1983; and Evans 1984b). However, the potential exists for deleterious long-term effects for perennial species, and these could affect fruit production (Fórsline et al. 1983b). Proctor (1983) observed latent foliar injury and inhibition of fruit set in apple trees after two seasons of acid rain treatment. Deleterious effects on fruit set and flowers, appearance, and size are reviewed in Sections 2.4.3.1.6 and 2.4.3.1.7.

2.2.3 Monocotyledons

2.2.3.1 Grain crops. Grain yielding species are the most sensitive monocotyledons, which as a class tend to be resistant to foliar damage from acidic wet deposition. Barley (Hordeum vulgare), tall fescue (Festuca arundinacea), and wheat (Triticum aestivum) experienced foliar damage from acid rain at pH 3.0 when grown in pots but not when grown in the field at the same location (Plocher et al. 1985). There are no reports of foliar damage to field grown grains.

2.2.3.2 Bulb crops. Although root crops are susceptible to foliar injury from acidic precipitation, the bulb crop reviewed, container-grown onions, did not experience significant foliar injury at pH 3.0 (Lee et al. 1981).

2.2.3.3 Forages. Forage grasses show a variability in tolerance of acidic deposition that appears to be related to growth environment (Plocher et al. 1985). Field grown forage crops appear to be highly tolerant of acidic precipitation incident on the foliage Lee et al. 1981; Evans et al. 1982c; and Amthor and Bormann 1983). In contrast, bluegrass (*Poa pratensis*) grown in pots has shown visible foliar injury from solutions with pH as high as 4.0 (Lee et al. 1981). Other forage crops, such as ryegrass (*Lolium perenne*), timothy (*Phleum pratense*), orchardgrass (*Dactylis glomerata*), and fescue, in the same study were visibly injured at pH 3.5. Ryegrass showed no foliar response to pH 3.0 in another controlled environment study (Amthor and Bormann 1983).

2.2.4 Discussion

From Table 3 and the above analysis, certain trends are elucidated. Broadly speaking, dicots are more susceptible to visible foliar injury from exposure to acid rain than are monocots (Lee et al. 1981). The morphological or physiological basis for this difference in sensitivity is not known. The pH at which 50% of the plants sustained significant visible foliar injury was pH 3.0. This corresponds well with thresholds ranging from pH 3.0 to pH 3.5 estimated by others. Rain in the ambient pH range of 4.0 caused foliar injury in 9% of the experiments, only one of which was field grown. Below pH 2.5, 70% of the cultivars showed foliar damage.

An important emphasis of current research is to address how likely foliar damage of the kind described from simulated acidic wet deposition experiments is at current ambient or projected concentrations of rain acidity. Jacobson and Van Leuken (1977) concluded that there is a substantial risk to susceptible species from rain events lasting two or more hours when pH is consistently below 3.0. They also concluded that current ambient levels of precipitation acidity in the eastern United States are close to the threshold for foliar injury to sensitive plants, and increased emissions pose a substantial risk in the future. Ambient levels of precipitation acidity in Alberta are quite differemt from eastern North America. The average annual pH of precipitation in Alberta between 1978 and 1984 was 5.5, with a median pH of 6.0 (Lau and Das 1985). This suggests that there is currently little or no acidic wet deposition in Alberta and therefore no current threat to agricultural crops.

2.3 DIRECT FOLIAR EFFECTS OF ACIDIC DEPOSITION

The plant leaf is not a solid structure, but rather a permeable tissue with a continuous exchange of gases, water, and dissolved substances. Foliage may react chemically with acidic solutions upon contact without sustaining any change in physical structure. In this section we discuss three changes in foliar nutrient exchange processes associated with exposure to acidic solutions: foliar fertilization, foliar buffering, and foliar leaching. Morrison (1984) uses the phrase "hidden effects" to describe these effects on foliage that may be direct, i.e., from contact with acidic wet deposition, but are not visible injury. The acidic solution may represent wet acidic deposition, or dry deposition that has hydrolyzed on the leaf's surface.

2.3.2 Foliar Fertilization

Simulated acidic wet deposition, composed of nitric and sulphuric acids, can act as a source of the nutrients nitrogen and sulphur if absorbed by the leaf (Irving and Miller 1981; Troiano et al. 1983; and Evans 1984b). Foliar fertilization, as this process is called, can be both beneficial and detrimental to plants. Although transfer away from the site of entry is slow, direct foliar application is a relatively fast means of supplying nutrients to leaves (Garcia and Hanway 1976). This can raise the nutrient concentration in the leaf for a short time, which could be beneficial, for example, by preventing nutrient depletion in soybean leaves during seed-filling and the resulting decrease in photosynthetic activity (Garcia and Hanway 1976). Nutrients applied to the foliage pose the risk of inducing foliar injury (Neumann et al. 1981). Nutrient flow into the roots uses physiological mechanisms developed for nutrient uptake and transfer. Roots provide a more continuous stream of nutrients from a relatively stable source. By contrast, topically applied nutrients are available directly to the leaf surface only in irregular pulses.

Although there are insufficient data for a definitive conclusion, it is widely assumed that very little of the nutrients from ambient deposition penetrate the foliage (Evans et al. 1981a, 1983; Evans 1984b). Even commercially available foliar fertilizers, which use added surfactants to aid foliar penetration, have had mixed results in stimulating plant growth. Research directed toward development of foliar fertilizer for commercial agriculture has provided information on plant response to aqueous application of nitrates and sulphates. Reductions in yield, observed in some cases, were often correlated with foliar injury from fertilizer salts. Neumann et al. (1981) concluded that all osmotically active fertilizer compounds can induce plasmolytic damage when sufficiently high concentrations penetrate the leaf. In fact, fertilizer doses small enough to prevent foliar injury may not allow penetration of enough fertilizer to stimulate growth (Neumann et al. 1981).

Commercial foliar fertilizer produced no consistent increase in yield when applied to rice (*Oryza sativa*) (Thom et al. 1981) or corn (*Zea mays*) (Neumann et al. 1981; Harder et al. 1982) and when applied two weeks before silking resulted in a 6.4% reduction in corn seed yield (Harder et al. 1982). Garcia and Hanway (1976) found significant increases in soybean yield only when a complete nutrient solution, containing N, P, K, and S in a 10:1:3:0.5 ratio was applied; nutrients applied singly, even in large amounts, e.g., 24 kg/ha of nitrogen or 12 kg/ha of sulphur, did not yield promising results.

In their research on the effects of simulated acidic precipitation, Evans et al. (1983, 1984) and Irving and Miller (1981) have considered the effects of the nutrients being added in precipitation. Evans et al. (1983), applied a pH 2.7 simulated rain to soybeans. The plants were thus exposed to 10 times the ambient atmospheric levels of N and S. The net effect of this treatment was a 23% reduction in seed yield. It is not known if the net reduction in productivity reflected an inhibitory effect of acidity partially ameliorated by foliar fertilization. If there was any stimulation due to nutrients applied on the foliage, it was not sufficient to counteract the negative effects of acidic precipitation on soybean yields.

Because the concentration and total deposition of nitrogen and sulphur in acidic precipitation are far lower than those found in foliar fertilizers, it appears unlikely that significant benefit to crops will be realized in the form of foliar fertilization (Evans et al. 1981a). To date, no data document foliar fertilization from ambient deposition (Evans 1984b). There is also limited evidence to suggest a risk from salt-induced damage to foliage at concentrations found in ambient deposition.

2.3.3 Foliar Buffering

Some plants appear to develop little or no foliar injury from acidic precipitation. It is possible that the plant tissue may effectively buffer the acid before any significant physical or physiological injury can occur, and that this ability may differ among species (Craker and Bernstein 1984). The reasons for this, and the mechanisms of neutralization are still under investigation (Craker and Bernstein 1984; Adams and Hutchinson 1984), although some characteristics of the process are known.

Craker and Bernstein (1984) investigated the buffering ability of red kidney bean, wheat, red clover, soybean, corn, and timothy by soaking leaf tissue in a simulated sulphuric acid rain solution (with pH 2.0, 3.0, or 4.0). The pH of each solution rose by the end of four hours. Red kidney bean and wheat gave the greatest increase, while corn and timothy had the least effect on solution pH. Subsequent visual analysis of leaf tissue damage suggested that the leaves with a greater buffering capacity were more susceptible to foliar injury. Adams and Hutchinson (1984) found that the ability of the leaf to buffer the droplets' pH was directly correlated with the extent of injury sustained by the leaf. Foliar leaching of K associated with exposure to acid rain may be a secondary effect of foliar injury (Keever and Jacobson 1983a). This is supported by work by Craker and Bernstein (1984), in which it was observed that acidic solutions experienced a more rapid rise in pH when injured leaf tissue was submerged than when healthy leaves were submerged. These results support the hypothesis that the buffering is due to the release of cellular material from dead or disrupted cells that neutralizes the acid. Similarly, senescent leaves have a much greater buffering capacity than young healthy leaves. Senescent foliage is more easily wetted than the relatively hydrophobic young leaves, and it also may be more reactive due to the onset of decay (Adams and Hutchinson 1984). Bicarbonate stored in the cell walls for photosynthesis may act to neutralize acid droplets (Oertli et al. 1977).

It is also possible that leachates or superficial aggregates contribute to the buffering of excess hydrogen. For example, foliar alkaline deposits formed from foliar leachates and atmospheric CO_2 can neutralize acidic solutions (Adams and Hutchinson 1984). However, Craker and Bernstein (1984) removed contaminants and microflora from one set of samples before treatment with no apparent effect on the extent of buffering or foliar injury. While cuticular penetration of aqueous chemicals may be selectively aided by metabolic activity (Evans 1984b), in this experiment the buffering was temperature independent, which indicated that it was not regulated by a metabolic process.

2.3.4 Foliar Leaching

Information about the mechanisms involved in foliar buffering may be contained in the chemical composition of an acidic solution after contact with foliage. In a number of studies, leaf surfaces were exposed to simulated acidic precipitation and the leachates were analyzed (Evans et al. 1977; Hindawi et al. 1980; Keever and Jacobson

1983a, 1983b, 1983c; and Adams and Hutchinson 1984). The change in rates of foliar leaching due to acidic precipitation varies, with most nutrients experiencing increased leaching. Table 4 summarizes the findings for eight agronomic crops.

Recent studies indicate that subjecting leaves to acidic solutions accelerates leaching of organic compounds as well. Scherbatskoy and Klein (1983) working on conifers reported that loss of foliar amino acids was increased, that loss of proteins decreased, and that loss of carbohydrates was unaffected by simulated acid rain.

Keever and Jacobson (1983a) examined the influence of nutrient status on the rate and products of foliar leaching with acidic solutions. Leaching of ^{86}Rb (a tracer for K) was increased for zinnias (_Zinnia elegans_) exposed to a simulated acid rain of pH 2.8 relative to the control of pH 5.6. Further acceleration of ^{86}Rb loss was recorded for zinnias under a nutrient-rich regime at pH 2.8. No effect on leaching was noted at pH 4.0, and no interaction with the nutrient supply was noted at pH 4.0 or pH 5.6. Keever and Jacobson suggest that the loss of differentially permeable characteristics of the foliar cellular membrane, caused by exposure to a pH 2.8 solution, was responsible for the observed increase in leaching. An increase in leaching of foliar K, associated with visible injury, has also been observed in soybean (Keever and Jacobson 1983c) and bean (_P. vulgaris_) (Evans et al. 1981c), with an estimated threshold of pH 4.0. The threshold for leaching of K is of the same order of magnitude as that observed for foliar injury in soybeans (Evans et al. 1983; Keever and Jacobson 1983c). The loss of foliar K may have been due to the death and subsequent degradation of cells resulting from exposure to a low pH solution (Keever and Jacobson 1983c). Inconsistencies in response of leaching of foliar K have been observed by Keever and Jacobson (1983a, 1983c), and Hindawi et al. (1980). The latter suggests that the inconsistency may be due to environmental differences in experimental conditions.

Foliar buffering and increases in leaching due to acidity are undoubtedly related processes. Buffering on the leaf surface is aided by alkaline deposits formed with leached or exuded foliar salts. Leaching occurs as exchangeable cations in the cuticle and cell walls are exchanged for H^+ in acidic solutions (Adams and Hutchinson 1984). The cuticle forms a barrier for ion movement in and out of the tissue, and the cuticle waxes play a role in inhibiting leaching of foliar nutrients (Neufeld et al. 1985b). Cuticular micropores are the principal route for cation exchange and loss, as well as for entry of chemicals into the leaf interior (Adams and Hutchinson 1984; Evans 1984b). Greater wettability is correlated with both higher leaching and higher buffering capacity (Keever and Jacobson 1983c; Neufeld et al. 1985b).

2.3.5 Foliar Nutrient Content

Increased foliar leaching may alter the nutrient content of leaf tissue. Experimental results are inconsistent, especially with regard to N, but do indicate that there is not a net loss of sulphur and there is a net loss of some micronutrients. A significant reduction of foliar N, P, Mg, and Ca was observed in soybean leaves exposed to acidic mist (Hindawi et al. 1980). Potassium content was not affected and S content was increased. In another experiment with soybeans, lower pH treatments resulted in an increase of foliar N as well as S, with a decrease only for Mg (Brewer and Heagle 1983). Foliar S was also increased in 'vernal' alfalfa treated with a pH 3.0 sulphuric acid

Table 4. Effect of increased solution[1] acidity on leaching of nutrients from foliage.

Species	Nutrient							Reference
	Ca	K	Mg	NH_4^+	NO_3^-	P	Zn	
Apricot	I	I	I					1
Bush bean	I	I	I					2
Pinto bean			NE	NE			NE	3
Soybean		I/D[2]						4
Soybean	I	NE	I		I	I		5
Sugar maple	I	I	I					1
Tobacco	I	I						1
Wormwood	I	I	I					6
Zinnia	I	I/D[2]	I					7

[1] Foliage submerged in solution.
[2] ^{86}Rb used as tracer for K.

I = increase
NE = no effect
I/D = both increase and decrease

References:
1. Evans (1984b)
2. Johnston et al. (1981)
3. Evans et al. (1981c)
4. Keever and Jacobson (1983c)
5. Hindawi et al. (1980)
6. Adams and Hutchinson (1984)
7. Keever and Jacobson (1983a)

solution (Plocher et al. 1985), while for 'alta' tall fescue the foliar content of N decreased, and only at pH 4.0. The nutrient content of kidney bean and soybean foliage demonstrated pH-independent response to applications of pH 6.0 and pH 3.2 solutions (Shriner and Johnston 1981). Apple tree foliage lost Ca when exposed to simulated acidic precipitation, but the foliar content of Ca recovered to control levels one week after the treatments ended (Forsline et al. 1983b).

2.3.6 Discussion

Changes in foliar nutrient content resulting from exposure to acidic solutions may be a factor in plant growth reduction (Hindawi et al. 1980; Evans et al. 1981a; and Neufeld et al. 1985a). Plant energy used to replace leached metabolites may be diverted from plant growth processes (Amthor 1984). In addition, reduction in the nutrient content of a crop could significantly affect its quality and economic value as a food commodity (Evans et al. 1981a; Evans 1984b). In managed systems, such as propagation beds or container nurseries, where root systems are limited or restricted, foliar leaching may lead to nutrient deficiency symptoms.

2.4 EFFECTS OF ACIDIC PRECIPITATION ON PLANT GROWTH

2.4.1 Introduction

Plant growth may be stimulated, inhibited or not affected by exposure to acidic wet deposition. The mechanisms by which acidic wet deposition alters plant productivity have yet to be established. The following discussion on plant growth and the possible mechanisms draws upon interpretations in the current literature. Dose-response data have been analyzed to present a qualitative ranking of plant growth sensitivity to simulated acidic wet deposition.

2.4.2 Growth

Simulated wet acidic deposition has been shown to affect crop growth and growth form in numerous experiments (Last 1982; Irving 1983; Evans 1984a; and Jacobson 1984). There were no field surveys found, however, that documented a reduction in crop productivity due to ambient rates of acidic wet deposition. In a review of agricultural experiments, Lefohn and Brocksen (1984) concluded that, above pH 4.0, simulated acidic rainfall has not caused significant inhibition of vegetation growth. The growth of many species is stimulated or not affected by simulated acidic rainfalls in the range of ambient acidic precipitation. When the acidity dose exceeds a plant's threshold, yield of the whole plant or some portions of the plant is decreased. An intermediate effect between the threshold pH and the control pH has been seen whereby the plant growth is increased by moderately low pH rain. Lee (1981) observed the intermediate response in seed germination, seedling growth, and crop yield between pH 3.5 and 4.0. Thus, acidic precipitation may not simply have a positive or negative effect on crop growth, but rather, it could have a combination of competing (inhibitory and stimulatory) effects. Irving (1983) reported that 13 out of 14 cultivars reviewed showed a similarly non-linear dose-response relationship.

Nevertheless, dose-response functions for crop yield and quality are an aid in predicting impacts of ambient and anticipated levels of acidity in rainfall (Troiano et al. 1982; Evans et al. 1983; and Evans et al. 1984). However, the dose-response functions generated thus far have been experiment specific. For a given cultivar, the observed dose-response relationship (e.g., the pH values for the maximum growth and the threshold for reduced growth relative to the control) will be influenced by many characteristics of the experiment, such as the dose concentration, composition, and method of exposure (Lee 1981).

As with foliar injury, the sensitivity of species and the threshold for deleterious effects on productivity depend on the growth conditions and the method of exposure.

All conclusions about the potential impact of acidic precipitation on agriculture based on experiments must take into account the influence of variation in experiments and the relationship to ambient levels of acidic precipitation. In addition, the relationship between crop yields in experiments versus crop yields under standard agronomic conditions must be considered.

Acidic wet deposition may affect growth form by altering the partitioning of photosynthate, or by altering the rate of formation of plant parts. Radish and soybeans, respectively, are two often-studied crops that clearly display these effects. Radish and soybean are also desirable for experiments because of their economic importance and rapid growth.

At this time, the mechanisms by which acidic wet deposition inhibits plant growth, or alters plant form, are not known. Visible injury has not been directly correlated, nor have short-term changes in soil conditions been identified.

Biomass yield may be measured in fresh weight or dry weight. Both provide information about productivity and yield of shoot, root, marketable portion, or whole plant. Marketable yield may refer to the plant foliage (leafy, cole, and forage crops), roots, bulbs, and tubers, or reproductive organs (bean, grain, flower, and fruit crops). If acid rain differentially inhibits growth of one part of the plant, marketable yield may or may not be affected. Dose-response research should measure all plant portions so that information can be gathered not only for economic concerns, but also for biological and ecological purposes.

Due to the short duration of most experiments and the limited number of characteristics (e.g., yield, foliar nutrient content, root growth) investigated, experimental results may not reveal the most significant components of change. For example, small-grain crops showed no change in productivity with increasing acidity of simulated acid rain, but they did show reduced root biomass. The effect of root growth on marketable yield or plant vigour might be observed only under stressful environmental conditions, such as drought, or in dry farming conditions (Lee 1981).

Reduction in yield was under 5 to 10% in most experiments reviewed. Although a reduction of 5% might not be statistically significant, it would be economically significant (Evans et al. 1981a). Because the variation in annual yields and the variability in experimental conditions is large, the ability to statistically discern the effects of acidic wet deposition may be insufficient to address economic concerns.

2.4.3 Sensitivity to Changes in Growth and Yield

The purpose of this section is to synthesize the available dose-response data in order to ascertain and demonstrate whether crops show a change in productivity after exposure to wet acidic deposition, to develop a relative ranking of crop sensitivity to acidic precipitation, and to estimate a general threshold pH for deleterious effects from simulated acid rain. Very limited data were available on plant response to non-gaseous dry acidic deposition (e.g., sulphate aerosols). Kratky et al. (1974) reported deleterious effects to tomato plants exposed to deposition of acidic particles or aerosols originating from a volcano, but no concentrations were given. More recently Chevone et al. (1986) reviewed the data on effects of sub-micron acid sulphate aerosols on soybean and pinto bean. No visible injury or significant loss in leaf chlorophyll were observed on the plants after a single four hour exposure to 500 $\mu g\ m^{-3}$ of acid sulphate aerosol. It is important to note that this exposure concentration is excessive relative to ambient conditions in the United States. Average ambient sulphate aerosol concentrations in general range from 1-5 $\mu g\ m^{-3}$ in rural areas, to 10-30 $\mu g\ m^{-3}$ in urban centres and up to 100 $\mu g\ m^{-3}$ in areas such as the south coast air basin of California (Garland 1978; Stevens et al. 1978).

The yield-response data are organized by crop groups according to growth form (Lee et al. 1981) to facilitate distinction of patterns of response. Such classification schemes can be useful for regional assessments and to suggest underlying mechanisms of observed responses.

Table 5 shows the response of each species tested to increasing acidity . No normalization with respect to differing experimental design was performed. The table does not allow inference of thresholds nor cross-species comparisons. Rather, it shows each species' response within the particular experimental conditions. This permits the use of data that were generated by experiments whose designs do not allow standardization. Standardized data, with control pH = 5.6, and volume and concentrations of applied solutions explicitly described, are used in Table 6.

Not all experimental designs or reports give enough information to allow inter-experimental comparisons. Experimental design is discussed further in Section 2.7.

Data on field grown crops are distinguished from those from controlled environment-grown crops because field grown crops consistently show higher tolerance of acidic rain (Irving and Miller 1981; Evans et al. 1981a; Cohen et al. 1982; Troiano et al. 1982; Evans 1982; and Keever and Jacobson 1983b). Since the relative significance of other experimental features is not known, experiments were separated only according to field or controlled conditions.

2.4.3.1 Dicotyledons

Dicots were found to be more likely to show inhibited growth than were monocots.

2.4.3.1.1 Root crops. Root crops are the most sensitive agronomic group, with low threshold and resistance for both foliar injury and yield reduction. Of the 14 field grown cultivars considered in Irving's (1983) review, only garden beets showed a consistently negative response to acid rain. All other field grown crops showed a growth peak at an intermediate treatment pH. Simulated acid rain has been associated with a decrease in leaf area, shoot mass, and root mass in radish (Harcourt and Farrar 1980; Lee et al. 1981; and Evans et al. 1982c), beets (Lee et al. 1981; Evans et al. 1982a) and carrots (Lee et al. 1981). These findings are in contrast to those of Evans et al. (1981a) and Troiano et al. (1982), in which root yield of radish increased after

Table 5. Effect of acid rain on marketable yield of roots and shoots.

Species	Marketable Yield Response to Increased Acidity	Growth Conditions	References
ROOTS			
Radish cv.Cherry Belle	no effect	F	1
Radish cv.Scarlet Knight	no effect	F	1
Radish	no effect	CE	2
Radish	decrease	CE	3
Radish	no effect	F	3
Beet	decrease	F	4
Beet	decrease	F	3
Beet cv.Detroit Dark Red	decrease	CE	5
Carrot cv.Danver's	decrease	CE	5
LEAFY			
Lettuce	decrease	CE	3
Mustard green	decrease	CE	5
Lettuce, Bibb	decrease	CE	5
Lettuce, head	decrease	CE	5
COLE			
Broccoli	decrease	CE	5
Cauliflower	no effect	CE	5
Cabbage	no effect	CE	5
TUBERS			
Potato cv.Russet	no effect	F	1
Potato cv.Kennebec	no effect	F	1
Potato cv.White Rose	decrease	CE	5
LEGUME			
Alfalfa cv.Honeoye	decrease [1]	CE	3
Alfalfa cv.Honeoye	no effect		1
Alfalfa cv.Vernal	no effect	F	6
Alfalfa cv.Vernal	increase	CE	5
FORAGE			
Ryegrass	decrease [2]	CE	7
Fescue cv.Alta	decrease [2]	F	1

CE = Controlled Environment
F = Field

[1]Decrease 1 harvest; no effect 2 harvests.
[2]Decrease after only 3 or 4 harvests

continued...

Table 5 (Concluded).

References:
1. Plocher et al. (1985)
2. Harcourt and Farrar (1980)
3. Evans et al. (1982a)
4. Troiano et al. (1982)
5. Lee et al. (1981)
6. Evans et al. (1982c)
7. Amthor and Bormann (1983)

Table 6. Percent change in yield of selected crops by frequent exposure to acid mist (pH 3.5 to pH 2.7).

Crop	Yield change (%)	References
LEGUMES		
Alfalfa cv. Vernal	-9	1
Alfalfa cv. Vernal	-6	2
Alfalfa	-2	3
Red Clover cv. Kenland	-1	2
FORAGE		
Ryegrass (perennial)	-4 to -9	2
Ryegrass cv. Linn	-1	2
Bluegrass cv. Newport	+2	2
Fescue cv. Alta	-4	2
Orchardgrass cv. Potamac	+23	2
Timothy cv. Climax	+24	2
GRAINS		
Barley cv. Steptoe	-2	4
Barley cv. Fieldwin	+5	2
Wheat cv. Steptoe	-3	2
Oats cv. Cayuse	-8	2
Mean and standard deviation[1]	-3 ± 4	

[1]Mean determined by excluding orchardgrass and timothy values

References:
1. Lee and Neely (1980)
2. Lee et al. (1981)
3. Evans et al. (1982c)
4. Harcourt and Farrar (1980)

treatment. There is greater sensitivity demonstrated by controlled environment plants, as shown in Tables 5 and 6. The increase in shoot:root ratio associated with exposure to acidic wet deposition represents a decrease in marketable yield for root crops. Market yield of carrots was 73% lower at pH 4.0 than at pH 5.6 in the Oregon State University (OSU) study (Lee et al. 1981).

2.4.3.1.2 Leafy crops. Although five out of six leafy crops tested showed foliar injury due to simulated acidic precipitation, only mustard greens experienced a reduction in market yield (Lee et al. 1981). Slight reduction in lettuce root development was not a threat to plant productivity. Fresh mass of lettuce was reduced by rain below pH 4.0 in a growth chamber, but not at pH 3.0 in another controlled environment study (Lee et al. 1981).

2.4.3.1.3 Cole crops. No data are available on dose-response of field grown leafy crops, cole crops, or bulb crops, with one exception; growth of field grown cabbage (*Brassica oleracea*) was reduced by simulated acidic precipitation treatments of pH 3.0 (Lee et al. 1981). In pot-grown trials of cole crops, market yield was reduced only for broccoli (*Brassica oleracea*) (Lee et al. 1981).

2.4.3.1.4 Tuber crops. Tuber crops exhibit inconsistent response to simulated acidic precipitation treatment. Lee et al. (1981) found a growth peak at pH 3.5 of fresh weight market yield with lower production at pH 3.0 for potatoes. In general, however, they are not inhibited by simulated acidic precipitation.

2.4.3.1.5 Legumes. The legumes include many economically important seed and forage crops, such as soybeans and alfalfa. Market yield of forage legumes is stimulated at moderate levels of acidity, above pH 3.0, although root mass may be reduced. Data on long-term acidic wet deposition on alfalfa suggest that there are no cumulative effects, but are not conclusive. Lee et al. (1981) and Evans et al. (1982c) found no decrease in alfalfa yield after two and three harvests, respectively. Red clover is tolerant of high soil acidity and appears to be unaffected by pH's above 3.0 (Plocher et al. 1985). Among the legumes, soybeans are relatively sensitive to acidic precipitation. Pod formation was inhibited by increasing acidity, resulting in decreased seed yield, in four experiments, while seed yield was increased in only one.

Decreases in *P. vulgaris* yield occurred only in controlled environment studies. The threshold for foliar injury and growth reduction for *P. vulgaris* is near pH 3.2 to pH 4.0. Waterlogging from the combination of simulated acidic rain and ambient rain was partially responsible for lower dry mass and growth rate of field grown snap beans compared with those grown under a rain exclusion cover. The growth form of *P. vulgaris* may be altered by simulated acidic precipitation. Below pH 3.0, Ferenbaugh (1976) reported morphological and anatomical differences, such as shortened internodes, increased bud formation, smaller leaves, and shorter, bushier plants. Simulated acidic precipitation retarded pollen tube elongation and pollen germination in bush beans, resulting in reduced fruit set in one experiment; seed yield was also reduced. Johnston et al. (1981) used two routes of acidic wet deposition (one on the foliage and the other directly on the soil), to compare the role of acid-foliar contact with that of acid-soil contact on plant growth. Productivity was inhibited only with direct foliar contact; no secondary effects through the soil were noted. The plants receiving foliar deposition displayed premature senescence and chlorophyll reduction but these were not believed to be responsible for the observed decrease in productivity; no causes of growth reduction were identified.

In addition to the market yield (biomass), seed quality also determines economic value of feed crops. Using treatments from pH 2.3 to 5.6, Evans et al. (1981b) found that increasing acidity was correlated with decreasing protein content and carbohydrate content in soybean cv. Amsoy 71. Yet Brewer and Heagle (1983) exposed soybean cv. Davis to simulated acidic precipitation from pH 2.8 to 5.5 and found no change in seed protein or oil content. The change in carbohydrate and protein content is of widespread economic concern, as well as an indication of physiological responses of plants to simulated acidic rainfall. More experiments under standard agronomic conditions are warranted to investigate the effect of simulated acidic precipitation as well as ambient acidic precipitation on nutrient content of feed crops.

2.4.3.1.6 Fruit crops. Herbaceous, fruit crop growth peaks at a moderately low pH. Lee et al. (1981) identified pH 3.5 as optimum for pot-grown strawberry, tomato, and cucumber (*Cucumis sativus*). Visible foliar injury occurring at this pH range may counteract economic benefit associated with an increase in biomass. There are no long-term studies on strawberries which might detect cumulative effects of acidic wet deposition. Woody fruit species show sensitivity to chronic deposition. Fruit set has been reduced by simulated low pH rain (i.e., pH 2.5) in grapes (*Vitus* sp.) (Forsline et al. 1983a) and apples (Proctor 1983; Forsline et al. 1983b). In an experiment by Proctor (1983), the third-year crop of apple trees was significantly decreased by acidity as shown by the gradient of fruit per limb for pH treatments from pH 1.5 to pH 5.6. Loss was observed up to pH 4.0. Golden Delicious was the most sensitive variety, although McIntosh was the most susceptible to premature fruit drop; Rhode Island Greening and Delicious apples gave intermediate responses. A corresponding reduction in fruit set of McIntosh was also observed by Forsline et al. (1983b). However, Golden Delicious and Empire showed no significant response. Exposure of McIntosh apples to simulated wet deposition below pH 4.0 also induced delayed fruit ripening. Delay in this late-ripening cultivar could have serious economic impact (Forsline et al. 1983b).

2.4.3.1.7 Flowers. Zinnia growth peaked at pH 4.0 relative to pH 2.8 (which gave the lowest biomass) and relative to pH 5.6. The visible foliar injury was limited to flower parts and first leaves and was not thought to be responsible for changes in yield (Keever and Jacobson 1983a). In a parallel experiment, zinnias regularly receiving a full strength fertilizer had a greater degree of injury from simulated acidic rain than did zinnias receiving 1/4-strength fertilizer solution (Keever and Jacobson 1983a).

2.4.3.2 Monocotyledons

Monocots are, in general, stimulated or not affected by exposure to simulated acidic rain above pH 3.0.

2.4.3.2.1 Grain crops. Among the grains, corn is the most sensitive crop. Other grains appear to be stimulated or not affected by moderate pH levels. Corn yield was inhibited by simulated acidic rain for three consecutive years (Plocher et al. 1985). In extensive field studies the productivity of 'pioneer 3992' corn was reduced by simulated acidic rain in the range of pH 4.0 to pH 3.0 (Lee et al. 1981; Plocher et al. 1985). Although inhibition was not consistent, Plocher et al. (1985) concluded that corn may be very sensitive to acidic precipitation under some conditions. In the same study, the sulphur to nitrogen ratio was varied, and the pH was varied about a mean value of pH 4.0; neither treatment had an effect on plant response. Work done in Great Britain on barley using sulphite and acidic mists suggested that barley is more sensitive to HSO^{3-} (bisulphite) than to low pH (Harcourt and Farrar 1980). Root yield of small grains (e.g., wheat) was stimulated by acidic rain (Lee et al. 1981; Plocher et al. 1985) without any other discernible effect on productivity.

2.4.3.2.2 Bulb crops. Simulated acidic rain had a minimal effect on Spanish onion in Oregon State University experiments (Lee et al. 1981).

2.4.3.2.3 Forage crops. Ryegrass forage production was 10% lower at pH 3.0 than at pH 5.6 only for the fourth regrowth in a glasshouse study (Amthor and Bormann 1983). Longer term responses may not be reflected in the results of short-term studies. Amthor and Bormann concluded that growth was inhibited due to long-term exposure to acid precipitation. Although 10 weeks of exposure did not reveal symptoms of injury or inhibition, they attributed lower productivity during weeks 11-14 to long-term detrimental effects. In contrast, Lee et al. (1981) found no change in shoot growth and did see inhibition of root growth at pH 3.0, 3.5, and 4.0. In the former study, ozone levels during the four regrowth periods were greater than, or equal to 0.18 mg m^{-3} for at least 1 h on 19 different days. Lee et al. (1981) did not report elevated atmospheric O_3 levels.

2.4.4 Ranking of Crop Species by Yield Loss in Chronic Foliar Application of Acid Mist

The dose-response relationship of crop plants to foliar applications of acidic mist or spray is apparently not reproducible at lower acidity, but the repeated exposure to more highly acidic applications does produce a negative response in terms of yield. From the literature, it is evident that at higher pH values (between pH 3.5 and 5.6), regardless of the ratio of nitric to sulphuric acid, and apparently regardless of the rate of deposition in a frequently (daily) applied mist, the response may be either positive or negative for reasons unknown. Below pH 3.5, the dose-response is approximately linear (in those cases with enough data), with an indication that the loss of yield is about 5% per pH unit (with a typical range of 1% to 9% per pH unit based on many experiments). For example, field studies of alfalfa by Lee and Neely (1980) and by Evans et al. (1982c) had a yield loss of 1% to 9% per pH unit below pH 3.5 as determined by linear regression. Also, field studies of soybean by Heagle et al. (1983a) and by Evans et al. (1984) had a yield-loss response of 2% to 7% per pH unit below pH 3.5 as determined by linear regression. There is no explanation for this wide range as yet, and at this point only a simple linear regression seems justifiable.

The uncertainty in this generalization of 1% to 9% yield loss per pH unit below pH 3.5 remains large. The study by Heagle et al. (1983a) showed that there were differences in the response of soybeans (cv. Davis) from season to season. Sometimes there were positive yield responses (greater yield) even at lower pH. For example, the same cultivar of soybeans (Williams) responded positively at pH 3.0 in a study by Troiano et al. (1983) but negatively at the same pH in a study by Evans et al. (1984). The range of response within a crop species is about the same as the range of response between crop species at the lowest pH value investigated (pH 3.5 to pH 2.7). For example, Table 6 gives values of observed yield response for crop species at the lowest pH investigated. The data variability is such that only changes of the largest magnitude are significantly different from the control at pH 5.6. Positive values (yield gain) generally have the largest magnitude. Since the number of samples is small, we treat these data as hypothetical realizations of the same population (all crops) and put aside the highest positive responses as anomalous. We also find that the statistically significant yield loss is only a few percent at the lowest pH values.

We conclude that there is no statistical significance to a ranking of species sensitivity, but there is evidence for a decline in yield of most species at exposures to acidic mist below pH 3.5, at a rate of 1% to 9% per unit decrease in mist pH.

2.5 EFFECTS OF ACIDIC PRECIPITATION ON PLANT REPRODUCTION

2.5.1. Introduction

Effects of acidic precipitation on plant reproduction processes can influence the yield and reproductive success of agricultural plants. Reproduction processes may be directly affected, or may be indirectly affected by altered plant productivity or by changes in plant-insect interactions. The formation, development, and survival of pods, flowers and fruits are sensitive to acid rain at moderately sub-ambient (below pH 4.0) pH values. The reproductive structures of fruit crops may be at greater risk of sustaining visible injury than is the foliage (Forsline et al. 1983b).

2.5.2 Growth of Reproductive Structures

Successful reproductive activity is important even for plants that are sown each year from seed because reproductive parts, such as pods, seeds, and blossoms, are often harvested. Flowering is important in the development of hybrid cultivars, seed development, and other breeding programs.

Yield may be reduced by lower plant productivity unless seed or fruit growth continues at the expense of vegetative growth. In the latter case, yields may be limited by overall plant vigour. The reduction in seed yield of soybeans reported by Evans et al. (1981a, 1983, 1984) was due to inhibition of pod formation or development. The number of seeds per pod and the mass of seed were not altered as acidity increased. Reduction in plant productivity, rather than inhibition of pod formation, was responsible for the lower dry pod weight reported by Hindawi et al. (1980) for soybeans, since the number of pods per plant did not change. Reduced apple yields on a third year crop were due to inhibited fruit set, rather than a reduction in apple size (Proctor 1983); these results are similar to those by Evans et al. (1981a, 1983, 1984).

Experimental data on the effect of simulated acidic rain on the market yield of seeds, pods, and fruits is given in Table 7. Yields of reproductive structures are more consistently decreased than are those of vegetative structures (see Table 4); insufficient data are available to allow comparison of acidity thresholds.

2.5.3 Seed Germination and Seedling Emergence

There is a large body of agricultural literature on the effect of soil acidity on plant germination (e.g., Haller 1983 on alfalfa; Duncan 1982, on sorghum [*Sorghum bicolor*]). However, there are very few data relating emergence of agronomic species to the direct effects of acidic wet deposition in the absence of changes in soil properties. Similarly, the significance of alterations in early growth patterns for plant vigour has not been studied (Morrison 1984). Seedling emergence of woody species has been reported to be inhibited, stimulated, and unaffected by acidic precipitation (Cox 1983; Evans 1984b). Dilute acids can have a scarifying effect on the seed coats, thus aiding germination (Morrison 1984).

2.5.4 Pollen Viability

Among agricultural species, acidity inhibited in vitro germination of pollen of apple, grape, tomato, and camellia (*Camellia japonica*) plants (Forsline 1983a, 1983b; Kratky et al. 1974; and Masaru et al. 1980, respectively). While there are no surveys of agricultural crops, estimates based on forest research suggested a threshold for inhibiting pollen germination in trees at pH 3.6 (Cox 1982). The evening primrose (*Oenothera parviflora*) experienced significant reduction in receptivity of the stigma to pollen at pH 4.6 (Cox 1984). Comparison of foliar injury relationships indicates that pollen germination of agricultural species may be more sensitive to acidic precipitation than that of forest species.

2.5.5 Fruiting

For perennial species such as fruit trees, acidic wet deposition may interfere with successful reproduction at different seasons, and/or at different stages of development. The reproductive cycle of a fruit tree, and some perennial fruit vines and shrubs, begins the year prior to harvest. Air pollutants may affect the fruiting process at the time of anthesis (flower initiation) during the first year, because the inflorescence can be very vulnerable to external influences. Flowering usually occurs in the spring, which coincides with periods of high-acidity rainfall in many regions (Forsline et al. 1983b). Alterations in the bloom can influence pollen germination and seed or fruit set, although the mechanisms for observed responses are not yet documented. During the second year, air pollutants may influence fertilization, fruit set, fruit development, and maturation.

The sensitivity of crop reproduction may vary widely among species and cultivars. Species differ considerably in the length and vulnerability of each stage, e.g, the duration and the extent of gametophyte exposure. The effects of acidic wet deposition on sexual reproduction of corn, wheat, snapbeans, soybeans, and other crops are currently being investigated at North Carolina State University by Du Bay and Stucky (Du Bay, letter 1985). Results are not yet available.

Table 7. Marketable yield of seeds, pods, and fruits.

Species	Yield Response to Increasing Acidity	Growth Conditions	References
LEGUMES			
Bean, bush	decr. pod	CE	1
Bean, bush	decr. pod	CE	2
Bean, kidney	no effect	F	3
Bean, kidney	no effect	CE	3
Bean, kidney	no effect	F	4
Bean, snap	no effect	F	5
Soybean	decr. seed	CE	2
Soybean cv. Lee	no effect	CE/F	3
Soybean cv. Davis	no effect	F	6
Soybean cv. Amsoy 71	decr. pod	F	7
Soybean cv. Amsoy 71	decr. seed	F	8
Soybean cv. Amsoy 71	incr. seed	CE/F	9
Soybean cv. Wells	decr. pod	F	10
FRUIT			
Tomato cv. New Yorker	no effect	F	11
Apples, Golden Delicious	no effect	F	12
Apples, Golden Delicious	decr. fruit [1]	F	13
Apples, McIntosh	decr. fruit [1]	F	13
Apples, Island Greening	no effect	F	13
GRAIN			
Barley cv. Magnum	no effect	CE	14
Barley cv. Steptoe	no effect	F	11
Corn cv. Pioneer 3992	decr. seed [2]	F	11
Wheat cv. Fieldwin	no effect	F	11
Wheat, Spring Hard	no effect	CE	15

CE = Controlled environment
F = Field grown
[1] = Decrease after one harvest; no effect after two harvests.
[2] = Decrease after three or four harvests.

continued...

Table 7 (Concluded).

References:
1. Johnston et al. (1981)
2. Hindawi et al. (1980)
3. Shriner and Johnston (1981)
4. Evans et al. (1982b)
5. Troiano et al. (1984)
6. Brewer and Heagle (1983)
7. Evans et al. (1983)
8. Evans et al. (1984)
9. Irving and Miller (1981)
10. Evans et al. (1981b)
11. Plocher et al. (1985)
12. Forsline et al. (1983b)
13. Proctor (1983)
14. Harcourt and Farrar (1980)
15. Evans et al. (1982c)

2.5.6 Visible Injury

Fruits and flowers are highly susceptible to visible foliar injury, and generally sustain injury at lower levels of acidity than does foliage (Jacobson and Van Leuken 1977; Keever and Jacobson 1983a; Proctor 1983; and Forsline et al. 1983b). Blemishes can reduce market value substantially if the fruit is to be sold fresh. Produce for canning or juicing will be devalued less, if at all (Lee 1981; Letter 1985 from Daley, Lawrence Livermore National Lab.). Presently there are no data relating visible injury on reproductive structures with an alteration in reproductive potential or success.

2.6 EFFECTS OF EXPERIMENTAL DESIGN

2.6.1 Introduction

Thus far the emphasis of this review has been to summarize the experimental data on plant dose-response to acidic precipitation, and to discuss plant characteristics and growth processes that may influence response. The dose in acidic rain dose-response research has been implicitly defined as the hydrogen ion concentration (i.e., pH) of the simulated or ambient rain. A more useful definition of dose is the combination of chemical composition and pH and method of exposure, since the plant responds to both. With respect to the dose, no general dose-response relations have been developed; marked inconsistencies in plant response have been reported. The extent to which results actually conflict is unclear, for the same reasons that conclusions drawn from the body of available data are tentative. Apparent discrepancies in results may stem from differences in experimental design known to influence plant response, such as the method of exposure, the growth environment, and the age and species of plant (Evans et al. 1982c; Troiano et al. 1982; and Jacobson 1984). The wide differences seen in experimental techniques and procedures render comparisons of data difficult (Troiano et al. 1982; Jacobson 1984). In addition, the ability to make rigorous comparisons between experiments is dependent upon the completeness of the experimental description (Jacobson 1984). In this section we outline the key experimental parameters and consider briefly their influence on experimental results.

2.6.2 Pollutant

The dose of acidity to which a plant is exposed is comprised of the amount of acidity (free H^+), the method of application (route, characteristics of exposure), and the chemical form (see Table 1). The most important components of acidic precipitation are the hydrogen ion concentration (pH) and the ratio of sulphates to nitrates (S:N). The relationship between pH and plant response has been discussed in this paper. In general, decrease of pH is associated with increase in plant response.

The selection of an appropriate control pH is important to avoid exaggeration or dampening of responses observed at ambient and sub-ambient rainfall pH's. Galloway et al. (1984) continue to research the most appropriate values for a regional background pH. Presently, pH 5.6 is the accepted control because that is the pH of atmospheric CO_2 in equilibrium with water. However, even before industrial expansion there were other acidic species in the atmosphere, such as SO_2 from volcanoes and organic acids from natural atmospheric and biogenic processes. The most appropriate control pH has not been determined. The pH in remote regions is as low as 4.8 (Lefohn and Brocksen 1984). Experiments by Troiano et al. in Ithaca, New York, had a least-acidic treatment of pH 5.0 (Troiano et al. 1984) and pH 4.0 (Troiano et al. 1983). Ambient rain varied from pH 3.4 to 4.1 over the season (Troiano et al. 1984). While the treatment values correspond well to the ambient rain quality at the experimental location, the absence of control data limits the intra-experiment comparisons (e.g., comparisons on the influence of growth conditions on yield).

Sulphate to nitrate ratios vary geographically. Experiments by Plocher et al. (1985) and others have shown that there is no significant dependence of plant response on the S:N ratio of the simulant. Earlier studies at the same site (Lee and Neely 1980) found that crop growth did respond differently to the two simulated rain compositions used, one with a S:N ratio of 2:1 and one containing only sulphuric acid.

The chemical and temporal characteristics of exposure are of critical importance in determining plant response. An increase in the frequency, duration, or number of treatment events is correlated with an increase in foliar injury and yield response (Irving 1983; Jacobson 1984). The rate of acidic wet deposition and the number of acidic wet deposition events determine the total hydrogen dose received by the plant. Some experiments do not specify the volume of pollutant applied (e.g., Proctor 1983), or the pH or volume of ambient rainfall (e.g., Lee and Neely 1980). In the absence of conclusive evidence, it is assumed that both the instantaneous dose (i.e., concentration) and the cumulative dose (i.e., total deposition) are significant in influencing plant response (Irving 1983). The constancy of pH also influences plant response. When comparing the yields of plants grown with a constant pH of 3.0 and those exposed to a pH range from 2.8 to 4.0 with a mean of 3.0, Lefohn and Brocksen (1984) in their review found that the higher peak level acidity had a greater inhibitory effect than did the constant pH level dose. Similar results have been reported by Johnston et al. (1981) for bush bean.

Acidic solutions applied to the soil had less effect on plant growth than did solutions applied directly to the foliage in an experiment by Johnston et al. (1981) on bush bean. Because the pH of solutions applied to the soil had little or no effect on plant growth, Johnston et al. (1981) concluded that the effects observed due to rain acidity were probably direct foliar responses rather than secondary responses via soil effects.

2.6.3 Growth Conditions

The growth conditions of the plant are comprised of a wide variety of factors including the location, environmental conditions, structural environment, and agricultural practice.

The experimental setting is generally quite different from the natural or standard agronomic environment. Most experiments reviewed followed standard agronomic practice in the use of fertilizers and pesticides. In controlled environment experiments, plants were often grown in commercial potting mixes, which tended to provide more optimal conditions than those found in the field. One would thus expect to see less fertilizer effect from the simulated acidic rain applications. However, Lee et al.

(1981) found a consistent peak of growth around pH 4.0 that indicated the presence of a positive effect from the simulated acidic rain, which was postulated to be foliar fertilization. Although the soil mixtures were well drained and nutrient-rich, the potted plants may have experienced some stress due to the limited size of the pots and thus limited root space, or there may have been changes in soil parameters, such as soil pH or populations of mycorrhiza or N-fixing bacteria.

With respect to standard growing conditions, irrigation was the parameter with the greatest disparity among experiments. Plants in experiments seldom undergo water stress as do commercial crops. A number of studies report their irrigation practice as "watering as needed" when the soil looked dry. To simulate natural conditions, Evans et al. (1984) used a rain-exclusion cover over field grown crops and matched the volume of applied rain to that of the ambient. By contrast, Amthor and Bormann (1983) applied only 10 mm/week simulated acidic rain while the ambient ranged from 21 to 42 mm/week. The research on snap beans by Troiano et al. (1984) provides a detailed analysis of experimental design using rain-exclusion covers. In the field trials of Troiano et al. (1984), the unprotected (ambient plus simulated rainfall) plant growth lagged behind that of the protected (only simulated rainfall) at all pH's. The unprotected plants had a greater total period of wetness and the plots were subjected to waterlogging by unusually heavy rainfall. Only the beans receiving ambient rainfall showed lower productivity correlated with increasing acidity. In subsequent seasons which had lower ambient rainfall, plant productivity showed no response to simulated acidic rains. Water stress did not act independently of pH, but rather increased plant sensitivity to acidity. Exclusion shelters do not alter the condensation or dew processes; however, they may alter influences of rain on gas-exchange and nutrient balance (Evans et al. 1981c). Rain-exclusion shelters may decrease the influence of dry acidic deposition on plants by preventing rainfall from wetting the deposition and increasing its reactivity (Kratky et al. 1974; Irving 1983).

In an experiment on alfalfa, wheat, lettuce, and radish, Evans (1982c) used Latin squares and selected statistical techniques to allow detection to 10% differences. However, data were analyzed using no rainfall as control rather than using simulated rain of pH 5.6 as control. This introduced water availability as a variable and may have tended to exaggerate the effects of the simulated acidic precipitation. In this instance, the plants with no simulated rainfall had higher productivity than plants receiving rainfall of pH 5.7 and lower. A similar effect of the moisture regime on productivity was observed by Evans et al. (1982a) for beets field-grown with rain-exclusion shelters.

2.6.4 Structural Environment

The structural growing environment has a significant influence on plant response to acidic precipitation, most likely through secondary effects, e.g., on root conditions or humidity. Plants grown in a controlled environment, such as a greenhouse, glasshouse, or growth chamber, show greater susceptibility to foliar injury and a lower threshold for yield reductions (Evans et al. 1981a; Irving and Miller 1981; Cohen et al. 1982; Evans et al. 1982b; Troiano et al. 1982; and Keever and Jacobson 1983b), which may be due to increased sensitivity of plants to stress when grown with a short photoperiod, low light intensity, medium temperatures, and adequate soil moisture-common greenhouse conditions (Irving 1983). Thus, controlled environments provide exaggerated estimates of plant response to acidic wet deposition. Plants insensitive to a given dose in a greenhouse will probably not be adversely affected by a similar dose under ambient conditions (Evans et al. 1982c; Jacobson 1984). The influence of growth conditions may involve complex interactions. In simultaneous field and greenhouse experiments on soybeans, Keever and Jacobson (1983c) found that the field grown plants experienced greater leaching and damage because they matured more slowly and thus had more newly expanding leaves at the time of treatment.

In a controlled environment experiment by Amthor and Bormann (1983) with perennial ryegrass, there were no visible symptoms of injury at pH 3.0; dry mass decreased, with no decrease in root growth reported. At the same pH, Lee et al. (1981) reported visible foliar injury on perennial ryegrass, while the dry mass was not decreased. One possible explanation is that the stresses presented by the growing conditions were different; another is that the method of pollutant exposure was different. The ryegrass grown by Lee et al. (1981) was field-grown, with rain-exclusion shelters, and received irrigation as needed. Amthor and Bormann (1983) grew the ryegrass in a greenhouse with greater diurnal temperature fluctuation, well irrigated root zone, and well buffered soil suggesting no soil-acidity effects, only effects from direct contact between shoot and simulated acidic wet deposition. This suggests that processes mediated through the shoots had little effect on the root.

2.6.5 Plant

The stage of plant development influences the plant's threshold for foliar injury and reductions in productivity; it is necessary to know the age and stage of development of experimental plants throughout the experiment.

Given that all experiments operate under budget and labour constraints, plant species and seed sources are chosen with the specific experiment's objectives in mind. There is no standardized methodology for evaluating the sensitivity of plant species to air pollutant stress, wet or dry, under all environmental conditions. The sensitivity classification of a given plant species, or cultivar, is dependent on the parameter used to assess the sensitivity. Thus, the effect of air pollution stress on a given species can only be determined by experiments using that species.

Although using a narrowly defined genotype increases the ability to detect treatment responses, it decreases the relevance of results to agronomic systems in general. Using commercial seed sources, on the other hand, reduces the ability to detect response to treatment but increases the relevance of results to agronomic systems. The same relationship exists in using a controlled environment to have a large number of replicates, versus fewer replicates in the field, or variations in the number and range of treatments (Jacobson 1984).

Since cultivars are developed in different regions, and since the chemistry and pH of ambient rainfall varies substantially within and between rain events and between regions, it is possible that cultivars are being bred with different tolerances to acidic wet deposition simply by virtue of being selected for performance in an area with differing acidic rainfall regimes (Irving 1983). The relationship between differing sensitivities of cultivars and the ambient air quality where they were developed should be considered in future comparisons of cultivar sensitivity.

2.6.6 Observation and Analysis

Within a given experiment, there are influences on plant response that may vary temporally or spatially, making it difficult to detect response to treatment. Spatial variation in local soil characteristics, micrometeorological characteristics, and pest infestation may significantly influence plant productivity. These variations occur in agricultural plots as well as natural terrestrial ecosystems.

Large numbers of replicates with adequate randomization are necessary to detect plant response to pollutant exposure. A realistic goal for experimental design is to detect differences in treatment-response within a 90% confidence level (Evans et al. 1981a). Interpretation of results depends on the method of statistical analysis and the selection of the error term used. The error term can reflect only plant-to-plant error or can also include a treatment-interaction term generated by multiple seasons of experiments. The latter facilitates extrapolation of results at the expense of the ability to discern effects by increasing the error term.

3. EFFECTS OF GASEOUS AIR POLLUTION ON AGRICULTURAL CROPS

In this section we discuss the effects of the gaseous pollutants SO_2, NOx, O_3, and H_2S on agricultural species. These gases are important components of dry deposition of pollutants in Alberta. The discussions will be limited to species important to Alberta agriculture except where there is a limited amount of data on these species or where comparisons with other species are important.

Sulphur dioxide is one of the major air pollutants in Alberta. It is very phytotoxic both in gaseous form and in its hydrated forms (HSO_3^- and H_2SO_4), as found in acid precipitation, or when dry deposited SO_2 dissolves on wet plant parts. Sulphur dioxide is extremely soluble in water. Susceptible plants may be damaged by 0.05 to 0.5 ppm of SO_2 after exposures for just eight hours when the gas is administered singly (Mudd and Kozlowski 1975).

In the discussions on oxides of nitrogen (NOx), NO_2 and NO will be considered because they are the oxides of nitrogen most often present at phytotoxic levels in polluted environments. Because NOx levels tend to decrease with time due to photochemical reactions, concentrations of NO and/or NO_2 high enough to cause adverse, direct effects on plant life are generally limited to areas proximal to urban and industrial development where emission concentrations are high. Continuous exposure to 0.25 to 0.5 ppm of NO_2 has caused visible foliar injury in sensitive plants (Taylor and MacLean 1970; National Academy of Sciences 1977b).

The phytotoxicity of O_3 has been known for four decades and research on the subject has been extensively carried out for the last two. Exposure of very sensitive plants to O_3 at concentrations as low as 0.10 ppm (for one hour) or 0.03 ppm (for several hours) can be detrimental to foliage, growth, and yield. Ozone exposure of plants of intermediate sensitivity will induce injury at concentrations of 0.30 ppm (for one hour) or 0.10 ppm (for several hours) (Guderian 1985). The National Academy of Sciences (1977a) has specified the threshold concentration for chronic O_3 exposure to be between 0.05 and 0.1 ppm for sensitive cultivars.

Phytotoxic levels of H_2S are well above known ambient concentrations (Heck et al. 1970). Concentrations as high as 0.3 ppm generally have no adverse effects on plants and can even stimulate growth. Younger plants are more susceptible to H_2S damage than older plants. In contrast to the effects of the other gaseous pollutants mentioned in this chapter, more injury is caused to plants in drier soils when exposed to H_2S than in more moist soils (Thompson and Kats 1978).

3.1 PHYSIOLOGICAL EFFECTS

Effects on plant physiology due to gaseous pollutants are important because the changes in physiological and metabolic processes are generally thought to initiate pollutant induced changes involving growth, development, and reproduction.

3.1.1 Sulphur Dioxide

3.1.1.1 Sulphur dioxide effects on stomata and transpiration. Sulphur dioxide directly affects the stomata, which may be induced to open or close depending on plant species, pollutant concentration, duration of exposure, and prevailing environmental conditions.

Sulphur dioxide induced stomatal opening has been observed in several species including: field bean (Vicia faba), corn (Zea mays), pine (Pinus sp.), bush bean, navy bean, white bean (Phaseolus vulgaris), pea (Pisum sativum), grapevine (Vitus sp.), radish (Raphanus sativus), sunflower (Helianthus sp.), tobacco (Nicotiana sp.), cucumber (Cucumis sativus), soybean (Glycine max),and two species of saltbush (Atriplex triangularis and A. sabulosa). These increases in stomatal opening occurred within a few minutes of SO_2 fumigation and resulted in a 10-20% increase in stomatal conductance in several four-carbon (C4) species and increases as high as 200% in the three-carbon (C3) species Atriplex triangularis (Black 1982).

Stomatal closing with subsequent transpiration inhibition has been observed in pinto bean (Phaseolus vulgaris), fish geranium (Pelargonium hortorum), pine , monkey flower (Diplacus aurantiacus), Christmas berry (Heteromeles arbutifolia), peanut (Arachis hypogaea), tomato (Lycopersicon esculentum), radish, perilla (Perilla sp.), spinach (Spinacea oleracea), castor bean (Ricinis communis), Swiss chard (Beta vulgaris), rice (Oryza sativa), poplar (Populus sp.), sycamore (Platanus occidentalis), sunflower, cucumber, wheat (Triticum sp.), corn, sorghum (Sorghum vulgare), apple (Malus sylvestris), and birch (Betula sp.). The maximum inhibition of transpiration rates observed in these studies ranged from 35-75% and occurred within ten minutes to four hours following exposure, depending on the species examined (Black 1982).

The majority of these investigations on stomatal response used concentrations of SO_2 higher than found in polluted environments; it is not known whether these species would show the same response with more realistic concentrations. Ziegler (1975) stated that increases in stomatal conductance and transpirational losses will occur at concentrations of SO_2 found in polluted environments. She has consistently observed an initial increase (approximately 15 to 20%) and then a decrease (approximately 50%) in transpiration in the species she has studied. Low concentrations of SO_2 (which are considered to be toxic) cause a permanent increase in transpiration (Ziegler 1975). Whether the increased stomatal aperture during these exposures is caused by increased turgidity of the guard cells, a reduction in turgidity within the epidermal cells adjacent to the guard cells, or other mechanisms is, as yet, unresolved (Black 1982).

Once the SO_2 enters the leaf through the stomata, it contacts mesophyll cells where it hydrolyzes in the surface fluid to become sulphite. The ratio of bisulphite to sulphite (HSO_3^- / SO_3^{2-}) depends on the pH of the cell. The buffer capacity of cytoplasm decreases with time and especially with an increased SO_2 concentration. The sulphites are mostly oxidized to sulphate and are stored. These sulphates can be converted to organic-sulphur compounds or exuded by the roots. Accumulation of sulphate occurs predominantly at edges and tips of leaves. Sulphate accumulation increases with increased photosynthesis and thus is at its maximum in young leaves as well as at late morning. If the plant's capability to oxidize sulphites is exceeded, sulphites build up to toxic levels and result in injury (Zeigler 1975).

3.1.1.2 Sulphur dioxide effects on photosynthesis. Most studies indicate a decrease in photosynthesis with increased SO_2 exposure (Mudd and Kozlowski 1975; Black 1982). Depression of photosynthesis occurs within 30 minutes to a few hours of exposure and is readily reversible at low concentrations. At higher concentrations, responses are less reversible and appear to be associated with breakdown of biochemical systems, tissues, and appearance of visible injury.

Irradiance and temperature seem to influence SO_2-induced changes in the photosynthetic process itself. This phenomenon is still being investigated. One hypothesis is that the presence of these factors may modify the rates of detoxification or biochemical processes (Black 1982).

3.1.1.3 Sulphur dioxide effects on respiration. Conflicting results exist from the studies of the effect of SO_2 on dark respiration and photorespiration. Some investigators have shown an inhibitory effect on dark respiration (Gilbert 1968; Taniyama 1972), while others have shown a stimulatory effect (Keller and Muller 1958; De Koning and Jegier 1968; Taniyama et al. 1972; Baddeley and Ferry 1973; and Black 1982).

Koziol and Jordan (1978) observed an increase in photorespiration in bean (*Phaseolus vulgaris*) with SO_2 exposure. This effect was attributed to greater use of energy in repair or replacement processes. Others have shown a decrease in photorespiration (Ziegler 1975; Black 1982).

3.1.2 Oxides of Nitrogen

After entering through the stomata, nitrogen oxides diffuse through the intercellular spaces to the mesophyll and parenchyma where they react with the hydrated cell surfaces to form a mixture of nitrous and nitric acids. When this acid exceeds a certain threshold the tissues are injured (Mudd 1973; Zeevaart 1976; and McLaughlin et al. 1979).

3.1.2.1 Oxides of nitrogen effects on stomata and transpiration. There are few data on the direct effect that oxides of nitrogen have on plant stomata. Hill and Bennett (1970) have reported stomatal closure after NOx exposure. This response, however, was not interpreted to be a direct effect of NOx, but rather an indirect effect caused by carbon dioxide buildup in the intercellular spaces due to NOx inhibition of photosynthesis.

3.1.2.2 Oxides of nitrogen effects on photosynthesis. Hill and Bennett (1970) compared the effects of NO and NO_2 on the rate of carbon dioxide assimilation (apparent photosynthesis) in alfalfa (*Medicago sativa*) and oats (*Avena sativa*). A threshold concentration of approximately 0.6 ppm of each gas was required to reduce carbon dioxide assimilation. Combining the two gases gave an additive effect. Nitric oxide produced a more rapid decrease in apparent photosynthesis than NO_2, and recovery of normal photosynthesis after fumigation with NO_2 was more rapid than with the NO fumigation. When fumigations caused a 25% decrease in photosynthesis, the NO_2-exposed plants took more than four hours to recover, whereas the NO-exposed plants recovered normal photosynthesis within an hour.

Increases in photosynthesis have been observed at very low concentration fumigations due to fertilizer effects (Bull and Mansfield 1974).

3.1.2.3 Effects on respiration. There are no data available concerning the direct effects of oxides of nitrogen on plant respiration.

3.1.3 Ozone

Ozone differs from the other gaseous pollutants mentioned in this review in that exposure to O_3 is believed to increase the permeability of cell membranes and cause leakage of ions. Once O_3 passes through the stomata, it attacks the plasmalemma lining of inner walls of cells. The permeability of plasmalemma is disrupted, allowing leakage of cell contents into intercellular spaces (Wedding and Erickson 1955; Perchorowicz and Ting 1974). Most researchers agree that when the stomata are closed, little ozone can enter the plant and little or no injury occurs, but this has not been proven and experimental results are contradictory.

3.1.3.1 Effects on stomata and transpiration. There is evidence that O_3 induces stomatal closure, thus decreasing the amount of O_3 entering the leaf and contributing to the resistance to O_3 injury of certain varieties (Engle and Gabelman 1966; US Environmental Protection Agency 1978; Tingey and Hogsett 1985). Transpiration is also inhibited with O_3 exposure as would be expected from the effect of O_3 on stomata (Hill and Littlefield 1969; Temple 1986).

3.1.3.2 Effects on photosynthesis. It is generally accepted among researchers that ozone inhibits photosynthesis (Tingey 1977; US Environmental Protection Agency 1978) and that this inhibition can occur without foliar injury. Ozone, in addition, alters the way in which the products of photosynthesis are distributed within plants (Jacobson 1982).

3.1.4 Hydrogen Sulphide

Few experiments have been conducted on the effects of H_2S on plant physiology. Shinn et al. (1976) reported stimulated photosynthesis and increased stomatal conductance in lettuce (*Lactuca sativa*) plants when exposed to various concentrations of H_2S as high as 5.0 ppm. At concentrations higher than 5.0 ppm, photosynthesis was depressed. This experiment was conducted with exposures to a gaseous mixture with the following volume ratio: $15CO_2$: $1H_2S$: $1CH_4$: $2N_2$: $1H_2$. For all practical purposes, CH_4, N_2, and H_2 are expected to be inert compared with H_2S at the same levels. Stimulation of photosynthesis was also found in sugar beets (Shinn and Kercher 1978) and snap beans (Coyne and Bingham 1978) when exposed to H_2S alone.

3.2 FOLIAR EFFECTS

The most readily observed symptoms of gaseous pollutant exposure are visible foliar injury. Foliar effects can be divided into two categories: acute and chronic.

Acute injury to plant tissue occurs within hours or days after exposure to short-term (less than 24 hours), high concentrations of gas. Chronic injury to plant tissue usually develops over a period of time (from more than one day to one or more years) from exposure to variable and lower concentrations of gas.

Foliar injury caused by SO_2, NOx, and H_2S is usually found in areas near emission sources. Foliar injury due to O_3 is usually found many kilometres from industrial and urban sources.

3.2.1 Sulphur Dioxide

Acute injury caused by SO_2 is usually found as foliar necrosis in which metabolic processes cease and plant cells are killed. Chlorosis may also be observed. Chronic injury includes chlorosis (sometimes changing to necrosis) in which the cells are not killed, but chlorophyll is converted to phaeophytin and leaves become bleached. The leaves remain turgid but function less efficiently (Linzon 1978).

Acute injury from SO_2 exposures is caused by a rapid accumulation of bisulphite and sulphite (Linzon 1978). When the oxidation product, sulphate, accumulates beyond a threshold value the plant cells can tolerate, chronic injury occurs. Linzon (1978) estimated that sulphate is about 30 times less toxic than sulphite.

Acute foliar injury has been observed in dosages as low as 0.03 ppm (one-hour exposure), 0.025 ppm (six-hour exposure), and 0.05-0.12 ppm (four- to eight-hour exposure) in sensitive species of eastern white pine (Pinus strobus) and peanut (Linzon 1978). Jones et al. (1979) working in the Tennessee Valley region concluded that the threshold dose for foliar injury on sensitive species was 0.32 ppm for one hour or 0.17 ppm for 3 hours. The probability that foliar effects would occur on any species examined was less than 50% for three-hour exposures to concentrations less than 0.50 ppm. To prevent SO_2 injury to most species under most conditions, SO_2 concentrations should not exceed 0.70 ppm for one hour, 0.4 ppm for two hours, and 0.26 ppm for eight hours (Linzon 1978).

Of the agricultural species, nearly all garden varieties of squash (Cucurbita pepo), including pumpkin (C. pepo), are very sensitive to SO_2 foliar injury and will show injury before other plants do. The foliar parts of plants are more sensitive to visible injury than the stems, buds, and reproductive structures (Barrett and Benedict 1970).

In dicotyledons, acute foliar injury is expressed as localized necrotic areas that are primarily intercostal, but sometimes (as with narrow leaves) occur on tips and margins. The necrotic lesions are visible on both sides of the leaf. Destroyed parts of tissue appear greyish-green and water-soaked, but become dry later and change colour to reddish-brown (or sometimes pale ivory). The colour is more prominent on the adaxial surface of the leaf. There may be a stippling of necrotic spots. Larger spots and areas may merge to form intercostal stripes. Injured areas may become brittle and fall out, leaving the leaves with a perforated appearance frequently called "shot hole". In monocotyledons the most common form of acute foliar injury is a light yellowish-white or ivory-coloured necrosis, beginning at the leaf tip and extending down the blades. Necrotic leaf margins may also occur as well as stippling or a definite pattern of stripes between the veins on the blade.

Chronic foliar injury is typified by silvering, yellowing, or bronzing, which may occur due to the presence of pigments previously masked by chlorophyll that has been destroyed. Chlorosis in chronic injury is generally interveinal.

Although these visual symptoms are characteristic of SO_2 induced foliar injury, they can only be used as a guide in identifying the cause of injury because other factors influence plant injury as well, including climate, insects and other pests, soil, nutrition, and genetic and physiological factors. Thus, all these factors, as well as emission sources, must be taken into consideration when assessing the cause of injury to a plant.

Table 8 shows threshold concentrations of SO_2 for foliar injury to various species taken from a number of different studies. The studies are of single short-term exposures. The threshold concentrations for visible foliar injury range from 0.18 ppm for eight hours to 2.0 ppm for one hour.

Table 9 shows sensitive agricultural crops found in Alberta. This sensitivity was based on visible foliar injury with SO_2 exposures under conditions favourable for gas absorption by plants (Barrett and Benedict 1970).

3.2.2 Oxides of Nitrogen

Nitrogen dioxide is the only oxide of nitrogen that has been found to injure vegetation at concentrations found in ambient air. When controlled fumigations of NO are conducted (with NO_2 excluded), visible symptoms are not seen with concentrations as high as 25.0 ppm (Legge et al. 1980). The foliage most susceptible to injury is the middle-aged and oldest leaves, though this may vary among species. Table 10 shows percent leaf injury to various crops at different dosages and concentrations.

The most commonly observed symptoms of acute NO_2 injury are interveinal water-soaked lesions appearing on the adaxial leaf surface, which appear one to two hours after exposure. These lesions rapidly collapse and bifacial necrotic areas develop. On drying, the areas bleach to a white, light tan, or bronze colour. These lesions gradually extend through the leaf to produce small irregular necrotic patches. Injury is similar to that seen as a result of SO_2 exposure (Taylor and MacLean 1970; Taylor et al. 1975). An overall waxy appearance that persists for about a week is seen in some species (pigweed [Cheopodium sp.], cheeseweed [Malva parviflora], Kentucky bluegrass [Poa pratensis], and mustard [Brassica sp.]) (Taylor and MacLean 1970). Lesions may also be marginal and tend to be near the apex, especially in sensitive species (Taylor and MacLean 1970). At high concentrations, abscission of leaves and fruit has been observed in citrus trees (Citrus sp.). Acute injury is generally considered to occur at an NO_2 concentration of 1.6 ppm to 2.6 ppm or greater for exposures of up to 48 hours (Legge et al. 1980).

Symptoms of chronic NO_2 injury include chlorosis (caused by alterations in chlorophyll content) and premature defoliation and fruit drop. An enhancement of the green colour may be observed before these symptoms develop (Taylor and MacLean 1970; Legge et al. 1980).

Benedict and Breen (1955) observed the foliar effects of NO_2 in outdoor transparent fumigation chambers at concentrations of 20 ppm to 50 ppm on common weed species. Two types of leaf markings were observed: (1) a discolouration with cell collapse and necrosis; and, (2) an overall waxy appearance on the leaf. At 20 ppm in moist soils, the weeds showed 0% to 9% (mean of 2.7%) leaf area injury after three weeks and 1% to 26% (mean of 5%) after six weeks. At 50.0 ppm in moist soils, the weeds had 0% to 32% (mean of 11.5%) leaf area injury after three weeks and 1% to 54% (mean of 12.8) after six weeks. Mustard (Brassica arvenis) experienced the most injury, followed by sunflower.

Van Haut and Stratmann (1967) fumigated 60 species of plants with a one:one mixture of NO and NO_2. They classified plants as sensitive, intermediate, or resistant. Those species classified that are widely grown in Alberta are shown in Table 11.

Table 8. Threshold sulphur dioxide concentrations (ppm) causing foliar injury to various agricultural species.

A. Field observations

Dreisinger and McGovern (1970) (Ni/Cu smelters - Sudbury, Canada)	1 hr	2 hr	3 hr	4 hr	8 hr
Sensitive crops	0.70	0.40	0.34	0.26	0.18
Intermediate	0.95	0.55	0.43	0.35	0.24
Resistant	1.88	1.1	0.86	0.70	0.49

Jones et al. (1979) (Power plants - Tennessee, US)	1 hr	3 hr
Sensitive	0.50 to 1.0	0.30 to 0.60
Intermediate	1.0 to 2.0	0.60 to 0.80
Resistant	2.0 +	0.80 +

B. Controlled environment fumigations

Van Haut and Stratmann (1967)	1 hr	2 hr	3 hr	4 hr	8 hr
Sensitive (rye)	2.3	1.9	1.1	-	0.75
Katz and Ledingham (1939)					
Sensitive (alfalfa, barley)	1.5	1.0	0.89	-	0.55

continued...

Table 8 (Concluded).

B. Controlled environment fumigations (continued)					
Thomas (1935)	1 hr	2 hr	3 hr	4 hr	8 hr
Sensitive (alfalfa)	1.2	0.71	0.55	0.48	0.36
Fujiwara (1975)					
Sensitive	–	0.60	0.45	–	0.25
Zahn (1961)					
Sensitive	0.70	0.62	0.60	0.58	0.50
Intermediate	1.2	1.1	1.0	1.0	0.9
Resistant	1.8	1.7	1.6	1.6	1.4

Adapted from the original table in International Electric Research Exchange (1981).

Table 9. Agricultural species sensitive[1] to sulphur dioxide.

Alfalfa (*Medicago sativa*)
Barley (*Hordeum vulgare*)
Bean, field (*Phaseolus vulgaris*)
Beet, table (*Beta vulgaris*)
Broccoli (*Brassica oleracea* cv. *botrytis*)
Brussel sprouts (*Brassica oleracea* cv. *gemmifera*)
Carrot (*Daucus carota* var. *sativa*)
Clover (*Melilotus* & *Trifolium* sp.)
Cotton (*Gossypium* sp.)
Lettuce (*Lactuca sativa*)
Oats (*Avena sativa*)
Radish (*Raphanus sativus*)
Rye (*Secale cereale*)
Safflower (*Carthamus tinctorius*)
Soybean (*Glycine max*)
Spinach (*Spinacea oleracea*)
Squash (*Cucurbita maxima*)
Sweet Potato (*Ipomoea batatas*)
Swiss Chard (*Beta vulgaris* cv. *cicla*)
Turnip (*Brassica rapa*)

[1]Sensitivity is based on foliar injury

Source: Barrett and Benedict (1970)

Table 10. Percent leaf area injured by designated dosage[1] of nitrogen dioxide.

Experiment 1			
Dosage (ppm x hr)	2.5	4	14
(ppm)	5	2	2
(hr)	0.5	2	7
Percent Injury			
Corn			
(*Zea mays* cv. Pioneer)	1	0	0
(*Zea mays* cv. Golden Cross)	0	0	0
Oats			
(*Avena sativa* cv. Clintland 64)	14	0	2
Experiment 2			
Dosage (ppm x hr)	2.5	4	21
(ppm)	5	2	3
(hr)	0.5	2	7
Percent Injury			
Wheat			
(*Triticum sativum*)	3	1	1
Oats			
(*Avena sativa*)	2	1	14
(*Avena sativa* cv. Pendek)	1	0	2
Cucumber			
(*Cucumus sativus*)	0	0	0

[1]Dosage = Concentration (ppm) * duration (hours)

Adapted from the original table in Taylor et al. (1975)

Table 11. Susceptibility of various agricultural species that occur in Alberta, to a combination of nitrogen dioxide and nitric oxide.

Plant Species
Sensitive
Alfalfa
Barley (*Hordeum distichon*)
Crimson or Italian clover (*Trifolium incarnatum*)
Oats (*Avena sativa*)
Red clover (*Trifolium pratense*)
Intermediate
Maize
Potato
Rye
Wheat, common
Resistant
Cabbage (*Brassica oleracea*)
Onion (*Allium cepa*)

Source: Van Haut and Stratmann (1967)

Sensitive species such as pinto bean, tomato, and cucumber may be injured by a two-hour exposure of concentrations of about 6.0 ppm NO_2 under full sunlight intensity. Under low light intensity (equivalent to a cloudy day) the same plants would be injured when exposed to concentrations of 2.5 ppm to 3.0 ppm NO_2.

Nitrogen dioxide concentrations rarely exceed 0.10 ppm in rural areas; therefore, plants are not commonly exposed to phytotoxic concentrations.

3.2.3 Ozone

Visible foliar injury as a result of O_3 exposure is almost always confined to green foliage of plants as opposed to fruits or floral parts.

The most common symptoms of foliar injury due to O_3 as described by Hill et al. (1970) are as follows:

(1) Pigmented Lesions
These lesions are most commonly observed on deciduous trees and shrubs, but are also observed on herbaceous plants. These lesions are primarily on the adaxial leaf surface and are caused by a localized thickening and pigmentation of cell walls resulting in small dot-like lesions. The lesions may be dark brown, black, purple, or red. Injury is limited to the palisade cells; epidermal cells are generally not damaged. Lesions occur between veins and therefore may have an angular appearance. The veins are not usually affected except in species where pigments colour sections of veins. Formation of pigments can produce an overall colouration of the adaxial leaf surface when the lesions are dense.

(2) Surface Bleaching
On most herbaceous and many woody species, small unpigmented necrotic spots or more general upper surface bleaching is common. Injury is more common on the adaxial surface but may develop on either surface (especially in species such as small grains and grasses which lack palisade tissue) or may spread to the abaxial surface with extensive injury. Each lesion is usually small but may become quite large depending on the species. Palisade cells (and with extensive injury, epidermal cells) collapse and become bleached. Usually generalized chlorosis is absent; but large chlorotic spots may occur around small necrotic centres. As the palisade cells collapse, a resulting air space results, giving the tissue a light grey, white, or tan colour. Lesions often become sunken areas in the adaxial leaf surface.

(3) Bifacial Necrosis
Bifacial necrosis occurs when the entire tissue through the leaf is killed. Injury may appear as almost white to orange-red. The adaxial and abaxial surfaces of the leaf are often drawn together forming a thin, papery lesion. Small veins are usually killed along with the other tissue, although large veins usually survive. Upper surface and bifacial necrosis often occur on the same leaf, in which case the bifacial necrosis is usually darker in colour. Some species (such as spinach) form a temporary shiny, oily, or waxy appearance on the adaxial leaf surface. Before

bifacial necrosis develops, there may exist a water-soaked appearance followed by drying and bleaching for one to two days.

(4) Chlorosis

Chlorosis is usually limited to a small group of palisade cells and injury is seen primarily on the adaxial surface of leaves with palisade parenchyma. Primary lesions usually range in size from a few cells to about one mm, but they may merge to give a yellow, mottled appearance. Many uninjured cells remain alive but suffer from disrupted chloroplasts and have reduced chlorophyll content. Small grains and grasses (with undifferentiated mesophyll) may develop fine chlorotic streaks or stippling on either surface between the veins. The injury is often most severe at the bend in corn, onion, and other grasses and may cause almost complete collapse of interveinal tissue in this region. Some plant species (such as alfalfa) maintain many irregular areas of normal green tissue around which large chlorotic lesions develop. After low-level, long-term exposure, older leaves with chlorotic symptoms (which may or may not show necrotic lesions) sometimes turn yellow and become senescent prematurely (Hill et al. 1970).

Foliar injury due to O_3 generally occurs on the whole leaf surface; however in younger leaves, injury tends to occur toward the tip of the leaf, and in older leaves, toward the base of the leaf. Markings often consist of a band across the leaf surface where tissue of only a particular age has been affected. Portions of a leaf may not show injury because of shading and protection from other leaves. In unifacial injury, the margins often remain uninjured. In bifacial injury the margins may be severely injured; this can result in a pinched appearance as the rest of the leaf continues to grow (Hill et al. 1970).

Leaves are most sensitive to O_3 injury as they reach 65% to 95% of their full size. Young leaves are generally resistant. The sensitivity of mature leaves depends on the species in question. In the field, older leaves may show symptoms of foliar injury sustained in an earlier, more sensitive stage of development. Generally speaking, young plants are more sensitive than mature plants, whereas young leaves are more resistant than mature leaves (Hill and Bennett 1970). Tingey et al. (1973b) reported a maximum sensitivity of soybean to foliar injury during the end of maximum leaf expansion when stomatal resistance was low.

External factors (such as pests and extreme soil conditions) may cause injury to foliage similar to O_3 injury. Certain sucking insects, like mites and leaf hoppers, cause injury that may be confused with O_3-induced injury. The two injuries may be distinguished because feeding insects tend to empty the palisade cells rather than just causing their collapse and insect injury tends to be less uniform than O_3 injury. Certain viral diseases produce injury similar to that caused by O_3, but chlorosis and mottling of younger leaves in the top of the plant will suggest the presence of a virus. Soils with a high soluble manganese content may induce injury similar to that seen in O_3-exposed plants. Radiation-type frost can cause adaxial surface bleaching of leaf tissue and moisture stress caused by hot, dry winds can cause bifacial necrosis which may resemble O_3 injury (Hill et al. 1970).

In fumigation experiments, O_3 concentrations between 0.05 and 0.12 ppm for two to four hours are usually required to injure the most sensitive species. Sensitive varieties of alfalfa, spinach, clover, oats, radish, sweet corn, and bean have been injured by two-hour exposures at concentrations of 0.10 to 0.12 ppm O_3 (Hill et al. 1970).

Brasher et al. (1972) reported 10% to 95% injury in three cultivars and 16 seedlings of potato after three days of ambient oxidant exposures that reached a maximum O_3 concentration of 0.15 ppm.

3.2.4 Hydrogen Sulphide

A typical foliar symptom of H_2S injury is wilting (without discolouration), which starts at the tip of the leaf. Scorching of young shoots and leaves and basal and marginal scorching of the next oldest leaves has also been reported (Miner 1969; Heck et al. 1970). Narrow-leaved plants may develop a general powdery appearance between tip and bend of the leaf. Colour of markings is usually white to tan. Some species (such as sunflower) may take on an orange-brown cast when leaves are in the bud stage (Miner 1969). Unlike the other gaseous pollutants discussed in this review, H_2S can injure the growing tip of plants (Heck et al. 1970).

Dobrovolsky and Strikha (1970) observed leaf necrosis at concentrations of 0.07 ppm of H_2S. They concluded that H_2S is markedly more phytotoxic than SO_2 and that acute tissue necrosis due to H_2S exposure occurs at concentrations 10 to 20 times lower than with SO_2.

Thomas (1961) and Thompson and Kats (1978) found that H_2S concentrations above 0.1 ppm caused foliage of most species to develop necrotic lesions or marginal leaf and needle tip burn in studies with alfalfa, grapes, lettuce, sugar beet, California buckeye (*Aesculus californica*), ponderosa pine (*Pinus ponderosa*), and Douglas fir (*Pseudotsuga menziesii*). However, at concentrations of 0.03 ppm and sometimes at 0.1 ppm, no significant leaf injury was found (Taylor 1984).

3.3 GROWTH AND YIELD

Gaseous pollutants may cause either increases or decreases in growth and yield. These changes can occur with or without visible injury. The effects of gaseous pollutants on growth and yield are of primary concern in agricultural systems. Crop yield can be affected through changes in weight, quantity, and quality. Crop losses due to air pollutants have been reported for over 30 years. Crop damage in the U.S. due to air pollutants is estimated to cost $1.8 billion: $1.7 billion is due to oxidants, and $3.4 million is due to SO_2 (Stanford Research Institute 1981).

3.3.1 Sulphur Dioxide

Low concentration SO_2 exposures can cause an increase in growth and yield in plants in sulphur-deficient soils. Plants normally obtain sulphur in the form of sulphate absorbed from the soil, but when soils are deficient in sulphur, plants may use atmospheric sources of sulphur such as SO_2 in polluted air (Freid 1948; Olsen 1957). Most researchers have found that the increases in yield a plant experiences in the presence of SO_2 do not occur in plants grown in soils with sufficient sulphur (Faller et al. 1970; Cowling and Lockyer 1978).

In addition, a plant may utilize the sulphate in the soil deposited there as gaseous particulates, or as washout of atmospheric SO_2. Jones et al. (1979) reported that atmospheric sulphur is a major contributor to the agronomic and horticultural crop needs for sulphur as a plant nutrient in South Carolina. Because soils are generally sulphur deficient and because commercial fertilizers providing sulphur are quite expensive, atmospheric sulphur could be an important sulphur source for farmers (Prince and Ross 1972).

Several studies have shown significant decreases in growth and yield due to SO_2 (Guderian 1977; Crittenden and Read 1978a,b; Heagle and Johnston 1979; Davies 1980; Irving et al. 1982: Noggle and Jones 1982; and Heagle et al. 1983b). The threshold for injury for agricultural crops has been determined by many investigators to depend just as much or more on peak concentrations than on the concentration average over time (Godzik and Krupa 1982).

This discussion on the effects of SO_2 on growth and yield will be limited primarily to grains and forage crops, which grow on approximately two thirds of the total acreage of improved land in Alberta.

Table 12 shows the effects of SO_2 on barley and alfalfa at concentrations from 0.015 ppm to 0.082 ppm (mean concentration over three growing seasons) using sources near an industrial area in Poland. At the highest concentration (0.082 ppm), barley grain yield decreased 34.9% and alfalfa forage yield decreased 30.3% relative to the control (Godzik and Krupa 1982). Peak concentrations were not given.

Guderian and Stratmann (1968) conducted extensive studies on the effects of ambient SO_2 on various agricultural crops and fruits near an iron ore roasting plant in West Germany. Table 13 summarizes these experimental data. At average growing season concentrations of 0.08 ppm plants suffered decreased yields ranging from 9.1% for canola to 44.4% for winter wheat. It is likely that peak concentrations had a greater effect on yield changes than these averages.

Godzik and Krupa (1982), in their review, reported decreases in yield of 8.1 to 28.3% for various crops in Czechoslovakia (Table 14). Although the pollutant concentrations of the experiment were considerably higher than those of Guderian and Stratmann (1968), the decreases in yield were no greater. Concentrations of the magnitude used in this experiment would only be found near major uncontrolled SO_2 sources.

Noggle and Jones (1982) reported an experiment by the Tennessee Valley Authority in which the effects of acute SO_2 exposure during wheat-head emergence were studied. Plants were fumigated for three hours during anthesis with high concentrations ranging from 1.47 ppm to 3.42 ppm, with reported reduction in seed weight of 6% to 55%. These findings are summarized in Table 15.

Response to a pollutant can differ among cultivars of the same species. Laurence (1979) exposed seven varieties of wheat to various concentrations of SO_2. The effects on yield of the different cultivars are summarized in Table 16. At low concentrations the plants responded with increased yields; but as concentrations increased, the cultivars responded with decreased yields. Significant decreases in yield were not observed at commonly occurring ambient concentrations, however.

Although studies on the effect of SO_2 on perennial ryegrass (Lolium perenne) have been extensive, they have not been conclusive. There have been major differences

Table 12. Yields of two field grown crops in different concentrations of sulphur dioxide.

Approximate SO_2 Concentration (ppm)	Percent Yield: Barley (Grain)	Alfalfa (Forage)
.015	100.0	100.0
.029	98.0	99.2
.036	94.0	98.2
.038	92.2	100.4
.040	90.2	98.6
.047	85.9	88.0
.058	79.7	85.7
.060	76.3	82.0
.062	71.8	76.3
.068	70.6	78.3
.079	64.7	70.0
.082	65.1	69.7

Source: Godzik and Krupa (1982)

Table 13. Effects of ambient sulphur dioxide on yield of various agricultural species.

Crop & Harvest Characteristics	Percentage of Control Value
Spring Canola (yield)	90.9
Alfalfa (yield)	81.0
Oats (yield)	76.1
Spring Wheat (yield)	73.4
Red Clover (yield)	63.6
Winter Rye (yield)	57.7
Winter Wheat (yield)	55.6

Exposure time: 4.3% of monitoring time

Concentration: 0.44 ppm - during exposure time*
0.083 ppm - average for monitoring time**

* The exposure time was calculated by summing all time intervals, Δt = 10 minutes, with a mean SO_2 concentration greater than or equal to 0.10 ppm.

** The monitoring time is essentially equal to the exposure time of the test plants.

Source: Guderian and Stratmann (1968)

Table 14. Yield of various crops in field plots exposed to sulphur dioxide.

Species:	Decrease in Yield (%)
Oats, grain	12.2
Oats, straw	8.1
Clover	15.5
Cereals[1] (wheat, barley, rye & oats)	20.0
Potatoes	16.2
Flax (seed, fibre)	28.3, 23.8

Concentration: 1.26 ppm to 1.37 ppm (weekly averages)

Decrease in yield is relative to control

[1]Data from a different growing season

Source: Maly (1974), cited by Godzik and Krupa (1982)

Table 15. Effect of high concentrations of sulphur dioxide on wheat (*Triticum sativum*).

SO_2 Concentrations (ppm)	Foliar Injury (%)	Reduction in Seed Weight (%)
1.47	4	6
1.95	24	20
2.4	55	41
2.9	62	35
3.42	86	55

Source: Noggle and Jones (1982)

Table 16. Effects of sulphur dioxide on cultivars of hard red spring wheat (HRS) and soft white winter wheat (SWW). Exposure times are long compared to real episodes.

Cultivar	Concentration (ppm)	Dry Weight After Exposure For: 30 h	78 h	100 h
Era (HRS)	0.0	0.089	0.112ab*	0.095ab
	0.2	0.113	0.138a	0.114a
	0.4	0.101	0.099ab	0.098ab
	0.6	0.105	0.084b	0.076b
Waldron (HRS)	0.0	0.168	0.164	0.152ab
	0.2	0.178	0.215a	0.173a
	0.4	0.142	0.165b	0.135ab
	0.6	0.159	0.127b	0.108
Thatcher (HRS)	0.0	0.127	0.144	0.132ab
	0.2	0.144	0.182	0.166a
	0.4	0.125	0.143	0.127ab
	0.6	0.130	0.140	0.092b
Prelude (HRS)	0.0	0.165	0.167	0.168
	0.2	0.179	0.207	0.186
	0.4	0.138	0.172	0.164
	0.6	0.171	0.156	0.122
Arrow (SWW)	0.0	0.146	0.201b	0.159ab
	0.2	0.163	0.268a	0.178a
	0.4	0.178	0.197b	0.138ab
	0.6	0.167	0.148b	0.117b
Ticonderoga (SWW)	0.0	0.156	0.154	0.151ab
	0.2	0.147	0.172	0.174a
	0.4	0.149	0.158	0.153ab
	0.6	0.136	0.126	0.103b
Yorkstar (SWW)	0.0	0.162	0.145	0.157a
	0.2	0.154	0.158	0.177a
	0.4	0.161	0.145	0.145ab
	0.6	0.141	0.120	0.095b

* Means followed by the same letter are not significantly different (P=0.05) based on Tukey's test for comparison of means. Absence of letters indicates no significant difference. All comparisons are made within one cultivar type and exposure period. Mean of 8 plants.

Adapted from the original table in Godzik and Krupa (1982)

Source: Laurence (1979)

and discrepancies between consecutive experiments conducted under the same conditions (Bell 1982). Similar results have been observed from experiments with significantly different concentrations. For example, Ashenden and Mansfield (1978) found reductions in shoot dry weight of 18% and 34%, respectively, in two fumigations with 0.12 ppm for 28 days, which were identical except for a 2°C temperature difference. Bell and Mudd (1976) concluded that perennial ryegrass is apparently very sensitive to SO_2. Researchers have found that perennial ryegrass is generally more sensitive than Italian ryegrass (Lolium multiflorum), an annual ryegrass, and other grasses. Table 17 shows effects of SO_2 on perennial ryegrass. The studies show significant decreases in yield at varying concentrations.

Ashenden and Williams (1980) reported a 28% decrease in yield for Italian ryegrass and a 25% decrease in yield for timothy (Phleum pratense) at weekly average SO_2 concentrations of 0.068 ppm. These findings are summarized in Table 18.

Davies (1980) exposed timothy for five weeks to a uniform concentration of 0.12 ppm SO_2 under two different irradiance conditions. Although under both environmental conditions there was a decrease in yield, under low irradiance ("winter light" conditions), Davies reported decreases in yield significantly greater than those under high irradiance ("summer light" conditions). She hypothesized that this sensitivity to low concentration SO_2 during low irradiance might be the general case in winter species whose growth is significantly limited by light. Table 19 summarizes these results.

3.3.2 Oxides of Nitrogen

Nitrogen dioxide in low concentrations can assume the role of a fertilizer and be a source of necessary nitrogen for the plant. Investigators have reported increases in plant growth and yield with low concentration NO_2 exposures. This fertilizer effect has occurred in both nitrogen deficient soils and in those with optimum nitrogen nutrition (Cowling and Koziol 1982). Concentrations of 0.05 ppm of NO_2 maintained continuously can cause small reductions in growth and yield for sensitive agricultural species (Taylor et al. 1975).

Most of the studies conducted on the effect of NO_2 on growth and yield have been at high concentrations (more than 1.0 ppm). This is in part because many agricultural species may have only slight changes in growth and yield at concentrations as high as 1.0 ppm when plants are exposed to NO_2 alone. Acute exposures appear more injurious (Taylor et al. 1975). Studies using NO_2 concentrations less than 1.0 ppm are described below.

In long-term field fumigations, Irving et al. (1982) found that NO_2 exposures of 0.06 ppm to 0.40 ppm did not affect soybean-seed yields. Similar exposures on snap-bean with concentrations of 0.1 ppm showed a 10% decrease in snap bean-pod fresh weight.

In outdoor fumigation chambers Whitmore and Mansfield (1983) exposed Kentucky bluegrass (Poa pratensis) to a weekly mean concentration of 0.062 ppm of NO_2. Total dry weight decreased 55% in one experiment and no significant change occurred in another.

Spierings (1971) studied the effects of NO_2 at concentrations of 0.25 ppm on tomato and found that after 128 days (the entire growing period), there was a 22% decrease in fresh weight, a 12% decrease in average fruit weight, and an 11% decrease in fruit number, as well as smaller leaves, petioles, and stems. After 49 days or at

Table 17. Effect of sulphur dioxide on perennial ryegrass.

Concentration (ppm)	Exposure Time	Effects	Reference
0.016	Continuous 173 days during winter	21% Reduction in growth	2
0.04	Continuous 173 days during summer	Reduction in growth Reduction in photosynthesis Leaf chlorosis	2
0.067	8 hrs/day 26 weeks	52% Reduction in growth	1
0.12	8 hrs/day 9 weeks	46% Reduction in growth	1

References: 1. Bell and Clough (1973)
2. Bell et al. (1979)

Table 18. Effect of sulphur dioxide on yield[1] of grasses.

Species	Concentration (ppm)	Exposure Time	Effect[2]	Reference
Perennial ryegrass	0.026	continuous 8 weeks	- 36%	1
Perennial ryegrass	0.022	continuous 8 weeks	- 26%	1
Italian ryegrass	0.068	103.5 hrs/wk 20 weeks	- 28%	2
Timothy	0.068	103.5 hrs/wk 20 weeks	- 25%	2

[1]Yield is expressed as dry weight

[2]Effects are relative to control

References: 1. Crittenden and Read (1978b)
2. Ashenden and Williams (1980)

Table 19. Effects of sulphur dioxide on timothy (*Phleum pratense*) under winter conditions (low irradiance and short days).

	Percent Reduction Relative to Control	
	Summer Light Regime: Irradiance: 130 W/m^2 =PAR-480 $\mu E/m^2/s$ 16 hour/day	Winter Light Regime: Irradiance:40W/m^2 =PAR-12 $\mu E/m^2/s$ 12 hour/day
Number of tillers	8	30
Number of green leaves	8	40
Green leaf area (mm^2)	2	63
Green leaf weight (g)	3	50
Dead leaf weight (g)	+143[1]	+355[1]
Stem weight (g)	7	55
Root weight (g)	11	58
Total shoot weight (g)	1	50
Total plant weight (g)	3	50

[1]Changes marked with "+" are increases

Concentration of SO_2: 0.12 ppm (343$\mu g/m^3$)
Exposure Duration: 5 weeks, continuous

Source: Davies (1980)

concentrations of 0.50 ppm after 10 days, the plants grew taller, and had thinner stems and smaller leaves.

3.3.3 Ozone

The phytotoxicity of O_3 was firmly established in 1937 (US Environmental Protection Agency 1978). Ozone has been proven to reduce growth and yield of many agricultural species. Many of the data available on growth and yield changes due to O_3 are from scattered sources in the literature and are largely qualitative; it is, therefore, difficult to form conclusions or generalizations about the effects.

For O_3, the lowest limit for injury follows several hours of exposure to a concentration range of 0.02 to 0.05 ppm for most sensitive species under general conditions (Guderian 1985).

Experiments using acute exposures of O_3 are summarized in Table 20. The exposures for these experiments varied in concentration from 0.05 ppm to 1.0 ppm and in exposure time from one hour to 24 hours.

A variety of experiments on the effect of chronic exposures of O_3 on agricultural crops has been conducted. Table 21 illustrates various experiments in which plants were exposed to a range of concentrations from 0.03 ppm to 0.35 ppm.

3.3.4 Hydrogen Sulphide

Thompson and Kats (1978) and Thompson et al. (1979) have conducted the most recent and reliable experiments on the effects of H_2S on growth and yield. These experiments are summarized in Table 22. For most species studied there were either no decreases or there were increases in yield with a concentration of 0.10 ppm; but with concentrations as high as 0.30 ppm, decreases in yield were quite evident. For more sensitive species (e.g., alfalfa and grape), yields were reduced at concentrations as low as 0.03 ppm.

3.4 PLANT REPRODUCTION

Gaseous pollutants can affect plant reproduction in two ways. First, they can have a direct effect on reproductive structures and processes. Secondly, they can have an indirect effect on the plant when the reproductive structures compete with vegetative structures for metabolic assimilates, causing adverse effects on flower and fruit development.

3.4.1 Sulphur Dioxide

Sulphur dioxide exposure can affect plant reproduction in both the flowering and fruiting stages. For agricultural fruit, seed, and nut crops, these effects on plant reproduction become quite important. Unfortunately, aside from several studies on pollen germination, there have been very few investigations on plant reproduction and how it is affected by SO_2. Several researchers have reported losses of fruit and seeds due to SO_2 exposure (Van Haut and Stratmann 1967; Tingey and Reinert 1975; Guderian 1977; Crittenden and Read 1978a,b; Bell et al. 1979; Irving and Miller 1981; Irving et al. 1982; Kress 1982; Noggle and Jones 1982; Unsworth and Ormrod 1982; Ormrod 1984; Pande 1984; and Kohut and Amundson 1985).

Table 20. Effects of acute ozone exposure on growth and yield of agricultural crops.

Plant Species	Ozone Concentration (ppm)	Exposure Time (h)	Plant Response[1] Per Cent Reduction	Reference
Cucumber				
cv. Ohio Mosaic	1.0	1	19, top dry wt	1
	1.0	4	37, top dry wt	
Grapevine				
(*Vitus labrusca*)				
cv. Ives	0.08	4	60, shoot growth	2
cv. Delaware			33, shoot growth	
Pinto bean	0.05	24	Significant reduction in leaf growth	3
	0.10	12	Significant reduction in leaf growth	
Onion				
cv. Sparan Era	0.20	24	0, no effect	1
	1.0	1	19, plant dry wt	
	1.0	4	49, plant dry wt	
Potato				
cv. Norland	1.0	4	0, tuber dry wt	1
		4(3X)	30, tuber dry wt	
Radish				
cv. Cavalier	0.25	3	36, top dry wt	4
cv. Cherry Belle	0.25	3	38, root dry wt	
Radish	0.40	1.5(1X)	37, root dry wt	5
		1.5(2X)	63, root dry wt	
		1.5(3X)	75, root dry wt	
Snap bean	0.30	1.5 (2X)	10, plant dry wt	6
			12, pod dry wt	
	0.60	1.5 (2X)	25, plant dry wt	
			41, pod dry wt	

continued...

Table 20 (Concluded).

Plant Species	Ozone Concentration (ppm)	Exposure Time (h)	Plant Response[1] Per Cent Reduction	Reference
Soybean	0.30 to 0.45	1.5	Threshold for reduction of shoot growth	7
Tall fescue (<u>Festuca arundinacea</u>) cv. Kentucky 3	0.30	2 (3X)	22, shoot dry wt	8
Tobacco cv. Bel W3	0.30	2	48, chlorophyll content	9
Tomato cv. Fireball	0.5	1	15, plant dry wt (grown in moist soil)	10
	1.0	1	20, plant dry wt (grown in moist soil)	
	0.5	1	+15, plant dry wt (grown in dry soil)	
	1.0	1	+25, plant dry wt (grown in dry soil)	
White clover (<u>Trifolium repens</u>) cv. Tillman	0.30	2	17, shoot dry wt 33, root dry wt	8

[1] Responses marked with "+" are increases

References:
1. Ormrod et al. (1971)
2. Shertz et al. (1980)
3. Evans (1973)
4. Adedipe and Ormrod (1974)
5. Tingey et al. (1973a)
6. Blum and Heck (1980)
7. Heagle and Johnston (1979)
8. Kochhar et al. (1980), cited by Guderian (1985)
9. Adedipe et al. (1973)
10. Khatamian et al. (1973)

Table 21. Effects of long-term controlled ozone exposures on growth, yield, and foliar injury of various agricultural species.

Species	Ozone Conc. (ppm)	Exposure Time (#/day)	Plant Response (% Reduction or Injury from Control)	Ref.
Alfalfa	0.10	2 // 21 days	16, top dry wt	1
	0.15	2 // 21 days	26, top dry wt	
	0.20	2 // 21 days	39, top dry wt	
Alfalfa	0.05	7 // 68 days	30, shoot dry wt, 1st harvest 50, shoot dry wt, 2nd harvest	2
Bean, pinto	0.13	8 // 28 days	79, top dry wt 73, root fresh wt 70, height	3
Bean, pinto	0.05	24 // 3-5 days	50, leaf chlorosis	4
	0.05	24 // 5 days	(fivefold increase in lateral bud elongation)	
Bean, pinto	0.15	2 // 63 days	33, plant dry wt 46, pod fresh wt	5
	0.25	2 // 63 days	95, plant dry wt 99, pod fresh wt	
	0.35	2 // 63 days	97, plant dry wt 100, pod fresh wt	
Bean, pinto	0.15	2 // 14 days	8, leaf dry wt	6
	0.15	3 // 14 days	8, leaf dry wt	
	0.15	4 // 14 days	23, leaf dry wt	
	0.15	6 // 14 days	49, leaf dry wt	
	0.225	2 // 14 days	44, leaf dry wt	

continued...

Table 21 (Continued).

Species	Ozone Conc. (ppm)	Exposure Time (#/day)	Plant Response (% Reduction or Injury from Control)	Ref.
Bean, pinto	0.225	4 // 14 days	68, leaf dry wt	6
	0.30	1 // 14 days	40, leaf dry wt	
	0.30	3 // 14 days	76, leaf dry wt	
Bean, pinto	0.06	5 days/week 40 days	48, shoot dry wt 50, root dry wt	7
Beet	0.20	3 // 38 days	50, top dry wt 40, storage root dry wt 67, fibrous root dry wt	8
Crimson clover	0.03	8 // 6 weeks	<10, dry wt	9
Corn, sweet cv. Golden	0.20	3 // 3 days/wk until harvest	13, kernel dry wt 20, top dry wt 48, root dry wt	10
	0.35	3// 3 days/wk until harvest	20, kernel dry wt 48, top dry wt 54, root dry wt	
	0.05	6 // 64 days	9, kernel dry wt 14, leaf injury	
	0.10	6 // 64 days	45, kernel dry wt 25, leaf injury	
Fescue, tall	0.09	6 weeks	17, leaf dry wt 15, shoot dry wt	12
Orchard grass	0.09	4 // 5 days/wk 5 weeks	14 to 21, shoot dry wt	13
Perennial ryegrass	0.09	4 // 5 days/wk 5 weeks	14 to 21, shoot dry wt	13

continued...

Table 21 (Continued).

Species	Ozone Conc. (ppm)	Exposure Time (#/day)	Plant Response (% Reduction or Injury from Control)	Ref.
Potato (2 seasons)	0.20	3 h (6X) 2 / week		14
cv. Norland:			30, tuber wt/19, tuber no. 20, tuber wt/21, tuber no.	
cv. Kennebec:			54, tuber wt/40, tuber no. 30, tuber wt/32, tuber no.	
Potato	0.05 (>or =)	326 to 533 total hours two years	34 to 50. tuber fresh wt	15
Radish	0.05	8 // 5 days/wk 5 weeks	54, root fresh wt	16
Ryegrass, Italian	0.09	8 // 6 weeks	36, dry wt	
Soybean	0.05	6 // 133 days	3, seed yield 22, plant fresh wt 19, injury	
Spinach	0.06	7 // day 37 days	18, fresh wt	18
	0.10		37, fresh wt	
	0.13		69, fresh wt	
Soybean	0.064 0.079 0.094	9 // 55 days	31, seed dry wt 45, seed dry wt 56, seed dry wt	18
Soybean	0.05 (>or=)	465 // growing season	28, seed wt	19

continued...

Table 21 (Concluded).

Species	Ozone Conc. (ppm)	Exposure Time (#/day)	Plant Response (% Reduction or Injury from Control)	Ref.
Tomato	0.20	2.5 // 3 days/wk 14 weeks	1, yield 32, top dry wt 11, root dry wt	10
	0.35	2.5 // 3 days/wk	45, yield; 72, top dry wt 59, root dry wt 8, tillering	
Wheat	0.20	4 // 7 days (anthesis)	30, yield	20
Wheat, winter	0.10	7 // 54 days	16, seed dry wt	21
	0.13	7 // 54 days	33, seed dry wt	

References:

1. Shinohara et al. (1974)
2. Neely et al. (1977)*
3. Manning et al. (1971a)
4. Engle and Gabelman (1966,1967)
5. Hoffman et al. (1973)
6. Maas et al. (1973)
7. Manning (1978)*
8. Ogata and Maas (1973)
9. Bennett and Runeckles (1977)
10. Oshima (1973)
11. Heagle et al. (1972)
12. Johnston et al. (1980)*
13. Horsman et al. (1980)*
14. Pell et al. (1980)*
15. Heggestad (1973)
16. Tingey et al. (1973a)
17. Heagle et al. (1974)
18. Heagle et al.(1979a)*
19. Kress and Miller (1981)*
20. Shannon and Mulchi (1974)
21. Heagle et al. (1979b)*

* References cited by Guderian (1985) are also included in the bibliography.

Table 22. Effects of hydrogen sulphide on yield[1] of various agricultural crops.

	Concentrations			
	0.03 ppm	0.10 ppm	0.30 ppm	3.0 ppm
Weight of marketable product:				
Lettuce (1st harvest)	+ 32.0%	+ 12.0%	- 100.0% (no head)	
Lettuce (2nd harvest)	+ 13.8%	+ 31.9%	- 34.1%	
Beets (1st harvest)	+ 50.5%	+ 50.0%	- 22.3%	
Beets (2nd harvest)	+ 27.3%	+ 36.0%	- 25.0%	
Beets (3rd harvest)	+ 69.3%	+ 18.0%	- 20.3%	
Total Dry Weight:				
Alfalfa (cv. El Dorado) (1st cutting)	- 1.9%		- 19.2%	- 69.2%
Alfalfa (cv. Hayden) (1st cutting)	no change		- 38.5%	- 78.8%
Alfalfa (cv. El Dorado) (2nd cutting)	+ 2.2%		- 31.1%	
Alfalfa (cv. Hayden) (2nd cutting)	- 6.5%		- 39.1%	

continued...

Table 22 (Concluded).

	Concentrations			
	0.03 ppm	0.10 ppm	0.30 ppm	3.0 ppm
Fresh and dry weight of foliage:				
Cotton	no change		no change	
Dry weight of leaves:				
Grape cv. Thompson seedless	+ 23.4%	+ 2.5%	- 27.5 %	
Dry weight of canes:				
Grape cv. Thompson seedless	- 6.5%	- 30.5%	-49.3%	

[1]Increases in yield are marked "+"
Decreases in yield are marked "-"

References: Thompson and Kats (1978)
Thompson et al. (1979)

Pollen germination can be affected by SO_2 exposure. Most studies on pollen germination have been conducted with pollen from forest species. The medium on which pollen germinates has been shown to be an important factor in the effect of SO_2 on pollen germination. Fumigations (10 ppm for six days) of pollen of the sensitive species, Swiss mountain pine (Pinus montana) and Scots pine (Pinus sylvestris), had no effect when the pollen was on a dry medium, but when on moist medium, germination was reduced and pollen tubes burst after an in vitro treatment for 45 minutes (Dopp 1931). Du Bay and Murdy (1983) investigated the effect of 0.6 ppm of SO_2 for four hours on the pollen of Virginia pepperweed (Lepidium verginicum). In vitro studies showed a reduction in germination of 94%. In vivo studies showed a reduction in germination of 50%. Seed set was not affected.

3.4.2 Oxides of Nitrogen

It has been known for several years that NOx causes detrimental effects on flowering and fruiting of vegetation. Decreases in yield of fruits and seeds have been observed by several investigators including Taylor et al. (1975), Irving et al. (1982), and Whitmore and Mansfield (1983). Little research has been conducted on the specifics of the effects on reproduction (i.e., such as changes in pollen germination, or in the occurrence of flowering) by NOx. Future research should investigate the mechanisms of decreased reproduction due to NOx.

3.4.3 Ozone

Ozone has been proven to cause detrimental effects on reproduction. These effects were expressed as decreases in grain or seed yield, floral yield, number and weight of fruit, and as delayed fruit setting. These effects can be found regardless of whether vegetative injury occurs (i.e., foliar injury, stem change). (National Academy of Sciences 1977a; Jacobson 1982; and Bonte 1982). In tobacco, both pollen germination and pollen tube growth can be inhibited by exposure to O_3. Sensitive plant varieties showed this inhibition with exposure to 0.1 ppm for 5.5 hours. Resistant varieties were unaffected with the same treatment (Bonte 1982).

Mumford et al. (1972) reported a threshold concentration of 0.03 ppm to 0.06 ppm for decreased pollen germination in corn. Gentile et al. (1971) reported a decrease in pollen germination of a sensitive tomato variety. Feder (1968) found a decrease in pollen germination in his studies on tobacco. Sinclair (1969), however, found no significant effects on pollen germination in similar experiments on tobacco.

Cameron et al. (1970), and Cameron and Taylor (1973) reported major decreases in yield of some varieties of corn after high ambient-ozone episodes during tasselling. They postulated that this decrease was due to poor fertilization.

A serious potential problem for plant reproduction in the presence of O_3 is the fact that O_3 can cause chromosomal breakage in plants at high concentrations. Sparrow and Schairer (1974) reported that O_3 appeared to be a weak mutagen causing an increase in pink somatic mutation rates in petals of spiderwort (Tradescantia sp). The mutagenic effect of O_3 at ambient concentrations is not fully understood. Bruton (1974) studied the potential mutagenic effects of O_3 on mouse-ear cress (Arabidopsis thaliana). Plants were exposed to acute doses for 6 hours a day, 3 days a week, for four weeks during their 35-day life cycle. Seed and biomass decreased in study plants but no mutagenic effects carried over into later generations.

3.4.4 Hydrogen Sulphide

Dobrovolsky and Strikha (1970) observed noticeable depression in seed germination (as well as depression in the appearance of green leaflets on the sprouts, the size of sprouts, and the catalase activity) at very low concentrations (0.07 ppm) of H_2S in fumigations under bell jars. A weaker colouration in sprouts was also noted. The researchers concluded that H_2S is: ten times more toxic than SO_2 to seed germination; three times more toxic than SO_2 in the formation of green leaflets; twice as toxic as SO_2 for sprout size; and 50 times more inhibitory to catalase activity than SO_2.

3.5 GASEOUS AIR POLLUTANTS AND PLANT SENSITIVITIES

From the research conducted on the effects of various pollutants on agricultural crops, it is useful to classify these crops by their sensitivity to each pollutant. This information would be helpful to a farmer faced with deciding which crop to plant on his land. In an area highly polluted with particular gases, he would know which crops would suffer the least damage. The economic advantage of a particular crop could be weighed against the possible effects of a pollutant. Sensitivity rankings are also useful to the farmer when attempting to identify crop damage due to a particular pollutant. If crop damage in a particular area is noted on one crop but not noted on crops considered more sensitive, it is unlikely that a pollutant alone is the cause of the crop damage. In addition, this information might be used by a plant breeder deciding which agricultural crops would benefit the most by development of more pollutant-resistant varieties.

In the following section, various crops are classified by their sensitivities to SO_2, NO_2, and O_3. The sensitivity rankings for SO_2 are based on statistical analyses of different experiments at various concentrations. The sensitivity rankings for NO_2 and O_3 are based on qualitative comparisons of experiments and should not be used for quantitative conclusions.

3.5.1 Sulphur Dioxide

Quantitative sensitivity rankings of agricultural species are difficult to make because of the paucity of single experiments conducted with a sufficient number of different concentrations of pollutants. The sensitivity ranking presented here results from analyses of data from experiments with at least six concentrations (including control or zero concentration).

Table 23 illustrates the relative sensitivities of forages and grains (potato is included only for statistical accuracy as explained later). We chose to calculate the relative sensitivities of forages and grains because they occupy the majority of the acreage of improved lands in Alberta (Alberta Agriculture 1982). Red clover was calculated as the most sensitive species followed by the winter grains, wheat and rye; next in sensitivity are other grains, barley, spring wheat, and oats; less sensitive is alfalfa; and the least sensitive of the species evaluated is canola.

The data used in the statistical analysis came from two studies (Guderian and Stratmann 1968, and Godzik and Krupa 1982). The experiments reviewed were conducted in

Table 23. Quantitative index for crop sensitivity to, and threshold concentrations for, yield reduction from sulphur dioxide.

Species	Sensitivity Index	Threshold (ppm)	Reference
Red clover	1290	0.0164	1
Potato[1]	1130	0.0075	1
Potato[1]	1070	0.0237	2
Winter wheat	1070	0.0045	1
Winter rye	1020	0.0075	1
Barley	830	0.0291	2
Spring wheat	690	0.0077	1
Oats	680	0.0040	1
Alfalfa	640	0.0327	2
Alfalfa	620	0.0076	1
Canola	480	0.0045	1

[1]Potato is included for statistical accuracy only.

References: 1. Guderian (1977)
2. Godzik and Krupa (1982)

the field with industrial ambient sources of SO_2; exposures were chronic. Comparison of the experiments in these two reports must be conducted cautiously. Although the experiments are very similar, differences in crop sensitivity could arise from various factors. The two most important are environmental and source differences. As discussed earlier, environmental factors have an important role in plant sensitivities, having the capacity to either increase or decrease them. Neither report described any inordinate environmental conditions, but extreme changes during the growing season could alter plant susceptibility to SO_2. Source differences could also change crop sensitivity. Both of the experiments were conducted with ambient industrial sources of SO_2, but great differences in the accompanying contaminants could account for differences in changed sensitivities of the plant. Since the main effects due to the pollutants in the Guderian and Stratmann (1968) report could be attributable to peak concentrations, this sensitivity ranking would be more accurately applied to areas at considerable distances. The data from the experiments reviewed are summarized in Tables 24 and 25.

The reductions in yield from the experiments were plotted against the SO_2 concentrations for all experimental trials. The slope of the line (or the correlation between SO_2 concentration and reduction in yield) was calculated to give the index of sensitivity. Species with higher sensitivities have a greater slope of this line. Warteresiewicz's data (Godzik and Krupa 1982) produced higher sensitivity rankings than Guderian's (1977). The species in common between the two experiments are alfalfa and potato. The ratios of Warteresiewicz's sensitivity indices to Guderian's indices for these two species are 2.48 and 2.27 for alfalfa and potato, respectively, or an average of 2.4. We chose to multiply Guderian's sensitivity indices by 2.4 to parallel his indices with those of Warteresiewicz. This manner of combining the data is the more conservative of the two options in order to avoid underestimating the sensitivities of the agricultural species.

The results from this relative sensitivity ranking (Table 23) correlate with the observations of other investigators (Barrett and Benedict 1970; Tingey and Reinert 1975; Godzik and Krupa 1982), but there is a discrepancy with the alfalfa ranking. Several researchers have stated that alfalfa is one of the most sensitive of crop plants to SO_2 (Thomas 1961; Barrett and Benedict 1970; and Bialobok 1984). One would expect alfalfa to have a high sensitivity to SO_2 because when grown under ideal agricultural conditions, it receives high light intensity, high relative humidity, adequate soil moisture, and moderate temperatures - all conditions which favour decreased stomatal resistance (Thompson 1982). Thompson (1982) states that clover has two thirds the sensitivity of alfalfa based on one-hour exposures.

Because of the paucity of experiments on the effect of SO_2 comparing yield changes of grasses, grains, and forages, the comparison of sensitivities among these species is difficult. For this reason, grasses were not included in the sensitivity rankings. Perennial grasses (e.g., perennial ryegrass) are more sensitive to SO_2 than alfalfa (Thompson 1982). Annual grasses seem to be significantly less sensitive than alfalfa to SO_2. Tingey and Reinert (1975) observed a 26% decrease in alfalfa yield at a concentration of 0.05 ppm, whereas Ashenden and Williams (1980) observed a 28% and a 25% decrease in yield for Italian ryegrass, an annual ryegrass, and timothy at double the concentration (0.11 ppm). Both experiments were conducted in glasshouses over the

Table 24. Changes[1] in yield of three field grown crops under different concentrations of sulphur dioxide (growing season average).

Approximate SO_2 concentration (ppm)	Percent Change in Yield		
	Barley Grain	Alfalfa	Potato
.015	0.0	0.0	0.0
.029	2.0	0.8	5.3
.036	6.0	1.8	14.3
.038	7.8	+0.4	10.3
.040	9.8	1.4	14.0
.047	14.1	12.0	26.7
.058	20.3	14.3	37.0
.060	23.7	18.0	44.0
.062	28.2	23.7	47.3
.068	29.4	21.7	48.3
.079	45.3	30.0	59.0
.082	44.9	30.3	55.0

[1]Changes are reductions unless marked with "+"

Source: Godzik and Krupa (1982)

Table 25. Decreases in yield of various grains and forages exposed to different concentrations of sulphur dioxide (growing season average).

Crop	Percent Reduction Concentration of SO_2 (ppm) 0.010	0.020	0.051	0.083	0.141
Alfalfa	4.4	2.6	6.9	19.0	36.2
Oats	+2.4[1]	7.0	15.3	23.9	37.6
Red clover	3.3	1.2	9.5	36.4	69.8
Canola	3.2	4.3	8.6	9.1	30.7
Spring wheat	1.0	1.4	11.7	26.6	36.0
Winter rye	0.8	3.5	14.6	42.3	52.3
Winter wheat	1.2	8.0	15.0	44.4	52.3
Potato[2]	1.7	9.6	16.9	32.0	65.6

[1]"+" Signifies an increase in yield
[2]Potato data were used for statistical accuracy only

Source: Guderian (1977)

growing season. The latter experiments show alfalfa to be more sensitive to SO_2 than these two grass species.

From the above data it can be concluded that the forage, grain, and grass species can be ranked for relative sensitivities as follows:

clover > winter grains > spring grains > alfalfa > canola

and

winter grasses > alfalfa > other grasses

The position of alfalfa in the first ranking is not definite.

3.5.2 Nitrogen Dioxide

The effects of NO_2 on agricultural crops have been investigated by several researchers. These data were compiled by the National Academy of Sciences (1977b) to give a qualitative assessment of the sensitivities of various agricultural crops to NO_2 as shown in Table 26. Of the field crops and grasses, the leguminous forage crops and some grains (barley and oats) are the most sensitive. Of intermediate sensitivity are an annual grass (bluegrass [*Poa annua*]) and other grains (wheat, corn, and rye), and a tuber (potato). Considered resistant is a perennial grass (Kentucky bluegrass [*Poa pratensis*]). Of the garden or "truck" crops, a bulb crop (leek [*Allium porrum*]), a root crop (carrot [*Daucus carota*]), a leafy crop (lettuce), and a stem crop (celery [*Apium graveolus*]) are classified as sensitive. Of intermediate sensitivity are a fruit crop (tomato), and the same stem crop (celery), and considered resistant are two cole crops (cabbage and kohlrabi [*Brassica oleracea*]), the same root crop (carrot), and another stem crop (asparagus [*Asparagus* sp.]).

3.5.3 Ozone

Although studies on the effects of O_3 on the growth and yield of agricultural crops are voluminous, the data are inadequate for a conclusive ranking of species sensitivities. Experiments have been conducted with a variety of concentrations, for varied lengths of time, at various stages of development, and with additional variables. All these factors make absolute comparisons difficult.

Several agricultural species considered relatively sensitive to visible foliar injury are listed in Table 27. Their ranking as sensitive comes from field observations and observations from fumigation studies. The correlation between foliar sensitivity and growth and yield sensitivity is tenuous, however.

Crop response data were gathered by the US Environmental Protection Agency (1978) for acute (one-hour to eight-hour) exposures. The crops were divided by species and/or variety into three categories: sensitive, intermediate, and resistant. To assess the relative sensitivity of the species, the authors extracted the response and dose from these data, dividing the former by the latter to attain a sensitivity index. The sensitivity indices are summarized in Table 28. The crops with the highest indices are the crops with the greatest sensitivities. As can be deduced from this table, leafy vegetables are the most sensitive in all cases and perennials and woody species are the most resistant. For the sensitive and resistant plant types, grasses and legumes are

Table 26. Susceptibility to nitrogen dioxide of various agricultural species which occur in Alberta.

Plant Species	Susceptible	Intermediate	Resistant
Alfalfa	+		
Annual bluegrass		+	
Barley	+		
Kentucky bluegrass			+
Oats	+		
Potato		+	
Red clover	+		
Rye		+	
Sweet corn		+	
Wheat		+	
Asparagus			+
Cabbage			+
Carrot[1]	+		+
Celery[1]	+	+	
Kohlrabi			+
Leek	+		
Lettuce	+		
Onion			+
Tomato		+	

[1]Different investigators reported different susceptibilities

Adapted from the original table in Legge et al. (1980)

Source: National Academy of Sciences (1977b)

Table 27. Agricultural crops found in Alberta which are relatively sensitive to ozone.

Alfalfa (*Medicago sativa*)
Barley (*Hordeum vulgare*)
Bean (*Phaseolus vulgaris*)
Red clover (*Trifolium pratense*)
Corn, sweet (*Zea mays*)
Grass, bent (*Agrostis palustris*)
Grass, brome (*Bromus inermis*)
Grass, crab (*Digitaria sanguinalis*)
Grass, orchard (*Dactylis glomerata*)
Muskmelon (*Cucumis melo*)
Oat (*Avena sativa*)
Onion (*Allium cepa*)
Potato (*Solanum tuberosum*)
Radish (*Raphanus sativus*)
Rye (*Secale cereale*)
Spinach (*Spinacea oleracea*)
Tomato (*Lycopersicon esculentum*)
Wheat (*Triticum Aestivum*)

Source: Hill et al. (1970)

Table 28. Sensitivity indices for agricultural crops under acute ozone exposures.

Agricultural Crop	Sensitivity Index
Sensitive:	
Bean	127.57
Tomato	115.07
Grasses	83.72
Legumes	83.54
Oat	65.79
Intermediate:	
Vegetables	62.97
Wheat	52.45
Grasses	49.60
Clover	38.66
Legumes	38.94
Perennials	22.21
Resistant:	
Cucumber	22.90
Vegetables	16.98
Legumes	16.90
Grasses	9.92
Woody species	8.62

Source: US Environmental Protection Agency (1978) more sensitive than oats (a grain); but for intermediate plant types, wheat (a grain) is more sensitive than the grasses, which in turn are more sensitive than legumes and clover.

3.5.4 Hydrogen Sulphide

Insufficient data exist on the effects of H_2S on agricultural species to extract any useful sensitivity ranking of the species. The effects of H_2S on growth and yield are discussed in a previous section (3.3.4), to which the reader can refer for general H_2S effects, as well as the phytotoxicity of H_2S relative to SO_2.

3.6 EXPERIMENTAL DESIGN AND DATA INTERPRETATION

In order to interpret experimental data correctly, it is important to understand experimental design and how this design affects experimental results. Experiments testing the same hypothesis can have significantly different results by employing different experimental designs. Upon analyzing results from different experiments, what appear to be conflicting results could simply be the result of differences in experimental methods and procedures. The variety of experimental designs makes comparison among experiments very difficult and ambiguous. In this section, experimental design and how it influences data interpretation is summarized as it pertains to research on the effects of gaseous pollutants on agricultural plant species.

3.6.1 Pollutant

As discussed in the Introduction, a plant is affected by a gaseous pollutant in several ways: by the type or composition of pollutant (i.e., SO_2, NOx, O_3, or H_2S), the concentration of pollutant, the duration of exposure, the temporal sequence of exposures, and by fluctuations in pollutant concentrations. Pollutants may occur singly, in mixtures, or sequentially.

The amount of pollutant an experimental plant receives may depend on the gas flux. Gas flux, on a leaf area basis, is frequently less with field plants than with plants exposed in greeenhouses or in chambers. This phenomenon can be attributed to two factors. First, there is generally substantial air movement around each plant in chamber studies (and to a lesser extent greenhouse studies) because of vertical air movement. The air movement in field conditions tends to be horizontal and air is considerably more stagnant. Secondly, field experiments tend to have more dense vegetation than greenhouse and chamber studies. The field plants, therefore, are exposed to less gas than the dosage implies (Jacobson 1982).

3.6.2 Environment of Experiment

The experimental apparatus used in air pollutant-plant studies may affect plant response. For example, agricultural plants in general have a lower resistance to foliar injury when grown in controlled environments than when field-grown (Evans et al. 1981b; Irving and Miller 1981; Keever and Jacobson 1983b; Troiano et al. 1982; and Cohen et al. 1982). The various experimental structures are explained in this section.

3.6.2.1 Controlled environment experiments. A controlled environment is a uniform environment within a chamber or a greenhouse. The environment is designed to resemble ambient conditions with as little deviation as possible. In controlled environments the researcher is able to control, with a high degree of accuracy, the pollutant concentration, exposure duration, and frequency and sequence of exposures. They are well suited for studies to determine the mode of action of a pollutant, for cause and effect studies, and for hypothesis testing. Controlled environment experiments have the advantage of lending themselves to experimental replication.

The key differences between controlled-environment experiments and field experiments are in the degree to which the experimental type influences environmental conditions. These differences are especially evident in the changes in light, temperature, and relative humidity which can be regulated in controlled environments. These climatic conditions are more controlled in chamber studies than in greenhouse studies. Greenhouses have less deviation from natural conditions than do chambers.

Plants are usually grown in pots in controlled-environment experiments (though they may be grown in plots in greenhouses), thus creating another variation from field conditions. Plants in pots are growing under edaphic conditions different from those in the field; differences exist in soil temperature, soil moisture, and available root space, and depending on the potting mix, in nutrient composition.

Plants may appear more susceptible to pollutant injury in controlled environments than in natural conditions because (as discussed in the Introduction) plants in controlled environments receive a greater gas flux per leaf unit area.

3.6.2.1.1 Fumigation chambers. The highly controlled environmental conditions of chamber studies cause them to be the most removed from natural field conditions. It is difficult to draw correlations between chamber studies and ambient conditions. This is especially true with long-term or high concentration studies.

3.6.2.1.2 Greenhouses. Climatic conditions in greenhouses tend to be different from those in the field. Relative humidity and temperature tend to be higher and light quality and intensity are altered. As with chamber studies, it is difficult to extrapolate the results of greenhouse studies to field conditions.

3.6.2.2 Controlled field experiments. Controlled field experiments are well suited for growth and yield experiments, dose-response relationships, experiments over long periods of time, and for assessment of pollutant effects on plant communities. They provide a realistic assessment of plant susceptibility when applied to natural conditions. With these types of experiments there is a minimal influence by the experimental apparatus on the plant reaction. The experimental conditions resemble natural conditions.

Controlled field experiments cannot be reproduced easily, and when conducted with ambient pollutants as the source, they cannot be reproduced.

3.6.2.2.1 Open-top chambers. Open-top chamber experiments can be conducted in two ways: first, by pollutant addition to the experimental plots with controls of ambient or filtered air; and, secondly, by ambient pollutant exposure with the controlled plots having filtered air. Air flows into the bottom of the chamber and rises up, preventing ingression of outside air.

The advantage of open-top chambers relative to greenhouses is that the plants are exposed to the atmosphere: rain may enter, differences in irradiance are only slight, and there are no significant increases in temperature. The slight differences in light and temperature in open-top chambers may make a difference in studies during the winter.

Comparable studies revealed only small differences in microclimatic parameters and the growth and yield of plants in chambers without air filtration and adjacent plots without chambers (Heagle and Johnston 1979; Heggestad et al. 1980; Heck et al. 1982; and Montes et al. 1982).

Studies in open-top chambers are usually conducted in plots but may be conducted in pots.

3.6.2.2.2 Linear gradient system. The linear gradient system (Shinn et al. 1976) is a series of inflated polymer film tubes, under positive pressure to distribute either carbon-filtered air or polluted air over the plant. The system is positioned between the rows of crops with holes oriented toward the plant canopy.

Because plants can be exposed to a large range of gas concentrations simultaneously, this method allows statistical regression analysis of the dose-response data.

The linear gradient system has the advantage in that it has little effect on the growth conditions of the plot. One disadvantage that this system and the following one (the zonal air pollution system) have is the influence of wind on the pollution concentration and therefore lessened control over this parameter. When the air is stagnant, as is the case at night-time, the pollutant concentration tends to build up.

3.6.2.2.3 Zonal Air Pollution System (ZAPS). The zonal air pollution system (ZAPS) (Lee and Lewis 1978) consists of aluminum pipes suspended above the plant canopy. It relies on atmospheric diffusion to dilute very high concentrations of pollutants emitted from the pipes.

3.6.2.3 Natural field experiments. Natural field experiments are conducted in the field with an ambient pollutant source. Comparisons among the agricultural crops grown close to the pollutant source (and therefore exposed to a high concentration of the pollutant) and the crops grown progressively further from the source (with progressively reduced pollutant concentrations) are made. This type of experimentation lends itself to studies on primary pollutants (i.e., SO_2, NO_2, H_2S), rather than on secondary pollutants (i.e., O_3, PAN) whose concentrations may be higher away from the source. The advantages of this type of study are that it produces results that can be realistically applied to the field, it allows for an accurate and realistic interpretation of crop susceptibility, and it is well suited to long-term studies and studies of ecosystems.

3.6.3 Internal Factors of a Plant Species

Individual plant species, cultivars, and even individuals of populations react with different sensitivities to a given gaseous pollutant. For farmers in polluted areas, it is important to identify the sensitive and resistant varieties of a particular crop.

The relative plant susceptibility or resistance to gaseous air pollutants is based on the expression of genetic traits that may change during development, determining the sensitivity of an individual plant (Guderian 1985). Because of this, the stage of plant development and leaf age can influence plant sensitivity to varying degrees depending on the particular pollutant.

Plant sensitivity may be determined by leaf characteristics particular to a species or cultivar. The type and number of stomata are the most important of these characteristics.

3.6.4 External Factors

External factors that influence plant response to gaseous pollutants include environmental and edaphic factors, as well as agricultural practices such as fertilization and irrigation. Environmental factors include parameters that may affect plant response to gaseous pollutants such as light (photoperiod, light quality, and light intensity), temperature, air movement, and relative humidity. Edaphic factors important to plant response to gaseous pollutants are soil moisture and soil nutrient composition.

Any environmental factors that promote wide stomatal aperture, and thereby allow increased diffusion of gases into the leaf, will increase the effect of gaseous pollutants on the plant by affecting the quantity and rate at which the gas enters the plant and arrives at metabolic sites. (Some uptake of pollutants also occurs from moist cuticular surfaces, but is of minor significance.) As water potential increases (as with an increase in relative humidity), the stomata open; as water potential decreases, the stomata close. High temperatures (35°C and higher) usually induce stomatal closing. Stomata of most plants open at sunrise and close in darkness allowing for the entry of CO_2 needed for photosynthesis during the daytime (most succulents, cacti, and some tropical plants behave in the opposite manner, opening their stomata at night) (Esau 1977).

Environmental conditions that favour rapid growth, including high light intensity, high relative humidity, adequate soil moisture, and moderate temperature may increase susceptibility of plants to gaseous pollutant injury by promoting stomatal opening, and therefore rapid absorption of pollutant gases. This is especially critical in crops like alfalfa that require these environmental conditions for optimal growth (Thompson 1982).

Soil moisture can affect plant response to gaseous pollutant exposure. With reduced soil moisture, and consequent water stress in plants, plant stomata often close. This response decreases pollutant uptake which may explain why plants under these conditions show a decreased sensitivity to some gaseous pollutants (Legge et al. 1980)

Another edaphic factor that may influence a plant's response to wet and dry deposition is soil nutrition. Generally, plants that are given an adequate supply of nutrients are less sensitive to injury than plants with a deficient or an excess supply (Leone and Brennan 1972; Guderian 1977; Cowling and Koziol 1982). Plants grown in sulphur and nitrogen deficient soils will often respond with increased growth and yield when exposed to low concentrations of SO_2 and NO_x respectively. The same plants will show no change or decrease in growth and yield when exposed to the same fumigations in soils with sufficient nutrients. Edaphic factors may be altered by agricultural practices as well as by pollutants.

4. MIXTURES OF POLLUTANTS

This section details the effects of pollutant mixtures on vegetation. The increased phytoxicity of a given pollutant in the presence of another has become an important consideration when assessing the impact of pollutants on vegetation.

Interactive effects of pollutants in combination can be described as follows:

(1) The plant response to the pollutant mixtures is additive, and is similar to the summed effects of the individual pollutants.

(2) The plant response may be antagonistic (less than additive). The response to the pollutant combination is less than the summed responses to the individual pollutants.

(3) The plant response may be synergistic (greater than additive) where the response to the pollutant combination is greater than the summed effects of the individual pollutants (Guderian 1985).

In addition, in sequential exposures, plants may become sensitized or hardened to a pollutant by a previous exposure to a different pollutant (Guderian 1985). Changes in injury type may also occur in plants exposed to pollutant mixtures compared to single pollutants; this response is discussed more thoroughly in the section on foliar injury. Plant responses to pollutant combinations depend not only on the components of the mixtures and their temporal succession, but also on the same factors that influence plant response to single pollutant exposure.

4.1 INTERACTIONS BETWEEN GASEOUS POLLUTANTS

Frequently, elevated concentrations of more than one gaseous pollutant exist as the result of atmospheric mixing, the emissions of a pollutant into already polluted air, the simultaneous emission of more than one pollutant, or the chemical interconversion of different pollutants. Most pollution sources emit more than one pollutant. These mixed emissions may be simultaneous or sequential over time (Runeckles 1984; Runeckles 1986). In this section, mixtures of SO_2, O_3, and NO_2 will be discussed.

Sulphur dioxide from combustible fuel sources and O_3 produced photochemically are the two pollutants most frequently found as a mixture in ambient atmospheres. Because NO_2 is also produced from combustible fuels, it is a third pollutant to consider in pollutant-mixture studies and evaluations (Reinert and Sanders 1982). The potential for synergistic responses from mixtures of NO_2 and SO_2 is considered to be the most important way that NO_2 reacts in the atmosphere with vegetation (Taylor 1984).

The mechanisms for injuries from mixtures of pollutants are not well understood, although they are being investigated. It can be assumed that the injury processes are governed by the same general processes that govern plant responses to single pollutants (Guderian 1985). As with single pollutant exposures, there does not seem to be any direct correlation between visible symptoms and growth effects (Tingey et al. 1971a,b, 1973a,b; and Mandl et al. 1973). It has been observed that the growth of roots is often inhibited more than that of other plant parts by mixtures of pollutants relative to single pollutant exposures (Ormrod 1984).

Careful attention must be paid to the relative concentrations of pollutants used in pollutant mixture studies. Concentrations employed in experimental exposures may or may not be representative of the concentrations of the area of interest. Relative concentrations of SO_2, NO_2, and O_3 vary with distance from emission sources.

4.1.1 Mixtures of Sulphur Dioxide and Ozone

4.1.1.1 Effects on Physiology. Beckerson and Hofstra (1979a,b) studied the effects of SO_2 and O_3 (at concentrations of 0.15 ppm for each gas) on stomatal conductance in radish (cv. Champion), cucumber (cv. National Pickling) and soybean (cv. Harosoy 63) and reported that SO_2 alone stimulated stomatal conductance, O_3 alone inhibited stomatal conductance, but a mixture of the two gases inhibited stomatal conductance to a greater degree than the exposure of O_3 alone.

4.1.1.2 Foliar Effects. In general, the foliar symptoms characteristic of O_3 injury are observed in plants exposed to a mixture of O_3 and SO_2 (Menser and Heggestad 1966; Menser and Hodges 1970; Tingey et al. 1971b; Tingey et al. 1973c; Heagle et al. 1974; and Elkiey et al. 1979).

In some cases, foliar symptoms may be observed as distinct from those found in exposure to either O_3 or SO_2 alone. Grosso et al. (1971) reported a general flecking or diffuse bleaching of upper leaf surfaces of all tobacco cultivars, whereas O_3 alone produced punctate flecking. Kender and Spierings (1975) and Shertz et al. (1980) reported distinctive symptoms of leaf injury to apple trees (cv. Golden Delicious) where development of large greyish-green water-soaked areas in the midshoot leaves was observed. With SO_2 and O_3 exposures of petunia (*Petunia* sp.), Lewis and Brennan (1978) observed an undersurface glazing, a symptom usually attributed to peroxyacetyl nitrate (PAN) exposure. After exposure to SO_2 and O_3, interveinal necrosis, a symptom not usually found after exposure to either gas singly, was observed in cucumber (Beckerson and Hofstra 1979a,b).

Foliar injury can be affected synergistically, additively, or antagonistically. Most of the studies indicate an antagonistic interaction between SO_2 and O_3 on foliar injury.

Two species that showed synergistic responses to foliar injury are tobacco (Menser and Heggestad 1966) and cucumber. In addition, the injury threshold for tobacco was decreased. Soybean (Hofstra and Ormrod 1977; Heagle and Johnston 1979), three cultivars of bean (Jacobson and Colavito 1976; Hofstra and Ormrod 1977), radish, and marigold (*Tagetes* sp.) (Reinert and Sanders 1982) showed antagonistic responses for foliar injury during SO_2 and O_3 exposures. Soybean showed a synergistic response at very low concentrations.

4.1.1.3 Effects on growth and yield. Various studies have shown that a synergistic response of decreased plant growth and yield can occur at low concentrations (at or below the threshold for visible injury) of SO_2 and O_3. This response is observed more often than an antagonistic response, but less often than an additive one. Growth and yield of various agricultural crops were influenced by a mixture of these two gases in the following studies. The mixture of SO_2 and O_3 (at concentrations ranging from

0.05 ppm to 0.10 ppm of each gas) reduced the yields of soybean, radish root, and tobacco leaf weight in an additive manner. Soybean root fresh weight was suppressed synergistically (Tingey et al. 1971a, 1973c).

Heggestad and Bennett (1981) observed a synergistic decrease in snapbean yields of all cultivars when exposed to 0.30 ppm SO_2 in the presence of O_3 (relative to exposures of SO_2 with O_3 excluded). Kidney bean, when exposed to a range of O_3 concentrations and 0.1 ppm SO_2, responded with a synergistic decrease in pod weight and weight and number of seeds (Oshima 1978).

Shew et al. (1982) observed a synergistic reduction in weight of the largest tomato of each cluster on tomato plants. The combined gases, however, had no effect on the total fruit weight per plant.

Foster et al. (1983) reported that there was an additive interaction of SO_2 and O_3 on potato (tuber) yield reduction.

Fescue (Festuca pratensis), exposed to long-term fumigations of SO_2 (concentrations of 0.0 and 0.1 ppm) and O_3 (four concentrations ranging from 0.0 to 0.3 ppm), showed an additive reduction in total dry weight and a decrease in the root/shoot ratio (Flagler and Younger 1982).

Soybeans exposed to varying concentrations of SO_2 (0.0 to 0.37 ppm) and O_3 (0.0 to 0.07 ppm) showed an additive interaction between the gases at low concentrations; but at higher concentrations the interaction was antagonistic for seed weight per metre row (Heagle et al. 1983b).

4.1.2 Mixtures of Sulphur Dioxide and Nitrogen Dioxide

The phytotoxic interactions between SO_2 and NO_2 are the most thoroughly researched of the pollutant mixture interactions. Because ambient concentrations of NO_2 rarely approach the injury threshold, potential interactions with other pollutants are a primary concern.

Researchers have reported a variety of interactions between these two gaseous pollutants ranging from synergism to antagonism. Most researchers have reported additive or synergistic effects (Tingey et al. 1971b; Bull and Mansfield 1974; Hill et al. 1974; Masaru et al. 1976; Ashenden and Mansfield 1978; Ashenden 1979; Ashenden and Williams 1980; Irving et al. 1982; and Reinert and Sanders 1982), and a few have observed antagonistic effects (Thompson et al. 1980; Reinert and Sanders 1982; and Whitmore and Freer-Smith 1982).

4.1.2.1 Physiological effects. In studies with pea (Pisum sativum), Bull and Mansfield (1974) found an additive interaction in the effects of SO_2 and NO_2 on photosynthesis. Over a few hours photosynthesis was initially stimulated, but this was short-lived; the final effect was an inhibition of photosynthesis. Ashenden (1979) found that although transpiration was stimulated when bean plants (Phaseolus vulgaris) were exposed to SO_2 and NO_2 singly (at concentrations of 0.1 ppm), the combined effect of the gases was to decrease transpiration.

4.1.2.2 Foliar effects. Symptoms of injury resulting from the pollutant mixture of SO_2 and NO_2 often resemble foliar injury caused by O_3. This similarity makes identification of the cause of pollutant injury difficult. Tingey et al. (1971b) observed synergistic injury on the adaxial surface from the combined gases, SO_2 and NO_2, that differed greatly from either pollutant alone, and generally resembled foliar injury caused by O_3. Injuries included chlorotic and necrotic flecking of the surface of the interveinal areas in tomato, radish, oats, and tobacco; but in pinto bean and soybean, foliar injury was a reddish-brown stipple. The visible injury threshold for the most sensitive agricultural species is between 0.05 ppm and 0.10 ppm for each gas, when SO_2 and NO_2 are present together (Tingey et al. 1971b).

Reinert and Sanders (1982) also found a synergistic interaction between these gases with respect to visible foliar injury on radish. Hill et al. (1974) found additive effects on foliar injury in their experiments with 87 desert species from the southwest US. Marigolds were reported to suffer less than additive foliar injury with exposures to SO_2 and NO_2 at concentrations of 0.3 ppm (Reinert and Sanders 1982).

4.1.2.3 Effects on growth and yield. Ashenden and Mansfield (1978) exposed four grass species to SO_2 and NO_2 in long-term exposures (at concentrations of 0.068 ppm) and found that reductions of total dry weight were affected synergistically in orchard grass (*Dactylis glomerata*), Italian ryegrass, and timothy, but only in an additive manner in Kentucky bluegrass.

In studies of Kentucky bluegrass, the dry weight of roots was first affected synergistically, then additively, and finally the grass recovered and showed an antagonistic response. This study was conducted in pots in a glasshouse and the researchers suggested that the grass may not have recovered in the field where competition with other plants exists and where environmental factors may cause additional stress (Whitmore and Freer-Smith 1982).

Studies on soybean (Irving et al. 1982) showed a synergistic reduction in seed yield after various exposures to SO_2 concentrations ranging from 0.06 to 0.40 ppm and NO_2 concentrations ranging from 0.13 to 0.42 ppm. Reinert and Sanders (1982) reported an antagonistic interaction on reduction of root and shoot weight studies with marigold. In experiments with ten species from the Mojave Desert, Thompson et al. (1980) also found an antagonistic interaction on growth and yield in some instances, especially with annuals. However, most interactions observed in these studies were additive.

4.1.2.4 Effects on reproduction. Few data are available on the effects of SO_2 and NO_2 on reproduction. Pollen tube growth was reduced synergistically in a lily species after 30 to 60 minutes exposure of an SO_2/NO_2 concentration ratio of 0.24 ppm/0.12 ppm (Masaru et al. 1976).

4.1.3 Mixtures of Nitrogen Dioxide and Ozone

The gaseous pollutant mixture of NO_2 and O_3 is the least studied of the three two-pollutant mixtures discussed here. Further research is necessary to assess the importance of this mixture.

4.1.3.1 Foliar effects. Synergistic, additive, and antagonistic interactions have been observed in foliar injury caused by exposures to NO_2 and O_3. Synergistic responses were seen in marigold (Reinert and Sanders 1982), and additive responses were observed in eight out of ten tree species studied by Kress (1980), whereas in the other two tree species an antagonistic response was observed. Radish was reported to have an antagonistic interaction for foliar symptoms due to NO_2 and O_3 (Reinert and Sanders 1982). Matsushima (1971) reported an antagonistic response for tomato and pepper (Capsicum frutescens) when exposed to a mixture of NO_2 (1.5 ppm) and O_3 (0.4 ppm).

4.1.3.2 Effects on growth and yield. As stated earlier, the temporal sequence of exposures is important. Runeckles et al. (1978) exposed wheat (cv. Sun) and radish (cv. Cherry Belle) to NO_2 and O_3 at concentrations of 0.1 ppm each and reported that both species increased in sensitivity to O_3 with exposure to NO_2.

Tree species have reacted in varying ways to exposures of NO_2 and O_3 mixtures. Kress and Skelly (1982) found Virginia pine (Pinus virginiana) and loblolly pine (Pinus taeda) growth (plant height) was significantly suppressed by the mixture but not by the pollutants separately. In sweetgum (Liquidambar sp.) the suppressed accumulation of root and total dry weight, and in white ash, the reduction of total dry weight were antagonistic.

4.1.4 Mixtures of Sulphur Dioxide, Nitrogen Dioxide, and Ozone

The last mixture of gaseous pollutants discussed in this section includes SO_2, NO_2, and O_3. Research is in its initial stage in this area relative to the research conducted on the other pollutant mixtures.

4.1.4.1 Foliar effects. Pollutant combinations containing O_3, including the mixture of O_3, SO_2, and NO_2, cause foliar injuries similar to those seen when O_3 is present singly.

Both marigold and radish showed an antagonistic response to foliar injury when exposed to equal concentrations (0.3 ppm) of SO_2, NO_2, and O_3 (Reinert and Sanders 1982).

4.1.4.2 Effects on growth and yield. The effects on growth and yield due to the pollutant mixture of SO_2, O_3, and NO_2 have not been thoroughly studied. Researchers have found that in nearly every instance, exposure to the three pollutants causes a greater loss in plant growth and yield than exposure to the single gases or to the two-pollutant mixtures. Studies conducted thus far have been important because they have shown that growth and yield responses to this mixture occur in the NO_2 concentration range of 0.05 to 0.30 ppm, well below the air quality standard for NO_2 and within ambient elevated NO_2 concentrations. The decrease in growth and yield caused by NO_2 in the presence of SO_2 and/or O_3 ranges from 5% to 20% at concentrations of NO_2 that cause little or no injury when the pollutant is present singly (Reinert 1984).

4.2 INTERACTIONS BETWEEN GASEOUS POLLUTANTS AND WET ACIDIC DEPOSITION

Studies on the effects of combined exposures of wet acidic deposition and gaseous pollutants on plants are only in their initiation. The studies thus far generally indicate synergistic and additive interactions. The interaction between gaseous pollutants and wet acidic deposition is significant because these pollutants usually occur concurrently. Studies of their interactions when present together and in sequence with each other are described below.

4.2.1 Foliar Effects

In experiments using mixtures of simulated acidic precipitation and O_3, Shriner (1983) reported an additive response for foliar injury in radish (cv. Scarlet Globe) at various simulated precipitation rain pH's and at various O_3 concentrations. He also reported an additive reduction in the chlorophyll content of the second and fourth leaves
of radish. Older leaves showed a synergistic response for foliar injury. An additive response for foliar injury was also observed in radish when exposed to a mixture of wet acidic deposition and SO_2.

Experiments for foliar injury conducted with soybean (Norby and Luxmoore 1983) showed no interaction between wet acidic deposition and a gaseous mixture of O_3 and SO_2.

4.2.2 Effects on Growth and Yield

Shriner (1983) showed an additive response in yield (dry weight of leaves and root) of radish (cv. Scarlet Globe) when exposed to various mixtures of simulated acid precipitation and O_3. Loblolly pine also showed an additive response for growth and yield with the same mixtures. Kidney bean showed a synergistic decrease in foliar dry weight with the same pollutant mixtures (Shriner 1978a). Radish showed an additive response when exposed to wet acidic deposition and SO_2.

Irving and Miller (1981) reported an additive interaction between wet acidic deposition and SO_2 on seed yield of soybean. An additive interaction between wet acidic deposition and a gaseous mixture of SO_2 and O_3 on growth and yield was observed in experiments with soybean (Norby and Luxmoore 1983), whereas Troiano et al. (1982) found a synergistic reduction in growth and yield (weight of pods, weight of seeds, number of pods, and number of seeds) in soybean when exposed to a mixture of wet acidic deposition and O_3. This discrepancy could be due to the fact that Norby and Luxmoore's experiments were pot studies conducted in fumigation chambers, while Troiano et al.'s experiments were conducted in the field with open-top fumigation chambers.

5. EFFECTS OF ACIDIC DEPOSITION ON PLANT-SOIL INTERACTIONS

5.1 INTRODUCTION

This section will address the effects on agricultural crops of changes in soil induced by acidic wet deposition or gaseous pollution. Changes in the soil as a medium for plant growth will change the suitability of the soil for specific crop species, and are considered below. The effect of air pollution and acid deposition on agricultural soils is the subject of numerous review articles (Prince and Ross 1972; McFee 1980, 1983) and experiments (Laverty and Carson 1977; Nyborg and Crepin 1977), and is considered specifically for Alberta, Canada, by Turchenek et al. (1987).

5.2 EFFECTS ON SOILS

Short-term impacts of acid rain or gaseous pollutants on agricultural soils will be small on intensively managed soil systems (Evans et al. 1981a; McFee 1983; Olson 1983; Coleman 1983; Cole and Stewart 1983; and Mortvedt 1983). Agricultural practice maintains the soil with a high buffering capacity against changes in the pH or nutrient cycling (Mortvedt 1983). The amount of nitrogen and sulphur deposited by ambient, acidic rainfall is on the order of 1% of the amount added as fertilizer and fungicide under standard agronomic practices (Jones and Suarez 1979; Evans et al. 1981a; and McFee 1983). At current or projected levels of ambient acidity, N and S deposited in acidic wet deposition will act as fertilizer supplements rather than as toxins, on soils of all degrees of management (Jones and Suarez 1979; Sandhu et al. 1980). The greater potential for toxicity lies in the free hydrogen concentration of wet acidic deposition. However, current agricultural practices have a much greater effect on soil pH than does atmospheric deposition. Estimates are that the H^+ flux from heavily acidified rain would be only 1% of the total H^+ flux from nitrogen fertilizers (Plocher et al. 1985). McFee (1983) estimates that ambient acidic inputs are 1 to 2 orders of magnitude smaller than the acidic or alkaline inputs from common agricultural practices such as N-fertilization, S-fungicide, and liming. From season to season the soil pH and nutrient status are maintained against changes due to utilization and, coincidentally, atmospheric deposition.

On less intensively managed lands, on long-term fallow lands, or on unimproved lands, acidic precipitation could have a significant effect on soil quality that could reduce the soil's fertility. While acidification is prevented or managed on agricultural soils, it is essentially irreversible in uncultivated areas (McFee 1980). Generalized responses of the soil environment to natural or anthropogenic changes in soil pH are summarized in Figure 1, from Brady (1974). The most likely changes in soil characteristics are a rise in acidity in the soil solution, a rise in exchangeable aluminum, zinc, copper, manganese, iron, and other transition metals, and a change in the composition of the exchangeable ion complex with a concomitant decrease in base saturation capacity (Russell 1973; Agrawal et al. 1985). The effect of increased deposition of atmospheric SO_2 on soil is similar, resulting in a pH decrease with associated increases in exchangeable aluminum and decreases in available N, P, K, and Ca (Lee et al. 1982; Heagle et al. 1983a; and Agrawal et al. 1985). Total sulphur and organic carbon in the soil are also increased by SO_2. Other effects on nutrient cycling and soil structure produced by soil acidification from acidic deposition include increased nutrient

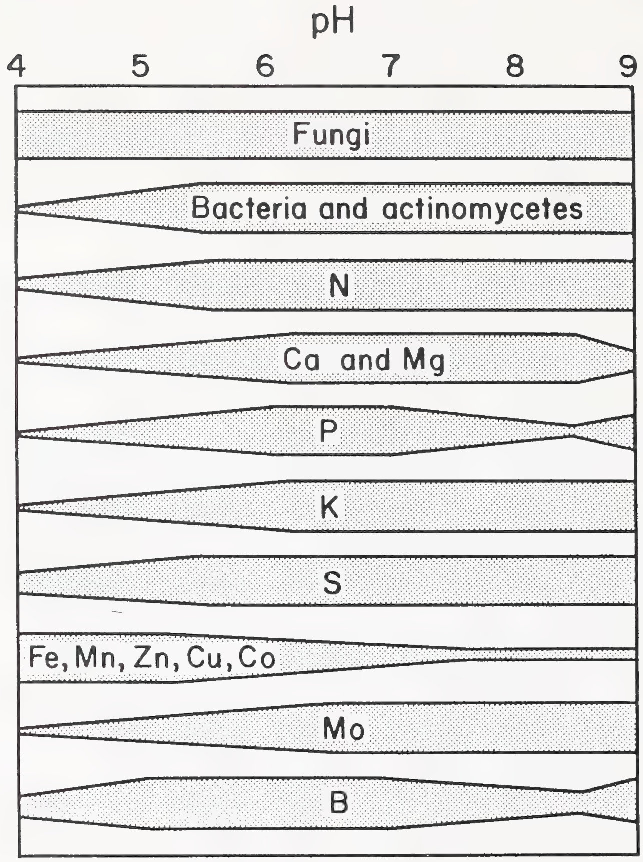

Figure 1. Relationship between soil pH and activity of microorganisms and availability of plant nutrients.
Source: Brady (1974)

leaching and inhibition of microbial activity, such as litter decomposition and nitrification (Agrawal et al. 1985). The mechanisms of change, and a more thorough description of soil changes, are discussed by Turchenek et al. (1987).

Very few articles were found that addressed the potential for pollution-induced changes in plant growth that could alter the plant's interaction with the soil. Irving and Miller (1981) measured soil sulphur after soybeans that were exposed to a gradient of pH values were harvested. Soil S was decreased in those plots receiving pH 5.6 simulated acid rain, or no rain, but not in plots receiving pH 3.0. In addition to the direct deposition of sulphur, foliar fertilization by the acidic treatment may have decreased S uptake by roots (Irving and Miller 1981).

5.3 EFFECT OF ALTERED SOIL ENVIRONMENT ON PLANTS

The threshold for direct toxicity to plants from soil solution acidity is at pH 3.0 (Russell 1973). Long before the soil becomes this acidic, related changes in the soil will render the soil unsuitable for most crops; these secondary effects are the primary route by which soil acidity is harmful (Russell 1973). The soil pH controls the concentration of ions in the soil solution, and so controls their availability to the plant. High aluminum concentration is the most common cause of crop failure on acidic soils (Russell 1973). Aluminum harms plants in two ways; aqueous aluminum in free root surface spaces may inhibit root uptake of phosphates and sugar phosphorylation may be inhibited by intercellular aluminum. Manganese toxicity can result from the excessive plant uptake of manganese associated with increased acidity (Russell 1973).

The toxicity of copper, zinc, or nickel depended only on the concentration in the leaf tissue and was independent of growth conditions in the five crop species studied by Davis and Beckett (1978). The rate of uptake, and the concentration in the tissue, did vary with growth conditions and concentration in the soil solution. Table 29 summarizes the data on toxicity of Cu, Ni, and Zn based on the work by Davis and Beckett (1978). At concentrations in the leaf tissue above the toxic level, reduction in yield was proportional to the log of the tissue concentration.

Nutrient requirements and tolerance of plants to metals differ considerably among species and even among cultivars. Little is known about the mechanisms that control this tolerance (Davis and Beckett 1978). Given the general soil characteristics associated with soil pH ranges, plants have been graded with respect to their tolerance of soil acidity. Crop tolerance of three acid-induced changes in soil are presented in Table 30. Recommended crops for different soil acidities are shown in Table 31 for Great Britain, and in Table 32 for Alberta. Oats (*Avena sativa*) are a good species for acid soils as they have low calcium requirements and tolerate high concentrations of aluminum and manganese (Russell 1973). Some common plants that prefer neutral soils are alfalfa, barley, beans, and sugar beets. Alkaline-adapted plants grown on acidic soils suffer from excessive aluminum uptake and deficiencies in phosphate and calcium. Although most soils contain moderate amounts of calcium, aluminum can interfere with calcium uptake enough to result in calcium deficiencies.

A pollutant's impact on plant nutrition may be two-fold: SO_2 deposition causes changes in the composition of ions available in the soil solutions, and SO_2

Table 29. Toxic concentration of copper, nickel, or zinc in leaf tissue.

Species	Cu	(ppm) Ni	Zn
Spring barley	19	12	210
Ryegrass	21	14	221
Lettuce	21		
Canola	16		
Wheat	18		

Source: Davis and Beckett (1978)

Table 30. Plant sensitivity to acid-induced changes in the soil environment.

Aluminum tolerance	Oats >> potatoes >> beets
Manganese tolerance	Oats >> beets >> potatoes
Calcium demand	Beets = potatoes >> oats

Source: Russell (1973)

Table 31. Crop-soil recommendations for Great Britain.

Soil Acidity	Crops Recommended
Neutral to low acidity	Alfalfa Barley Sugar beet
Medium acidity	Peas Red clover Wheat
High acidity	Oats Rye White clover

Source: Russell (1973)

Table 32. Sensitivity of cereal and range crops to soil acidity in Alberta.

	Pot-Grown	Field-Grown
Very high sensitivity	Alfalfa	Alfalfa
High sensitivity		Galt Barley
Medium sensitivity	Olli Barley Canola	Olli Barley Canola
Low sensitivity	Oats	Red Clover

Source: Sandhu et al. (1980)

exposure interferes with nutrient uptake (Agrawal et al. 1985). A review of environmental sulphur research in Alberta, Canada (Sandhu et al. 1980) found that the potential effect of sulphur emissions on agriculture was often greater through effects on soil acidity rather than through direct interaction with foliage. Soil acidity is a significant factor in the growth of cereal and range crops, which are the dominant agronomic species in Alberta (Alberta Agriculture 1982). The data for Table 33 on crop sensitivity are based on studies using soil of pH 5.0 and a control soil of pH 6.0 (Sandhu et al. 1980). A drop of 1 pH unit would preclude growth of alfalfa in Alberta soils, and limit the range of barley.

Data collected in South Carolina (Jones and Suarez 1979) showed that cotton (Gossypium sp.) and soybean grew poorly when planted on orchard sites that had received 200 kg ha^{-1} y^{-1} S-fungicide. Chemical transformations of S, e.g., S from S-fungicide, in the soil resulted in the input of free hydrogen (Russell 1973). In the 0 to 30 cm soil layer on the South Carolina sites, soil S, soil pH, and soil Al were significantly correlated with each other and with aluminum concentration in leaf tissue. The higher foliar aluminum concentration was correlated with higher tree mortality (Jones and Suarez 1979).

Because the harmful effects of soil acidity on crop growth are not directly due to the H^+ concentration in the soil solution, there can be no exact relation between the pH of a soil and its suitability for a given crop (Russell 1973).

5.4 EFFECT OF ALTERED SOIL ENVIRONMENT ON SOIL ORGANISM-PLANT INTERACTIONS

The pH of the soil influences the success of soil-borne organisms. Soil organisms may be either beneficial or harmful to plants. Some soil organisms are at an advantage in acidic soils; others are inhibited by acidity. Therefore, the net effect of acid deposition or gaseous pollutant exposure on plant health will encompass four factors: (1) the deleterious effects on commensalists or mutualists; (2) the stimulation or inhibition of pests; (3) the stimulation or inhibition of plant health; and (4) the effects of altered plant biochemistry on plant-organism interactions.

The following empirical results illustrate potential effects of soil acidification on plant health:

(1) Brassica crops are more vulnerable to club-root, or finger-and-toe (Plasmodiophora brassica) in acidic soils.

(2) Potatoes are less likely to get scabs in acidic soil, because the actinomycete Streptomyces scabies is inhibited below the neutral pH range (Russell 1973).

(3) Legume rhizobium may be inhibited by acidity; the number of nodules per plant for both soybeans and kidney beans was reduced by plant exposure to pH 3.2 acid rain in greenhouse and field studies (Shriner and Johnston 1981). Plant exposure to acid rain inhibited formation of nodules but did not significantly affect nodule development or nitrogenase activity (see Table 34). This three-part experiment applied acid either to the soil, to the foliage, or to both. The greatest decrease in nodules was found in the foliage-only exposure plants, while soil-only showed the least effect. The pH of the soil did not change appreciably during the nine-week study.

Table 33. Effect of drop of 0.1 unit in soil pH on barley and alfalfa yield.

Crop	Initial pH Range	Reduction in Yield
Barley	5.2 - 5.5	161 kg/ha
Alfalfa	5.5 - 6.0	448 kg/ha

Source: Sandhu et al. (1980)

Table 34. pH threshold for reduction in nodulation.

Crop	pH	Reference
Alfalfa	5.6	1
Red clover	5.0	1
Kidney bean	3.2 (74% lower than pH 6.0)	2
Soybean	3.2 (73% lower than pH 6.0)	2

References: 1. Sandhu et al. (1980)
2. Shriner and Johnston (1981)

(4) Ozone exposure caused a decrease in nodule number in soybean rhizobium, accompanied by decreased soybean growth. Ozone did not affect nodular activity or size (Tingey and Blum 1973). The effects of air pollution on soil organisms are reviewed in the publication by Visser et al. (1987).

5.5 RECLAMATION AND MITIGATION

Acid soils can be reclaimed with at least partial success in most cases, although the cost can be large. The literature on the cost, efficacy, and secondary effects of liming soils for reclamation is voluminous and will not be reviewed here. Many acid-tolerant cultivars have been developed as a cultural response to natural and anthropogenic acidity problems. These varieties may require different agronomic practice in irrigation, fertilization, and so on. The use of acid-tolerant cultivars will allow continued production on acidified soils and decrease farm expenses necessary for liming or amending soil (Duncan 1982). Air quality regulating agencies or farmers may, however, become complacent about pollution-induced changes in soil fertility. These changes will limit the economic and ecological options in crop selection and modes of production. While acid-tolerant species may mitigate economic effects of soil acidification on farming, they do not ameliorate the damage to the cultivation environment.

6. EFFECTS OF ACIDIC DEPOSITION ON PLANT-SYMBIONT INTERACTIONS

6.1 INTRODUCTION

This section will consider the effects of acidic precipitation, sulphur dioxide (SO_2), nitrogen oxides (NOx), and ozone (O_3) on the life cycle of pathogens, on plant vulnerability to pathogens, and on plants as hosts for beneficial organisms. A better understanding of the entire complex of interactions between pollution, plant, and pathogen is needed to address the agronomic response to atmospheric pollution in a comprehensive manner. A general overview of some of the literature pertaining to the pollution-plant-pathogen relationship is attempted here in order to assess more effectively the possible directions that future research might take and to consider the potential damage from changes in atmospheric quality. Table 35 provides a comprehensive list of experiments done before 1982 with O_3, SO_2, and acidic precipitation on agricultural crops and their pathogens.

6.2 EFFECTS ON PLANT RESISTANCE

The effect of pollutants on host plant integrity and resistance to disease, and the effect of pollutants on the plant pathogens themselves have received greater attention in recent years. Although there are reviews on these subjects (Shriner 1977, 1978b, 1980; Shriner and Cowling 1980; Laurence 1981; Hughes 1983; Hughes and Laurence 1983; and Laurence et al. 1983) and experimental reports (Hughes et al. 1981, 1982, 1983; Troiano and Butterfield 1984) the literature is still rather limited. Table 36 summarizes changes in the plant likely to affect plant-pathogen interaction. Increases in plant disease occur when plant defenses are weakened or pathogen ability to invade is enhanced. It is generally recognized that pollution weakens, directly or indirectly, a wide variety of plants (Hughes and Laurence 1983). Leaf surface changes by wet and dry deposition of atmospheric pollution are perhaps the most important pathway for modification of host-parasite relations (Shriner 1980). Direct effects of acidic precipitation on foliage have been documented by a number of researchers. Shriner (1980) discusses the types of changes and effects that occur at the cuticle of the leaf and notes that they are of fundamental importance in evaluating the impact of pollutants on the host-pathogen relationship. The necrotic lesions caused by pollution are generally thought to favour bacterial plant-pathogens which enter the plant by colonization of dead tissue (Shriner and Cowling 1980). Shriner (1980) has documented increased penetration by the pathogen _Pseudomonas phaseolicola_ due to foliar injury of red kidney bean by pH 3.2 simulated acid rain. Shriner and Cowling (1980) point out that weathered surfaces generally pose a less formidable barrier to penetration by bacterial pathogens. Shriner and Cowling (1980) showed that acid-weathered leaves had increased wettability resulting in more water-borne propagules remaining on the leaf surfaces, and a favoured penetration potential. Weathered leaf surfaces foster infection courts (e.g., lesions) due to acid-induced foliar damage. One threshold for this effect was given as pH 3.4 or below (Shriner and Cowling 1980).

Table 35. Effect of pollutants on plant-pathogen interactions.

Plant/Pathogen	Exposure[1]	Effect on Disease	Effect on Pollutant Injury	Ref.
OZONE				
Barley/ Erysiphe graminis	S	Reduced infection from exposed spores, colony size reduced. Multiple exposure caused increases in colony size.		1
Wheat/ Puccinia graminis	S	Reduced sporulation.		2
Oats/P. coronata	S	Reduced sporulation.		2
Oats/P. coronata	S	Reduced growth of uredia.		3
Wheat/P. graminis	A	Decreased growth of hyphae. Decreased number of spores. Reduced infection.		4
Wheat/P. graminis	A		Reduced O_3 sensitivity.	5
Corn/ Helminthosporum maydis Race T	S	a) 18 pphm increased colony size b) 12 pphm increased number of spores		6
Geranium/Botrytis cinerea	A	Reduced sporulation. Reduced infection by exposed spores.		7
Geranium/B. cinerea	A	Flocculent material produced.		8
Broad bean/B. cinerea			Reduced O_3 sensitivity.	9
Potato/B. cinerea		Increased disease development. Predisposition to infection.		10
Geranium flowers/ B. cinerea	A	Reduced disease development.		11
Geranium leaves/ B. cinerea	A	Increased disease development.		12
Poinsettia/ B. cinerea	A	No effect on disease development.		9
Pinto bean/Root inhibiting fungi	A	Increased number of fungal colonies. Decreased nodulation.		13
Cabbage/Fusarium oxysporium	S	Decreased disease development slightly.		14
Rose/Diplocarpon rosae	S	Reduced disease development.		4

continued...

Table 35 (Continued).

Plant/Pathogen	Exposure[1]	Effect on Disease	Effect on Pollutant Injury	Ref.
OZONE				
Tobacco/Tobacco mosaic virus	F		Reduced O_3 sensitivity.	15
Tobacco, Pinto bean/ Tobacco mosaic virus	A		Reduced O_3 sensitivity.	16
Pinto bean/bean common mosaic virus	A		Reduced O_3 sensitivity.	12
Pinto bean/alfalfa mosaic virus, tobacco ringspot virus, tobacco mosaic virus, tomato ringspot virus	A		Reduced O_3 sensitivity.	13
Tobacco/Tobacco etch virus	A		Reduced O_3 sensitivity.	17
Tobacco/Tobacco streak virus	A		Increased O_3 sensitivity.	18
Soybean/*Rhizobium japonicum*	A	Root growth and nodulation reduced.		19,20
Alfalfa/*Xanthomonas alfalfa*	A	Reduced disease development.	Reduced O_3 sensitivity.	21
Kidney bean/*Pseudo monas phaseolicola*	A		Reduced O_3 sensitivity in halo.	22
Soybean/*Pseudomonas* sp.	A	Increased and modified Hypersensitive reaction (HR) (Pre-exposure inoculation). No HR (Post-exposure inoculation).	Inoculation 24 h before exposure prevented O_3 injury.	23
Soybean/*P. glycinea*	A	Reduced disease incidence.	No effect.	24
Wild strawberry/ *Xanthomonas fragaiae*	A S	Reduced disease incidence. No effect.	No effect.	25
SULPHUR DIOXIDE				
Wheat/*Puccinia graminis*	S	Reduced disease development.	No effect.	26
Corn/*Helminthosporium maydis*	S	Reduced disease development.		26
Bean/southern bean mosaic virus	S	Increased virus titer.	Increased sulfur uptake.	27

continued...

Table 35 (Continued).

Plant/Pathogen	Exposure[1]	Effect on Disease	Effect on Pollutant Injury	Ref.
SULPHUR DIOXIDE				
Corn/maize dwarf mosaic virus	S	Increased virus titer. Increased symptom severity.	No effect.	27
Tomato/tobacco mosaic virus	S	No effect.	No effect.	27
Corn/*Corynebacterium nebraskense*	S	Reduced and delayed disease development.	No effect.	28
Soybean/Mex. bean beetle	S	Increased beetle fecundity.		29
ACIDIC PRECIPITATION				
Corn/*Helminthosporium maydis* (N cytoplasm)	A	Increased disease development.		30
Corn/*H. maydis* (N cytoplasm)	A	No effect.		30
Corn/*H. maydis*		No effect.	No effect.	31
Kidney bean/*Uromyces phaseoli*	A	Decreased disease development.		30,32
Kidney bean/*Pseudomonas phaseolicola*	A	Post-exposure inoculation; increased disease development.		30,32
Kidney bean/root knot nematode	A	Decreased disease development.		30,32
Soybean and kidney bean/*Rhizobium* sp.	A	Decreased nodulation.		32
Phaseolus vulgaris/*Meloidogyne hapla*		No effect.	No effect.	31
Phaseolus vulgaris/*Uromyces phaseoli*		Inhibited growth.	No effect.	31
Phaseolus vulgaris/*Pseudomonas phaseolicola*		Inhibited growth.	Increased injury.	31

[1] F = Field exposure
S = Sub-acute exposure
A = Exposure causing acute injury
F(A) = Field exposure with acute injury

continued...

Table 35 (Concluded).

References 1-28, and 30 cited by Laurence (1981)

References:
1. Heagle and Strickland (1972)
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21. Howell and Graham (1977)
22. Kerr and Reinert (1968)
23. Pell et al. (1977)
24. Laurence and Wood (1978a)
25. Laurence and Wood (1978b)
26. Laurence et al. (1979a)
27. Laurence et al. (1979b)
28. Laurence (unpublished data)
29. Hughes et al. (1983)
30. Shriner (1977)
31. Shriner (1980)

Adapted from Laurence (1981)

Table 36. Host changes likely to affect insect success.

A. Host vulnerability to discovery

1. Host density
2. Behavioural cues (physical and chemical)

B. Host nutritional quality

1. Plant nutrition
2. Levels of plant metabolites
3. Plant water balance
4. Metabolic activity
5. Plant hormones

C. Plant defenses

1. Constitutive
    a. Surface morphology
    b. Toughness
    c. "Secondary" metabolites
2. Induced

Source: Hughes (1983)

6.3 EFFECTS ON THE PLANT AS HOST ORGANISM

Certain characteristics of the host-pathogen relationship appear to be sensitive indicators of the overall stress of the plant due to gaseous and aqueous pollutants (Shriner 1980). Pollutants may alter the primary metabolites, affecting digestibility of the host and the feeding behaviour of insects (Hughes 1983). For example, Mexican bean beetles developed more slowly and were less fecund when feeding on Phaseolus vulgaris fumigated with hydrogen flouride (Hughes 1983). Even small changes in plant biochemistry produce significant changes in insect populations because of associated alterations in insect location, recognition, and acceptance mechanisms (Laurence et al. 1983). Insect behaviour and survival rate are also affected by plant metabolites, which may act as deterrents, toxins, or growth inhibitors. Pollutants may reduce the ability of the plant to produce defensive chemicals. Production of protective chemicals may be reduced (Hughes 1983) or increased (Schultz and Baldwin 1982) by insect injury to the plant.

6.4 EFFECTS ON VIRUSES, FUNGI, AND BACTERIA

Stimulation and inhibition of growth and reproduction due to acidic precipitation have been shown to vary widely for bacteria, yeast, and fungi. Bacteria are the least resistant to acidity, while fungi are the most tolerant (Shriner 1978a). Pathogen vulnerability to acidic pollutants varies over the pathogen's life-cycle. Table 37 summarizes those stages in the life-cycle where the potential for interference by acidic pollutants is greatest.

Hughes and Laurence (1983) reported that viruses are more successful on plants exposed to air pollution, but studies of the interaction of the pollutants with viral disease are quite limited except for those dealing with O_3. In this case, viral infection often affords protection to the plants from the O_3 (Laurence 1981; Hughes and Laurence 1983). Diseases caused by obligate fungal parasites have been found, as a rule, to be restricted in development by air pollutants. Ozone, for example, reduces the incidence and severity of diseases caused by fungal obligate parasites, although colonies of powdery mildew were found to be more successful after multiple exposure of barley plants to sub-acute levels of O_3 (Hughes 1983). The effect of sub-acute levels of O_3 on wheat innoculated with Puccinia graminis was the reduction of sporulation and growth (Laurence 1981). Acute O_3 exposure of wheat with P. graminis reduced infection of hyphae and decreased the number of spores (Laurence 1981). Isoflavenoids accumulated in soybean leaves after exposure to O_3, PAN, NO_2, and SO_2, resulting in a high concentration of cuomestrol, which can prevent growth of the bacterium P. phaeolica (Hughes and Laurence 1983). Hughes and Laurence note that inhibition also occurs in many other species. In the same study, sub-acute levels of SO_2 reduced P. graminis development on wheat. Air pollution stress may increase the incidence and severity of disease from non-obligate fungal parasites (Laurence 1981). This is significant since these numerous and widely distributed pathogens are often associated with important agricultural crops (Laurence 1981).

Table 37. Acid rain-fungal life cycle interaction.

Stage	Process	Effect of Low pH
Spore dissemination	Dissemination by water splash	Germination inhibited
Spore on tissue	Spore germinates and grows prior to penetration	Growth stimulated or inhibited
Penetration	Penetration through cuticle stomata or wounded tissue	Wounded tissue increase, stomata close, cuticle eroded
Colonization	Pathogen dependent on host metabolism	Changes in primary and secondary metabolites

References: 1. Shriner and Cowling (1980)
2. Laurence and Hughes (1983)

6.5 EFFECTS ON NEMATODES

Acute doses of O_3 reduced reproduction of soybean cyst nematodes and stubby root nematodes in experiments conducted by Weber et al. (1979). However, neither SO_2 exposure, nor the combination of SO_2 and O_3 had a significant effect on the nematodes. Sulphur dioxide may protect nematodes against effects of O_3 on reproduction. Shriner (1978a) found a 66% inhibition of root-knot nematode (Meloidogyne hapla) on field-grown kidney beans with application of low pH simulated rain.

6.6 EFFECTS ON INSECTS

In discussing research on pollution-plant-insect interactions, Hughes (1983) noted that SO_2 stimulated growth and reproduction of the milkweed bug. Carbon monoxide and nitric oxide were also found to stimulate growth. Feir (1978) concluded that plant feeding insects are relatively unaffected by contact with gaseous pollutants such as O_3, but are significantly affected by water-soluble pollutants such as acidic sulphate aerosols.

In studies involving SO_2-fumigated soybean and Mexican bean beetle (Hughes et al. 1981, 1982; Hughes 1983), beetles grew larger and were more fecund on field grown beans exposed to SO_2 than on field grown controls. The developmental stage of the plant greatly influences beetle fecundity, which is greatest during the time of maximum translocation of photosynthates and nutrients from the leaves. Accordingly, fecundity of the beetle was greatest near the peak of pod fill. In one study (Hughes et al. 1982) female insects preferred to feed on SO_2-fumigated young plants or on unfumigated mature plants, over unfumigated young plants. This suggests that SO_2 may induce physiological changes which also occur with natural maturation. The effect of SO_2 may thus be to lengthen the duration of threat of predation by beetles, since the Mexican bean beetle usually thrives on older plants. An increased nutritional value of leaves may occur just prior to senescence brought on by SO_2 (Hughes et al. 1982), a conclusion supported by Amundson (1983).

6.7 DISCUSSION OF EXPERIMENTS AND FUTURE RESEARCH NEEDS

Shriner (1980) extrapolated that wet deposition is of greater significance than dry deposition in affecting the host-pathogen relationship. The effect of acidic deposition on foliage must also be viewed in light of its interaction with various pollutants in the production of tissue injury and changes in microflora. Studies are needed that take into consideration prolonged exposure of both agronomic and natural ecosystems, and that address the cumulative, subtle, and indirect influences on individual plants and on community structure and function.

In many experiments, sulphuric acid solutions applied to plants contain low concentrations of other ions that may occur with acidic rainfall. The impact of these ions and of the lack of nitrate in the solution on plant-pathogen interactions is not known. Most experiments also used values at the extremes of ambient pH ranges, e.g., 2.5 and 6.0, with no control for ambient gaseous-pollutant levels. From these experiments it is not possible to identify the pH levels at which significant biological stress would be observed under ambient levels of pollution (Shriner and Cowling 1980). More research is needed using pollutants of realistic composition and application, with appropriate background ambient air controls. More research is also needed to determine whether lower acidity has similar effects in natural and experimental conditions.

Hughes (1983) came to a similar conclusion with regard to the need for more research on agro-ecosystems, but added that a need exists to break down large regions into smaller units for analysis of agriculture and forestry. Further investigation is needed into the mechanisms by which pollutants affect insects and their interactions with agricultural crops.

Laurence (1981) emphasized the difficulty in distinguishing, from laboratory experiments alone, between the direct effects of pollution on pests and pathogens and effects due to changes in the host plant itself. Hughes (1983) has suggested a three part approach to research involving single plants or pests in controlled conditions, in growth chamber studies of small populations, and field population studies, with the desired goal of integrating the results into a model of plant-pathogen relations. Other factors, such as soil fertility, will need to be considered.

Establishing cause-effect relations is difficult when assessing plant-pest interactions because many different species of microorganisms are present on plant surfaces in the natural environment; thus, disease may reflect a succession of pathogens (Laurence et al. 1983). In addition, there are many different stages in the life cycle of the plant or pathogen during which either one or both may interact with the pollutant (Shriner and Cowling 1980). The data by Hughes et al. (1983) on growth, fecundity, and development were consistent with other reports on cultivars grown in field and greenhouse conditions. The mechanisms by which SO_2 affects host suitability are not known, and research is needed in this area as well as with regard to the effects of pollution on primary and secondary metabolites, and on plant water balance as these affect plant-pathogen interactions (Laurence et al. 1983).

7. CONCLUSIONS

Agricultural production contributed 10.2% of Alberta's gross domestic product in 1981, with grain crops such as wheat and barley accounting for over 75% of Alberta's total farm cash receipts (Alberta Agriculture Statistics Branch, letter 1985). Almost 30% of Alberta's land area is used for farming, with 12% being cultivated at a given time (Alberta Agriculture 1982). The estimated farm cash receipts and acreage under cultivation are detailed in Table 38. Ecologically, agriculture and grazing are dominant in four ecoregions of Alberta: Short Grass, Mixed Grass, Fescue Grass, and Aspen Parkland Regions, which cover about 25% of Alberta (Strong and Leggat 1981). Thus, the effect of air pollutants on agriculture is of both economic and ecological concern. The conclusion emphasizes grain crops and forage grasses because they are the most important agricultural groups in Alberta, in terms of both economic value and land use.

This conclusion considers the risk to Alberta posed by plant responses (e.g., reductions in plant yield, foliar injury) at ambient, maximum permissible, or projected levels of wet acidic deposition and gaseous pollutants in the province.

The Clean Air Act of Alberta establishes maximum permissible levels of gaseous air pollutants in the ambient air. These regulations are summarized in Table 39. Section 7.2 evaluates the role of the standards for sulphur dioxide (SO_2), nitrogen oxides (NOx), ozone (O_3), and hydrogen sulphide (H_2S) in preventing reductions in growth or yield of agricultural plants in Alberta. Comparable air quality standards, however, have not been set with respect to acidic precipitation.

Based on a review of the scientific literature on the effects of acidic wet deposition and gaseous pollutants on agriculture, on Alberta agricultural data, and on limited deposition data, Section 7.1 identifies sensitive species and plant communities, and areas of research that warrant further study in Alberta.

7.1 ACIDIC WET DEPOSITION

This review has shown that foliar injury and yield reductions have been documented for agricultural crops experimentally exposed to "simulated" acidic wet deposition at or below pH 3.0-3.5. There were no documented cases, however, of foliar injury and/or yield reductions reported for agricultural crops grown in the field which were attributable to ambient acidic wet deposition.

The major reason for this contrast in observations between the responses of agricultural crops to "simulated" versus ambient acidic wet deposition is likely due to the extreme and artificial nature of the chemistry of "simulated" acidic wet deposition compared with the chemistry of ambient acidic wet deposition. The fundamental difference is that "simulated" acidic wet deposition in a given experiment has a constant chemical composition and pH while the chemical composition and pH of ambient wet deposition, whether it is acidic or not, varies within and between individual wet deposition events at any geographical location (Pratt and Krupa 1983; Hales 1986). Additionally, since the frequency distribution of acidity (pH) in ambient wet deposition is not normally distributed (bell-shaped) computation of the mean or average pH overestimates true ambient conditions while the medians are free of this bias (Knapp et al. 1987).

Another factor contributing to the difference in responses of agricultural crops exposed to "simulated" versus ambient acidic wet deposition in the field is the

Table 38. Agricultural production in Alberta, 1981.

Crop	Acreage hectares (acres) (thousands)		Farm Cash Receipts (thousands)	Cash Receipt Decrease from 5% Yield Loss[1] (thousands)
Wheat	2,712	(6,700)	$ 1,151,000	$ 58,000
Oats	733	(1,810)	25,000	1,000
Barley	2,602	(6,430)	463,000	23,000
Rye	117	(290)	30,000	2,000
Flaxseed	41	(100)	16,000	1,000
Canola (Rapeseed)	591	(1,460)	279,000	14,000
Sugar beets	16	(40)	38,000	2,000
Potatoes	8	(20)	23,000	1,000
Vegetables	4	(10)	16,000	1,000
Floriculture and nursery			23,000	1,000
Other crops			42,000	2,000
(Hay)	1,416	(3,500)		
(Forage seed)	81	(200)		
TOTAL	8,321	(20,560)	$ 2,106,000	$ 105,000

TOTAL IMPROVED FARM LAND 12,525,927 hectares

TOTAL FARM AREA 19,109,193 hectares

[1]Ignoring price elasticity

References: Alberta Agriculture (1982)
Alberta Agriculture Statistics Branch (letter 1985)

Table 39. Maximum permissible concentrations of air contaminants in the ambient air, Alberta.

Sulphur dioxide in the ambient air shall not exceed an average maximum permissible concentration, at standard conditions, of

(a) 30 micrograms per cubic metre (approximately 0.01 ppm) as an annual arithmetic mean;

(b) 150 micrograms per cubic metre (approximately 0.06 ppm) as a 24 hour concentration;

(c) 450 micrograms per cubic metre (approximately 0.17 ppm) as a one hour concentration.

Nitrogen dioxide in the ambient air shall not exceed an average maximum permissible concentration, at standard conditions, of

(a) 60 micrograms per cubic metre (approximately 0.03 ppm) as an annual arithmetic mean;

(b) 200 micrograms per cubic metre (approximately 0.10 ppm) as a 24 hour concentration;

(c) 400 micrograms per cubic metre (approximately 0.20 ppm) as a one hour concentration.

Oxidants as equivalent ozone in the ambient air shall not exceed an average maximum permissible concentration, at standard conditions, of

(a) 50 micrograms per cubic metre (approximately 0.025 ppm) as a 24 hour concentration;

(b) 160 micrograms per cubic metre (approximately 0.08 ppm) as a one hour concentration.

Hydrogen sulphide in the ambient air shall not exceed an average maximum permissible concentration, at standard conditions, of

(a) 4 micrograms per cubic metre (approximately 0.003 ppm) as a 24 hour concentration;

(b) 14 micrograms per cubic metre (approximately 0.01 ppm) as a one hour concentration.

Source: Alberta Environment (1984b)

fact that the median pH of ambient precipitation in northeastern North America ranged between 4.2 and 4.7 from 1979 through 1984 (Knapp et al. 1987). In contrast to eastern North America, the pH of precipitation in Alberta between 1978 and 1984, determined from 11 monitoring stations in two networks was 6.0 (Lau and Das 1985). It is concluded from this review, therefore, that there is currently no risk to agricultural crops in Alberta due to regional scale acidic wet deposition.

The following areas of research are of particular relevance to Alberta, should acidic wet deposition become a problem in the future.

Wheat, barley, oats, canola, and hay crops (e.g., alfalfa mix and other tame) have the highest cash receipts, and occupy the most improved land. The small grain crops, such as wheat and barley, and non-leguminous hay crops were not sensitive to acidic precipitation in the experiments reviewed. Forage seed, leguminous forage, perennial forage, root, and fruit crops were the most sensitive Alberta crops reviewed. Among species prominent in Alberta, oats are the most tolerant of acidic soils. Alfalfa, barley, and canola are the most sensitive.

Long-term (i.e., two to three years) research on perennial forages, such as perennial ryegrass and alfalfa, under standard agronomic conditions is warranted by existing experimental results.

Very few data are available on the response of canola to acidic wet deposition; cole crops were of middle-to-high sensitivity. In light of its potential sensitivity and its importance in Alberta, field experiments using canola are recommended.

Because it is estimated that dry deposition accounts for over one half of the sulphur deposition in Central Alberta (Klemm 1977; Nyborg and Crepin 1977; Alberta Environment 1978; Kociuba et al. 1984; and Sandhu and Blower 1986), research on short- and long-term effects of dry deposition of acidifying substances on plant yield is recommended.

Root growth was the most likely to experience reduction for all crop groups; marketable yield of root crops sustained the greatest reductions due to increasing acidity. Sugar beet, the most important crop in Alberta after forages and grains, has a high sensitivity to acidic precipitation, which suggests that its production should be monitored for reductions in yield.

To establish a baseline of crop yield and atmospheric quality data, field surveys, ideally combined with a precipitation monitoring network, should be carried out over multiple seasons in districts rich in canola, leguminous forage, perennial forage, forage seed, sugar beet, or fruit crops.

The ecological impact of acidic wet deposition on natural grasslands is another important concern. Natural ecosystems in which leguminous species are major components appear to represent potentially sensitive targets of acidic wet deposition, especially on marginal sites where soils are sensitive to acidification (Shriner and Johnston 1981). There seems to be minimal risk in Alberta; the grassland regions are poor in legumes, and they tend to have rich, well-buffered soils (Strong and Leggat 1981). Nevertheless, the effect of acidic wet deposition on grasslands, albeit subtle, could have a large impact because of the areal extent of grassland in Alberta.

Plants exhibited a differential susceptibility to acidic wet deposition in simulated acidic wet deposition experiments. This implies that acidic wet deposition could cause changes in species composition of plant communities and perhaps alter natural food chains (Ferenbaugh 1976). Because the sensitivity of reproductive and growth processes to acidic precipitation varies among species, acidic wet deposition may change the relative abilities of species to reproduce. Thus, over time, the species composition of grassland communities may be altered. Populations that traditionally occur in small numbers because of weaker resistance to environmental stress may be favoured by increased air pollution (Lee 1981). The relative increase in the populations of such species may render the community as a whole more vulnerable to periodic ecological stresses, such as droughts or blights (Lee 1981).

7.2 GASEOUS AIR POLLUTION

The maximum permissible concentrations of SO_2 are 0.01 ppm as an annual mean concentration, 0.06 ppm as a 24 hour concentration, and 0.17 ppm as a one hour concentration. If these standards are met, there should be no adverse effects on agriculture under most conditions and with most agricultural plants. To injure the most sensitive species, concentrations of between 0.05 and 0.5 ppm for several hours are usually required (Mudd and Kozlowski 1975). Studies using concentrations close to the maximum permissible standards and showing injury include that of Guderian and Stratmann (1968) in which crops were exposed to an average of 0.083 ppm SO_2 over the monitoring time. This dosage could be described as within the permissible concentrations except for the fact that the experimental crops were affected by peak concentrations higher than the permissible concentrations. In studies by Crittenden and Read (1978b), injury to perennial ryegrass occurred at a concentration of 0.022 ppm over eight weeks. This is also very close to the permissible concentrations established by the Government of Alberta. In addition, Bell and Clough (1973) observed injury to perennial ryegrass at a continuous concentration of 0.016 ppm during winter. These studies suggest that the most sensitive agricultural species, exposed to concentrations of SO_2 at or slightly higher than permissible allowances and under environmental conditions conducive to gas exchange, may be injured by SO_2 exposure.

The most vulnerable of Alberta species to SO_2 are clover, winter grains, perennial grasses, alfalfa, and some leafy vegetables. These species may be susceptible to SO_2 injury when grown near a source of the gas, because of high concentrations in the spring when young plants are growing rapidly, and during weather periods of temperature inversion and no wind. Sulphur dioxide, which is heavier than air, can settle to the ground and reach toxic levels around young, growing crops. Agricultural practices and environmental factors conducive to increased stomatal conductance will also increase susceptibility, as discussed earlier. The authors advise that farmers reconsider planting proximal to SO_2 emission sources unless resistant cultivar varieties are to be used.

The maximum permissible concentrations of NO_2 are 0.03 ppm as an annual mean concentration, 0.10 ppm as a 24-hour concentration, and 0.20 ppm as a one-hour concentration. Concentrations of 0.25 to 0.50 ppm for long periods of time are required to induce injury in sensitive plants (Taylor and MacLean 1970; National Academy of Sciences 1977b). However, a few studies have shown injury to plants at concentrations at or below the maximum permissible concentrations. For example, Thompson et al. (1970) reported decreases in navel orange (Citrus aurantium) yields at concentrations as low as 0.06 ppm. Irving et al. (1982) reported a 10% decrease in snap bean pod fresh weight at NO_2 concentrations of 0.10 ppm over long periods. No reports of injury are available for acute exposures higher than the maximum permissible concentration. For this reason we believe that if the Government of Alberta standards are adhered to for acute NO_2 exposures, no injury should occur on agricultural species. In light of the few experiments showing injury at chronic exposures at or above the maximum permissible concentrations of NO_2, there is some question as to whether these standards will protect sensitive agricultural species. This should be investigated further. Alberta species most at risk to chronic exposures of NO_2 are: leguminous forage crops, including alfalfa, red and Italian clover, barley, oats, and leafy vegetables, such as lettuce and spinach.

The maximum permissible concentrations of O_3 are 0.025 ppm as a 24-hour concentration and 0.08 ppm as a one-hour concentration. Ozone concentrations of 0.03 ppm (for very sensitive species) and 0.10 ppm (for species of intermediate sensitivity) are required to induce injury to agricultural plants when exposed to O_3 for several hours (Guderian 1985). Research indicates that the maximum permissible concentrations specified for acute injury are sufficient to protect agricultural plants. Although the maximum permissible concentration is not specified as an annual mean, if this concentration follows the same relative patterns as those for the other pollutants, it should also be adequate to protect plants. Damage to agricultural species of intermediate sensitivity due to chronic exposures is generally not seen at concentrations below 0.05 ppm. The most vulnerable of Alberta species to O_3 are: leguminous forage crops, truck crops, bean, sweet corn (whereas field corn is relatively resistant), oats, wheat, various grasses, and potato.

The maximum permissible concentrations of H_2S are 0.003 ppm as a 24-hour concentration and 0.01 ppm as a one-hour concentration. From the most recent research on the effects of H_2S on agricultural crops, these standards appear adequate for the maintenance of plant health.

Because injury to sensitive agricultural species has been observed during chronic exposures at or near maximum permissible levels of gaseous pollutants when present singly, there is concern over the possible synergistic effects of these pollutants at the same concentrations when present together. If these pollutants react synergistically for injury induction, then they are more phytotoxic than the government standards indicate.

Atmospheric quality data for Alberta are not complete because of the paucity of permanent monitoring stations in rural sites except in the vicinity of industrial point sources. Urban sites (such as Edmonton and Calgary) are monitored more closely. The annual mean values of SO_2, NO_x, and O_3 concentrations in Edmonton and Calgary for downtown, industrial, and residential areas for the years 1977 to 1984 are well below the maximum permissible concentrations and are apparently at safe (non-phytotoxic) levels (Alberta Environment 1984a,b). In any agricultural area, or area being considered for agricultural use, monitoring data for various pollutants should be taken into account assuming at least additive interactions between pollutants.

8. RECOMMENDATIONS

A review of the existing literature on the effects of acidic wet deposition and gaseous pollutants on agriculture suggests that certain areas of research warrant investigation in the future. In addition to investigations of plant response, information concerning the influence of the pollutant dose, the experimental conditions, and the plant types is required.

Broadly defined, the objectives for future research are as follows:

1. to enable estimation of present crop losses due to atmospheric pollution;
2. to enable prediction of damage from changes in atmospheric deposition; and
3. to determine causative agents in crop loss, and safe thresholds of those agents, when occurring singly and in combination.

The following research recommendations were developed to allow data of current and future experiments to be used as outlined above. Most of the recommendations for experimental design and for subjects of future research are similar for acidic precipitation and gaseous pollutant deposition.

8.1 ACIDIC WET DEPOSITION

The following discussion and recommendations are presented for consideration should regional scale acidic wet deposition become a problem in Alberta in the future.

8.1.1 Plant Growth and Yield

Despite the growing number of experiments investigating agronomic plant response to exposure to acidic wet deposition, very few conclusions or generalizations can be drawn about plant growth response. Cross-experiment comparisons of quantitative results are not supported by a unified experimental methodology. This lack of accepted protocol also limits the extent to which qualitative or mechanism-oriented results can be generalized.

Quantitative relationships between pollutant exposure and response of plant growth are desired for use in generating a relative ranking of species sensitivity to acidic wet deposition. The qualitative ranking thus developed could be used to compare species sensitivity without conducting large multi-species experiments. The primary goal of understanding crop response is to aid in assessing and predicting regional agronomic responses to changes in atmospheric quality.

Similarly, an index of injury that would relate visible foliar injury to changes in growth or yield could be used to extrapolate from existing data on foliar injury to estimates of reductions in plant yield.

8.1.1.1 Crops. Data indicate that more experiments under standard agronomic conditions are warranted for perennial crops and for crops that have demonstrated sensitivity to acidic precipitation or are of significant economic or ecological importance. These include fruit trees, root crops, soybeans, ryegrass, alfalfa, and leafy crops.

Because it is expensive to test each important cultivar or even each crop species, current research should be conducted to allow extrapolation of data about one species to another, such as by grouping crops by growth form (Personal Communication, J.

Koranda, Lawrence Livermore National Laboratory, 1985). Research should attempt to identify plant characteristics that indicate sensitivity, such as foliar wettability.

The relationship between differing sensitivities of cultivars and the ambient air quality where the cultivars were developed should be investigated. There is insufficient work to date on predisposition to, or inheritance of, and resistance or sensitivity to air pollution.

Design recommendations for experiments investigating the effect of acidic wet deposition on plant growth, including experiments on dose-response, physiology, and foliage, are given in the sections on growth conditions, pollutants, and plant-pathogen interactions.

8.1.1.2 Dose-response. Complex factorial research designs and multivariate analyses should be used to describe the relationships between a dose of acidic precipitation and plant response rather than simple univariate analyses (e.g., pH versus yield). Dose-response research should measure all plant portions so that information can be gathered not only for economic but also for biological and ecological purposes.

8.1.2 Reproduction

Experiments indicate that reproduction of agricultural plants is sensitive to changes in atmospheric quality and that more research on the effects of acidic wet deposition on reproduction is needed. Specifically, the following studies are recommended:

1. Long-term studies that consider the effects on anthesis, pollen germination, fertilization, fruit set, development, and maturation, with emphasis on perennial plants.
2. Surveys of the threshold pH for deleterious effects on reproduction, such as inhibition of pollen germination.
3. Comparisons of the effects on reproduction for different species and cultivars.

A comparison of the reproductive processes of species with differences in sensitivity would facilitate identification of sensitive structures and stages of plant development. This, in turn, would facilitate identification of possible mechanisms of influence.

8.1.3 Plant Physiology

Plant responses at cellular and biochemical levels, their thresholds for occurrence, and their effect on plant yields need to be better understood. Research is recommended on physiological responses to acidic deposition, e.g., changes in photosynthesis, respiration, transpiration, and metabolism.

More experiments under standard agronomic conditions are warranted to investigate the effect of acidic precipitation on nutrient content of feed crops. Changes in carbohydrate and protein content are of widespread economic concern, as well as indicators of significant physiological responses of plants to acidic precipitation.

8.1.4 Foliar Response

Foliar injury is the most thoroughly researched aspect of plant response to simulated acidic wet deposition. Future research should concentrate on other aspects of foliar response, including the mechanisms and physiological effects (e.g., effects on photosynthesis and net productivity) of foliar fertilization, foliar buffering, and foliar leaching. Research and analysis are needed concerning the existence and nature of a correlation, if any, between visible foliar injury and growth and yield.

An index of injury correlated with changes in growth and yield, if rigourously derived, could be used to extrapolate from existing data on foliar injury to estimates of reductions in plant yield. It is likely, however, that any correlation would be qualitative and would simply describe, for example, whether the relationship was direct or indirect, and which kinds of injury were more likely to induce growth changes.

8.1.5 Pollutant

An increased understanding of plant response to acidic wet deposition was the primary purpose of most of the research reviewed. However, ambient acidic wet deposition varies in ways that may influence plant response, and experimental data were inconclusive as to the relative importance of various properties of ambient acidic deposition. To enhance evaluation of existing and future research, it is recommended to investigate the influence of different acidic wet deposition and exposure characteristics on plant response.

In particular, investigation is recommended on the influence of:

1. S:N ratio and total ionic composition of simulated and ambient rain;
2. simulant chemical composition, and/or temporal pattern of deposition delivery, that does or does not match the characteristics of the ambient deposition;
3. the instantaneous dose (i.e., concentration) versus the influence of the cumulative dose (i.e., total deposition), of hydrogen ion as well as sulphur and nitrogen species and other ions;
4. a dose with a pH that varies during and among exposure events versus that of a dose that is of constant pH; and,
5. the chemical form of acidic deposition, i.e., wet or dry.

Research should address how information generated using acute doses of high acidity can be used to shed light on plant response to chronic doses of lower acidity.

Recommended research design:

1. The best available local data on atmospheric and precipitation quality (e.g., chemical composition, concentration, pH, volume, pattern of deposition) should be incorporated into the experimental design to the extent feasible.
2. It is strongly recommended that future experiments use a commonly agreed upon control pH. Since most data have been generated using a control pH of 5.6 , it is recommended that pH 5.6 be used until a more appropriate value has been documented.

3. For regional assessments and long-term and ecological studies, the use of a realistic dose (chemical composition, concentration, pH, duration, and method of exposure) is recommended. For mechanism- or process-oriented studies, more extreme values and a less detailed gradient may be sufficient.
4. For experiments using acid aerosols or fogs, droplet size, distribution, and number should be reported.

8.1.6 Growth Conditions and Experimental Design

The influence of growth conditions on plant response is an important concern for future research. An understanding of how environmental and edaphic conditions regulate plant response to acidic wet deposition would help in interpretation of results from different experimental conditions. In particular, edaphic conditions, such as variations in nutrient supply, soil texture, and soil moisture, should be investigated. Soil conditions may vary considerably among agronomic systems, depending on the degree of management. Whether irrigation practices should follow a standard research protocol or should resemble the standard regional practice for the crop under study is an important consideration. Research is also needed to determine the influence of experimental conditions on actual plant exposure to pollutants (e.g., effect of rain-exclusion shelter on reactivity of dry deposition).

Recommended research design:

1. Field plots are recommended for regional assessments. They incorporate geographic variables into results better than do controlled environment studies.
2. Documentation of experimental design in the current literature is weak. For any agronomic crop experiment, the geographic location, season, and weather should be listed as well as the temperature, humidity, wind speed, solar radiation, and length of daylight (and/or artificially-lit hours), for the entire duration of the experiment. The age and stage of development of experimental plants throughout the experiment should also be reported.

8.1.7 Long-Term and Ecosystem Studies

Studies are needed to investigate the effects of acidic wet deposition on natural systems, to investigate the long-term effects on agronomic systems, and to aid in quantifying the correlation between dose-response relationships found in experiments to dose-response relationships in commercial and unmanaged fields, e.g., for regional crop loss assessments.

Long-term research is recommended on perennial legumes and fruit crops. Perennial cultivated monocots appear relatively tolerant to acidic wet deposition and therefore require less attention. However, natural grasslands are potentially sensitive ecosystems.

Studies of whole ecosystems are needed to investigate the interactions among responses in plant reproduction, plant growth, soil, and plant-symbiont relationships. Long-term ecosystem studies would provide data on the changes in plant yield due to the cumulative ecosystem response to acidic wet deposition.

Suggested subjects for future research include:

1. the long-term changes in species populations and in community vigour;
2. the influence of alterations in early growth patterns on plant growth and reproduction; and,
3. the ways in which those plant or pathogen responses that have no immediate deleterious effects may affect future plant or pathogen responses to periodic, rare, or acute stresses.

Experiments should employ long-term exposures and continued observation on natural and agronomic ecosystems, with consideration given to possible cumulative effects.

The following areas of research are of particular importance to Alberta should acidic wet deposition become a problem in the future:

1. Long-term (i.e., two to three years) research on perennial forages such as perennial ryegrass and alfalfa, under standard agronomic conditions, is warranted by existing experimental results.
2. Very little data are available on the response of canola to acidic wet deposition; cole crops are of middle-to-high sensitivity. In light of its potential sensitivity and importance in Alberta, field experiments using canola are recommended.
3. Because dry deposition accounts for over one-half of the sulphur deposition in central Alberta (Klemm 1977; Nyborg and Crepin 1977; Alberta Environment 1978; Kociuba et al. 1984; and Sandhu and Blower 1986), research on short- and long-term effects of dry deposition of acidifying substances on plant yield is recommended.

8.2 GASEOUS POLLUTANTS

Although research progress has been enormous in the last few decades on gaseous pollutant-plant interactions, many gaps exist, especially in the area of pollutant mixtures. In this section recommendations will be made for research in areas relevant to the effects of gaseous air pollutants on agricultural plants.

8.2.1 Pollutant

The method of pollutant exposure is determined from the basic objectives of the research. For growth and yield experiments, dose-response relationships, experiments over long periods of time, and assessment of pollutant effects on ecosystems, experimental design should incorporate the pollution monitoring data for a particular region. In addition to the pollutant species investigated, average concentrations, peak concentrations (which are often not taken into account), the duration of each of these concentrations, and temporal patterns of pollutant types should reflect these monitoring data so results may realistically be applied to actual agronomic situations. Research should be conducted under conditions similar to those found in the field so results can be more readily applied to the field. Traditionally, exposures have been conducted at a constant concentration and for poorly defined periods of time. Such fumigations are not realistic and should be avoided.

8.2.2 Plant Physiology

In the field of plant physiology, research is needed to achieve an understanding of plant response to gaseous pollutants in general terms on the level of the whole plant as well as on cellular and metabolic levels. The effects of gaseous pollutants on plant respiration are still unclear. In many cases a physiological response is known, but the mechanism for this response has not been determined. For example, changes in stomata due to both SO_2 and O_3 exposure have been observed, but the mechanisms have yet to be determined. In other cases (as with the effect of SO_2 on photosynthesis), there are many theories as to the mechanism, but there is no agreement among researchers. Further research is needed to clarify if observed physiological symptoms due to gaseous pollutants are a direct result or an indirect result of the pollutants. For example, SO_2 exposures have been shown to affect respiration, but it has not been determined if these changes are a direct effect of the SO_2 or an indirect effect due to cell damage or impairment of photosynthesis.

From an agriculturist's perspective, the emphasis of research on the effects on plant physiology should be to understand the processes that affect productivity and vulnerability to injury. For example, plants are more susceptible to NO_2 when exposed in darkness than when the plant is exposed to greater quantities of NO_2 in daylight (Taylor 1970). This phenomenon can only be explained through investigation of physiological processes.

Most of the experiments on the effects of air pollutants on plant physiology and reproduction have been conducted at very high pollutant concentrations. Further research is needed to determine whether or not these responses hold true for ambient concentrations of pollutants. Future studies should be conducted with low concentrations typically encountered under field conditions.

8.2.3 Foliar Injury

The amount of research on visible foliar injury due to gaseous pollutants has been enormous. Detailed descriptions of foliar injury caused by the most common pollutants have been formulated. These descriptions are necessary for identification of the cause of injuries as well as for an overall understanding of plant response to specific pollutants. Further research on foliar injury for descriptive purposes using SO_2, NO_2, or O_3 is unnecessary. Dose-response experiments for foliar injury have not been very relevant or useful, particularly since there is no direct correlation between visible foliar injury and effects on growth and yield. The authors recommend that dose-foliar response experiments be substituted with dose-response experiments determining the effects on growth and yield.

8.2.4 Plant Reproduction

Research on reproduction has been limited primarily to experiments on (marketable) fruit or seed yield, pollen germination, and a few seed germination experiments. These experiments should be continued and expanded. Few studies have been conducted on the effect of pollutants on different organs of reproduction. These experiments are necessary to determine empirically if the effects of pollutants on seed and fruit production are a result of direct action on sexual organs or indirect action by injury to other plant parts or processes. Long-term, more comprehensive studies are needed to assess the effects of gaseous pollutants on continuous plant propagation, especially on unmanaged lands. Research is needed on the effects of pollutants on annual grass reproduction and propagation to assess the long-term impact of pollutants on these forage species. Grasses and forages are some of the least-managed agricultural plants and have the potential for greatest damage due to pollutants.

8.2.5 Growth and Yield

More research is needed, using several different concentrations of a pollutant, on important agricultural species and cultivars to assess their relative sensitivities. Most experiments have been conducted with a limited number of different concentrations of a pollutant or with a single species or cultivar. Because experimental methods and procedures differ among researchers, it has been very difficult, if not impossible, to compare these experiments. Consequently, ranking important agricultural species and cultivars with respect to their sensitivity has been extremely difficult.

When possible, experimental analysis should include both changes in partitioning of photosynthetic assimilates and growth analysis. This information is essential and would support modelling of plant response as noted by Krupa and Kickert (1987).

8.3 POLLUTANT MIXTURES

Studies on the effects of mixtures of atmospheric pollutants on plants are quite limited. The effects of pollutant mixtures on plant physiology, including stomatal response, photosynthesis, and transpiration, are still uncertain. As with single pollutants, the effects on reproduction need further investigation. Growth and yield studies should be conducted on important agricultural species, and assessments of plant sensitivities should be made. The authors feel that research in the area of pollutant mixtures and pollutant and CO_2 (carbon dioxide) mixtures demands more attention because pollutants are rarely found singly under natural conditions. Because pollutants are more commonly found in combination, and because of the potential for synergistic effects on agricultural species, the potential impact of pollutant combinations exceeds that of single pollutants. The effects of pollutant mixtures must be compared with the effects of control applications of ambient concentrations and of single pollutants. The recommended research design for experiments with pollutant mixtures is in accordance with that made for single pollutants.

8.4 PLANT-PATHOGEN INTERACTIONS

For the study of acidic precipitation effects on plant-pathogen interactions, several questions that should be addressed by future research emerge, such as:

1. What are the direct chemical effects of acidic precipitation on pathogens?
2. What are the effects of physical and chemical degradation of leaf tissues?
3. Can changes in pH cause genetic transformations among competitive microflora?
4. What are the pollution-induced changes in plant vulnerability to infection, and how do these influence plant response to other pollutants?
5. What are the reciprocal pathogen-induced changes in plant resistance to pollutant injury?

Research is recommended to describe:

1. the mechanisms by which pollutants affect insects and their interactions with agricultural crops;
2. the mechanisms by which SO_2 affects host suitability, or the effects of pollution on primary and secondary metabolites, and on plant water balance, as these affect plant-pathogen interactions;
3. the possible benefits to agriculture from alterations in the interactions of plant and pathogen; and,
4. the difference in response to lower acidity between natural and experimental conditions.

Especially with regard to the last recommendation, experiments are needed that use pollutants of realistic composition and application, with appropriate pollutant-free controls.

9. SUMMARY

The current scientific literature on the effects of acidic precipitation, SO_2, NOx, O_3 and H_2S on agricultural production was reviewed for this publication. Our findings are summarized in three sections, each with its own objective: the Conclusions (Section 7) address the possible impact of these pollutants, specifically on Alberta agriculture; the Recommendations (Section 8) pertain to research objectives and preferred research protocol.

This section summarizes the current status of knowledge, based on our literature review and data analysis. An attempt was made to limit repetition among these three sections; they form one concluding discussion.

Literature was acquired through computer-assisted searches (e.g., of the DIALOG data bases AGRICOLA (USDA), ENVIROLINE, and BIOSIS), library searches, and correspondence with governmental, informational, and research organizations in the US, Canada, and England.

While the entire body of literature concerning acidic deposition on agriculture was considered, the focus of this review was on crops, pollutants, and processes particularly relevant to Alberta, Canada. The focus of subject matter was especially important in the review of gaseous pollutants, where the literature was voluminous. Data used quantitatively were selected on the basis of sound experimental design and reporting.

The pollutants considered in this review include simulated wet acidic precipitation in the form of sulphuric acid and nitric acid, and various species of gaseous air pollutants, including the acidic gases SO_2 and NOx, the oxidant O_3, and H_2S. Sulphur dioxide, H_2S, and NOx are primary pollutants; O_3 and sulphuric and nitric acids are secondary pollutants. The total annual emissions of SO_2 and NOx in the province of Alberta were approximately 488,297 tonnes and 353,511 tonnes, respectively (Sandhu and Blower 1986). The majority of the SO_2 emissions in Alberta are emitted by the petroleum industry and the coal-fired power plants of the electric utilities. The majority of the NOx emissions in Alberta are emitted by the petroleum industry, the coal-fired power plants of the electric utilities, urban centres, commercial industry, and motor vehicles on highways. Although the petroleum industry is the principal source of H_2S emissions, the pulp and paper industry is also a contributor. Twenty-five to 50% of the sulphur deposition in Alberta is estimated to be in the form of wet acidic deposition (Nyborg and Crepin 1977; Kociuba et al. 1984; and Sandhu and Blower 1986).

The effects that these pollutants can have on agriculture, particularly Albertan agriculture, have been reviewed in five distinct sections: the effects of acidic precipitation, the effects of gaseous air pollution, the effects of mixtures of pollutants, the effects of acidic deposition on plant-soil interactions, and the effects of acidic deposition on plant-symbiont interactions.

Approximately half (nearly 6 million hectares) of Alberta's 12.5 million hectares of improved land is utilized for grain crops, including barley (2.6 million hectares), wheat (2.7 million hectares), rye (.12 million hectares), and mixed grains (.06 million hectares). Forages, including grasses and leguminous forages, are farmed on approximately 1.8 million hectares. Oil-seed crops occupy .6 million hectares. Other important crops are sugar beets (16,200 hectares), potatoes (8,000 hectares), field beans (3,600 hectares), and field peas (3,600 hectares).

9.1 ACIDIC PRECIPITATION

The effects of simulated acidic precipitation on agricultural plants include reduction in growth and yield, interference with reproduction, foliar injury, and alteration of foliar processes such as fertilization, buffering, leaching, and nutrient accumulation. For both ecological and economic concerns, changes in plant yield, growth, and reproduction are the most important plant responses. Research on the effects on reproduction is in its initial stages. More is known about the effects of acidic precipitation on growth and yield. In the experiments reviewed, dicots were more likely to show inhibited growth than were monocots. No experiments reported an inhibition of growth, for any species, above pH 4.0.

This review has shown that foliar injury and yield reductions have been documented for agricultural crops experimentally exposed to "simulated" acidic wet deposition at or below pH 3.0-3.5. There were no documented cases, however, of foliar injury and/or yield reductions reported for agricultural crops grown in the field which were attributable to ambient acidic wet deposition.

The major reason for this contrast in observations between the responses of agricultural crops to "simulated" versus ambient acidic wet deposition is likely due to the extreme and artificial nature of the chemistry of "simulated" acidic wet deposition compared with the chemistry of ambient acidic wet deposition. The fundamental difference is that "simulated" acidic wet deposition in a given experiment has a constant chemical composition and pH while the chemical composition and pH of ambient wet deposition, whether it is acidic or not, varies within and between individual wet deposition events at any geographical location (Pratt and Krupa 1983; Hales 1986). Additionally, since the frequency distribution of acidity (pH) in ambient wet deposition is not normally distributed (bell-shaped) computation of the mean or average pH overestimates true ambient conditions while the medians are free of this bias (Knapp et al. 1987).

Another factor contributing to the difference in responses of agricultural crops exposed to "simulated" versus ambient acidic wet deposition in the field is the fact that the median pH of ambient precipitation in northeastern North America ranged between 4.2 and 4.7 from 1979 through 1984 (Knapp et al. 1987). In contrast to eastern North America, the pH of precipitation in Alberta between 1978 and 1984, determined from 11 monitoring stations in two networks was 6.0 (Lau and Das 1985). It is concluded from this review, therefore, that there is currently no risk to agricultural crops in Alberta due to regional scale acidic wet deposition.

9.1.1 Foliar Injury

Foliar damage resulting from exposure to simulated acidic wet deposition can lower economic yield and lower resistance to pathogens and has been linked with reduced plant productivity. Although not directly correlated with growth, research on foliar injury is valuable because it may provide information on the influence of environmental conditions and dose characteristics on plant threshold for response.

Visible foliar injury (VFI) is the most often reported symptom of plant response to simulated acidic precipitation. Simulated acidic wet deposition has induced visible injury on the foliage, fruit, and flowers of agricultural and horticultural crop species. The most commonly reported symptom of foliar injury from acidic wet deposition is brown necrotic lesions. Chlorosis, changes in the cuticular waxes, and gall formation have also been reported. Galls are a protective reaction which decrease moisture retention and further injury where they occur. At the cellular level, reduction in mesophyll conductance, decreased intracellular space, and reductions in the size of starch granules have been observed. The effects on plant growth of cellular and biochemical responses are still being investigated.

Most reports of VFI occur at or below pH 3.5, i.e., acidities much greater than commonly found in ambient precipitation; however, sensitive species exposed to ambient acidic rainfall events of pH 3.0 lasting two or more hours face a significant risk of incurring foliar injury. Thus, generally, there is a low risk of foliar injury to field-grown vegetation from exposure to current ambient levels of acidity (Irving 1983). Increased emissions may pose a risk to sensitive plants and plant communities.

Visible damage to foliage or fruit can lower the market value or market yield of crops sold fresh. In the experiments reviewed, foliar lesions reduced market yield of most truck crops tested, such as tomato, apple, mustard green, Swiss chard, broccoli, and sunflower. Market yield is generally independent of visible injury for grains, forages, and processed fruits and vegetables.

The extent and nature of injury caused by contact with simulated acidic precipitation is a function of the characteristics of the species, the cultivar, the pollutant, and the method of exposure.

The stage of plant development at the time of exposure influences susceptibility to foliar injury. Expanding and newly expanding leaves are highly susceptible to injury, as are the older, pre-senescent leaves. Sensitivity is also a function of leaf characteristics, which vary among species. Greater moisture retention is correlated with higher frequency and greater severity of injury. Wettability, which describes the amount of surface area in contact with a droplet, varies with age and species. It is positively correlated with occurrence of visible foliar injury; however, the threshold for visible injury is not directly linked with wettability or other leaf characteristics.

The occurrence and severity of visible foliar injury are directly correlated with the dose of simulated acidic precipitation. Increasing acidity, frequency, duration and/or number of simulated acidic rain events increases the extent and degree of foliar injury.

Susceptibility to foliar damage from simulated acidic wet deposition varies among species, and among cultivars within species. The relative sensitivity of 36 crop species was analyzed, based on data from 13 field and 14 controlled environment experiments that exposed plants to simulated wet acidic deposition. The highest pH resulting in visible foliar injury and the lowest pH applied without resulting in visible foliar injury are listed in Table 3. The range between the two pH values approximates a threshold for foliar injury, for each cultivar, under specific environmental conditions. Crops grown in a controlled environment, such as a greenhouse or growth chamber, consistently displayed a lower tolerance of deposition than did field grown crops.

The pH at which 50% of the plants sustained significant visible foliar injury was pH 3.0. This corresponds well with thresholds of from pH 3.0 to pH 3.5 estimated by others. Simulated acidic precipitation in the ambient pH range of 4.0 caused foliar injury in 9% of the experiments, only one of which was field grown. Below pH 2.5, 70% of the cultivars showed foliar damage.

The groups of crops most susceptible to visible injury from simulated acidic precipitation were root, leafy, cole, legume, fruit, grain, and leafy and seed forage crops, in descending order. There were insufficient data on tuber and bulb crops to allow ranking. The potential for economic loss was greatest for leafy, cole, and fruit crops, arranged in descending order of potential. Leafy crops show slightly less vulnerability to foliar injury than root crops. The threat to economic yield is greater with the leafy crops, however, which may lose value if blemished. The threshold for damage to cole foliage is pH 3.0 to 3.5, higher than for the leafy crops. Sensitivity of legume species varied; leafy varieties (e.g., soybean) with high wettability tended to be more susceptible to foliar damage from acidic precipitation. Foliar injury was observed for almost all fruit species studied. In addition, perennial fruit trees have shown latent foliar injury after cessation of simulated acidic precipitation treatments. However, growth of annual fruit crops is, in general, stimulated by simulated acidic precipitation. Monocots, such as wheat, barley, and timothy, were resistant to foliar injury above pH 2.5.

9.1.2 Foliar Processes

Very little is known about the physiological effects of foliar exposure to simulated acidic wet deposition. There has been some research on fertilization through the leaf, foliar buffering and leaching, and changes in foliar nutrient content.

Foliar fertilization may occur when sulphur or nitrogen, from sulphuric or nitric acids in precipitation, is absorbed by foliage. Foliar fertilization by acidic deposition would explain observations of alterations in photosynthate partitioning, and of a stimulatory effect on growth, due to exposure to acidic precipitation. Nevertheless, the potential for benefit or harm to agricultural plants is limited. Commercial foliar fertilizers, which use surfactants to aid in penetration, have been only marginally successful in stimulating plant growth. Since the concentration and total deposition of nitrogen and sulphur in acidic precipitation are far lower than those found in commercial fertilizers, it appears unlikely that acidic wet deposition could be a significant source of foliar fertilizer to crops. There is also limited evidence to suggest a risk from salt-induced damage to foliage at ambient concentrations.

Some plants appear to develop little or no foliar injury from simulated acidic precipitation. It is possible that the plant tissue may effectively buffer the acid before any significant physical or physiological injury can occur. The ability of foliage to neutralize simulated acidic precipitation varies among species and cultivars within species. The reasons for this, and the mechanisms of neutralization, are still under investigation. The ability of the leaf to buffer the droplets' pH was directly correlated with the extent of injury sustained by the leaf, which suggests that buffering may occur upon the release of cellular material from dead or disrupted cells. It also suggests that there is a correlation between the length of time the acidity is in contact with the leaf and the extent of both foliar injury and buffering. Bicarbonate stored in the cell walls for photosynthesis, leachates, or superficial aggregates may act to neutralize acidic droplets. However, in the few experiments on the subject, foliar contaminants, foliar microflora, and metabolic activity were of limited importance in foliar buffering.

Foliar contact with acidic solutions may increase the rate at which ions are leached from vegetation. Most nutrients are leached from foliage faster as the acidity of the simulated precipitation increases (see Table 4). Leaching of organic compounds may also be accelerated by exposure to acidic solutions.

Foliar buffering and increases in leaching due to acidity are related processes. Buffering on the leaf surface is aided by alkaline deposits formed with leached or exuded foliar salts. Leaching occurs as exchangeable cations in the cuticle and cell walls are exchanged for H^+ in acidic solutions. The cuticle forms a barrier for ion movement in and out of tissue, and the cuticular waxes play a role in inhibiting leaching of foliar nutrients. Cuticular micropores are the principal route for cation exchange and loss, as well as for entry of chemicals into the leaf interior. Greater wettability is correlated with both higher leaching and higher buffering capacity. Foliar leaching of K associated with exposure to acidic solutions may be a secondary effect of foliar injury.

While the risk of damage from foliar leaching or buffering appears small, investigations of the processes reveal valuable information about the mechanisms leading to foliar injury or changes in productivity, and may thus shed light on the relationship between foliar injury and plant yield.

Increased foliar leaching may alter the nutrient content of leaf tissue. Experimental results are inconsistent, especially with regard to N, but do indicate that there is not a net loss of sulphur and that there is a net loss of other nutrients, such as Ca, Mg, and P.

In managed systems, such as propagation beds or container nurseries where root systems are limited or restricted, foliar leaching may lead to nutrient-deficiency symptoms. Changes in foliar nutrient content resulting from exposure to acidic precipitation may be a factor in plant growth reduction. Plant energy used to replace leached metabolites may be diverted from plant growth processes. In addition, reduction in the nutrient content of a crop could significantly affect its quality and economic value as a food commodity.

More experiments under standard agronomic conditions are warranted to investigate the effect of acidic precipitation on nutrient content of feed crops. Changes in carbohydrate and protein content are of widespread economic concern, as well as indications of significant physiological responses of plants to acidic precipitation.

9.1.3 Plant Growth

While the mechanisms of plant response to acidic precipitation are of interest, the most significant practical aspects are the integrated effects on plant growth and productivity (Amthor and Bormann 1983).

Several studies, covering many plant species, suggest that precipitation acidity may inhibit biomass accumulation by whole plants or organs. Exposure to acidic precipitation may reduce total biomass and/or biomass of some parts of the plant. Biomass was reduced in 14 out of 19 species reviewed in this report. Lee et al. (1981) exposed 28 crops grown in pots in field chambers to simulated acid rain. Marketable yield was reduced for five crops, stimulated for six crops, and not consistently affected for 16. Altered partitioning of photosynthate, i.e., a change in the biomass yield of the shoots relative to the roots, was also observed. In general, root growth tended to be inhibited more than did shoot growth, i.e., there tended to be an increase in the shoot to root ratio.

Attempts have been made to determine dose-response functions for crop yield and quality for use in predicting impacts of ambient and anticipated levels of acidity in rainfall. So far, there is little evidence for a linear dose-response function (Irving 1983); frequently no response was observed at doses greater than those producing a positive or negative response. Garden beet was the only crop out of 19 reviewed by Irving to show a consistently negative response to treatment acidity. Thus, acidic precipitation may not simply have a positive or negative effect on crop growth. Rather, it could have a combination of competing (inhibitory or stimulatory) effects. The yield of a plant peaks at the pH where the net effect of acidic precipitation is the most stimulatory, which may be an intermediate value between the control and the threshold pH for inhibited yield. Lee et al. (1981) observed a peak in stimulation of seed germination, seedling growth, and crop yield between pH 3.5 and 4.0 for many of the species tested.

Biomass yield may be measured in fresh weight or dry weight. Both provide information about productivity and yield of shoot, root, marketable portion, or whole plant. Marketable yield may refer to the plant foliage (leafy, cole, and forage crops), roots, bulbs and tubers, or reproductive organs (bean, grain, flower, and fruit crops). If acidic precipitation differentially inhibits growth of one part of the plant, marketable yield may or may not be affected. Dose-response research should measure all plant portions so that information can be gathered not only for economic concerns, but also for biological and ecological purposes as well as for predictive modelling.

The generalization that dicots are more sensitive to acid rain than are monocots (Lee et al. 1981) appears in many reviews. These observations have been based for the most part on visible foliar injury rather than on growth or yield criteria, because it is more difficult to screen large numbers of plants using growth and productivity as a basis for evaluation (Amthor and Bormann 1983). In addition, there are fewer factors contributing to visible foliar injury than there are to changes in plant yield. Thus, it is easier to explain the observation of foliar injury after exposure than it is to isolate acidic precipitation as the cause of growth reductions. Since a good correlation between visible injury and growth has not been established, a ranking system based on visible injury has limited economic application, except where cosmetic damage decreases market value, and may have limited relevance to ecological considerations.

Due to the short duration of most simulated acidic wet deposition experiments, and the limited number of characteristics (e.g., yield, foliar content, root growth) investigated, experimental results may not reveal the most significant components of change. For example, small grain crops showed no change in productivity with increasing acidity of simulated acidic precipitation, but they did show reduced root biomass. The effect of root growth on marketable yield or plant vigour might only be observed during a drought, or in dry farming conditions (Lee 1981).

9.1.4 Sensitivity of Growth and Yield

To summarize plant sensitivity to simulated acidic wet deposition: dicots were more likely to show inhibited growth than were monocots, and no experiments reported an inhibition of growth, for any species, above pH 4.0. The threshold dose for change in yield and the scope of change vary among species and cultivars. Growth conditions (e.g., greenhouse or field plots) and dose characteristics (e.g., duration and acidity) also influence plant response.

Data from over 20 experiments were analyzed to determine plant-growth response to increasing acidity. There were significant differences among experiments, in growth conditions and pollutant exposure; thus, it was not justifiable to compare dose-response curves quantitatively. Some experiments used treatments with a pH as low as 2.0. Responses were reported only if observed above pH 2.5 (i.e., if a plant showed a decrease in yield only at pH 2.0, the table will show no effect of increasing acidity).

Table 5 lists the impact of simulated acidic precipitation on the yield of roots and shoots for 19 agricultural crops. Changes in the marketable yield of seeds, pods, and fruits are given in Table 6. Insufficient data are reported to allow comparison of acidity thresholds. Yields of reproductive structures are more consistently decreased than are those of vegetative structures.

Field grown crop data are distinguished from controlled environment crop data because field grown crops consistently showed higher tolerance of simulated acidic precipitation. As the relative significance of other experimental features was not known, experiments were separated only according to field or controlled conditions for analysis in this review.

The groups of crops most susceptible to reductions in yield were root, cole, leafy, tuber, legume, fruit, grain, seed forage, and leafy forage crops, arranged in order from the most susceptible to the least susceptible. There were insufficient data to rank bulb crops.

Dicots, which include root, leafy, cole, tuber, legume, fruit, and flower crops, showed sensitivity to simulated acidic solutions with pH lower than 4.0. Root crops are the most sensitive agronomic group, with low resistance to both foliar injury and yield reduction. Cole crops experienced significant reductions in marketable yield. Biomass partitioning was also affected, favouring root growth in most cases. Legumes include many economically important seed and forage crops, such as soybeans and alfalfa. Market yield of forage legumes was stimulated at moderate levels of acidity, above pH 3.0, although root mass may be reduced. Pod formation was inhibited in soybean and bean (P. vulgaris) crops. More study of legumes, under standard agronomic conditions, is recommended. The long-term effects on perennial legumes also warrant continued study. Herbaceous fruit growth peaks at a moderately low pH, around pH 3.5; however, visible foliar injury occurring at this pH range may counteract economic benefit associated with an increase in biomass. While apple trees are resistant to simulated acidic precipitation above pH 3.0 in a single season of exposure, fruit set was inhibited after two seasons of treatments. Subambient pH (below pH 4.0) solutions induced delayed fruit ripening in McIntosh apples, which could have serious economic impact. Monocots, which include grain, bulb, and forage crops, are in general stimulated or not affected by exposure to simulated acidic precipitation above pH 3.0. Among the grains, sweet corn is the most sensitive crop. While market yield was not affected, root growth was inhibited for many grains and some forage species. There was some evidence of cumulative effects among perennial forages, such as ryegrass.

To address crops of importance to Alberta in more detail, data from four selected experiments were treated statistically to generate a rough dose-response relationship. These experiments were well documented and of similar methodology. Between pH 5.6 and pH 3.5 no consistent dose-response relationships were found. Below pH 3.5 the dose-response approached a linear relationship, with a yield loss of about 5% per drop in pH unit below pH 4.0. Table 6 summarizes this effort.

A direct correlation between visible foliar injury and yield has yet to be established. An insufficient number of species has been studied to support generalizations. Also, reductions in yields have been observed in the absence of foliar injury. Thus there must be other, or additional, mechanisms responsible for growth inhibition. In addition, simulated acidic wet deposition exerts numerous, competing influences on plant growth, as do environmental conditions. Reliable dose-response predictions cannot usually be made without at least two to three years of replicate studies conducted using standard agronomic practices.

9.1.5 Reproduction

The impact of acidic wet deposition on successful reproduction of plants is both an economic and an ecological concern. The formation, development, and survival of pods, flowers, and fruits are sensitive to acid precipitation at moderately low pH's (below pH 4.0). The reproductive structures of fruit crops may be at greater risk than is the foliage (Forsline et al. 1983a), in terms of both visible injury and reductions of marketable yield. There are very few experiments investigating the impact of acidic wet deposition on reproductive processes of agricultural plants. Research is needed on all aspects of reproduction, including seed germination, seedling emergence, pollen viability, and fruiting. Pollen viability, which has been tested for apple, grape, tomato, and camellia, appears to be more sensitive in herbaceous species than it is in woody species. Acidic wet deposition may interfere with anthesis, fertilization, and fruit set, development, and maturation. In perennial species, deposition may have cumulative effects on fruiting.

9.1.6 Pollutant

The atmospheric pollutants reviewed were sulphuric and nitric acids in simulated precipitation, and where published material was available, dry acidic particulates and aerosols. Acidic wet deposition can vary in ways that affect crop yield (e.g., S to N ratio, chemistry, intensity of rain, level of acidity). To determine and describe plant response, it is necessary to be able to describe the dose in terms of all significant components. More research is needed to determine which aspects of the pollutant exposure affect plants the most. For example, it is not known whether the dose can be sufficiently described by the pH (concentration of acidity) or if reporting the total hydrogen deposition over a time-period is also necessary or if some other approach is required.

In the absence of conclusive evidence, it is assumed that both the instantaneous dose (i.e., concentration) and the cumulative dose (i.e., total deposition) are significant in influencing plant response. Other parameters of precipitation composition, such as the sulphate to nitrate ratio and the peak or constancy of pH (over multiple treatments), appear to influence plant response, as do temporal factors such as length of time during and between rain events.

Since rainfall patterns vary with season, and therefore with stages of plant development, an understanding of the relationships between precipitation characteristics and foliar injury is necessary to enable prediction of damage from changes in atmospheric quality. For flowering plants, the brief bloom period is very vulnerable to external influences. Usually the bloom is in the spring, which coincides with periods of high acidity rainfall in many regions of North America. Atmospheric monitoring is needed throughout entire growing seasons, with temporal aspects of deposition also reported.

In numerous experiments the presence of other atmospheric pollutants, such as ozone, was detected; most experiments did not monitor the field site for gaseous pollutants. Clearly, monitoring for all significant pollutants is necessary to correctly interpret plant response.

9.1.7 Growth Conditions

Environmental and edaphic conditions regulate plant response to simulated acidic wet deposition (Troiano et al. 1984) The growth conditions that were shown to influence plant dose-response were irrigation, the structural environment, and plant nutrition. Edaphic factors, climate, location, and season, are also significant in plant growth and can vary among experiments. Plants are more sensitive to stress (i.e., pollution) in controlled environments such as greenhouses and growth chambers than in field plots. Water stress and waterlogging were identified as causative agents in reductions in plant growth. Plants were more susceptible to foliar injury under a nutrient rich regime. The relationship between crop yields in experiments and crop yields under standard agronomic conditions is an important concern for future research.

9.2 GASEOUS POLLUTION

The effects of gaseous air pollutants on agriculture have been studied to varying degrees in the last three decades. In the following pages the effects of gaseous air pollutants on agricultural crops are summarized. The effects considered are: physiological effects, foliar response, effects on growth and yield, and effects on reproduction. Experimental design as it affects these responses is then reviewed. Lastly, agricultural species' sensitivities are summarized.

Effects on plant physiology due to gaseous pollutants are important because the changes in physiological and metabolic processes initiate pollutant induced changes involving growth, development, and reproduction.

Sulphur dioxide directly affects the stomata, which may be induced to open or close. Once the SO_2 enters the leaf through the stomata, it contacts mesophyll cells where it hydrolyzes in the surface fluid to become sulphite. If the plant's capability to oxidize sulphites is exceeded, sulphites build up to toxic levels and cause injury.

Most studies indicate a decrease in photosynthesis with increased SO_2 exposure. Conflicting results exist from the studies of the effects of SO_2 on dark respiration and photorespiration.

After entering through the stomata, nitrogen oxides diffuse through the intercellular spaces to the mesophyll and parenchyma where they react with the hydrated cell surfaces to form a mixture of nitrous and nitric acids. When this acid exceeds a certain threshold, the tissues are injured. Most studies indicate a decrease in photosynthesis due to NOx at elevated concentrations. Increases in photosynthesis have been observed with fumigations of very low concentrations.

Ozone differs from the other gaseous pollutants mentioned in this review in that exposure to it is believed to increase the permeability of cell membranes and cause leakage of ions. Once O_3 passes through the stomata, it attacks the plasmalemma lining of inner walls of cells. The permeability of the plasmalemma is disrupted, allowing leakage of cell contents into intercellular spaces. Most studies indicate that O_3 induces stomatal closure and inhibits transpiration. It is generally accepted among researchers that ozone inhibits photosynthesis and alters the way in which the photosynthetic products are distributed within the plants.

Few experiments have been conducted on the effects of H_2S on plant physiology. Stimulated photosynthesis and increased stomatal conductance at ambient concentrations of H_2S have been reported.

The most readily observed symptoms of gaseous pollutant exposure are visible foliar injury. Foliar effects can be divided into two categories: acute and chronic. Acute injury to plant tissue occurs within hours or days after exposure to short-term (less than 24 hours), high concentrations of gas. Chronic injury to plant tissue develops over a period of time (from more than one day to one or more years) from exposure to variable and lower concentrations of gas.

The most commonly observed foliar symptom of acute SO_2 injury is foliar necrosis, in which metabolic processes cease and plant cells are killed. Acute foliar injury has been observed in dosages as low as 0.03 ppm (one hour exposure), 0.025 ppm (six hour exposure), and 0.05-0.12 ppm (four to eight hour exposure) in sensitive species. Chronic injury includes chlorosis (sometimes changing to necrosis) in which the cells are not killed, but leaves become bleached. The leaves remain turgid but function less efficiently.

Nitrogen dioxide is the only oxide of nitrogen that has been found to injure vegetation at concentrations found in ambient air. The most commonly observed symptoms of acute NO_2 injury are interveinal water soaked lesions appearing on the adaxial leaf surface. These lesions rapidly collapse and bifacial necrotic areas develop. Symptoms of chronic NO_2 injury include chlorosis, premature defoliation, and fruit drop.

The most common symptoms of foliar injury due to O_3 are pigmented lesions, surface bleaching, bifacial necrosis, and chlorosis.

Typical foliar symptoms due to H_2S include scorching and wilting (without discolouration). Colour of markings are usually white to tan. Hydrogen sulphide concentrations above 0.1 ppm may cause plants to develop necrotic lesions or marginal leaf and needle tip burn.

Gaseous air pollutants may cause either increases or decreases in growth and yield. The effects of gaseous pollutants on growth and yield are of primary concern in agricultural systems. They can have more of an economic impact on the agricultural industry than any of the other effects of pollutants.

Low concentration SO_2 exposures can cause an increase in growth and yield in plants in sulphur-deficient soils. Most researchers have observed that the increases in yield a plant experiences in the presence of SO_2 do not occur when plants are grown in soils with sufficient sulphur. Several studies have shown significant decreases in growth and yield due to SO_2. To avoid deleterious effects on growth and yield to agricultural crops, average concentrations of ambient SO_2 should not exceed 0.01 ppm and hourly averages should not exceed 0.06 ppm.

Nitrogen dioxide in low concentrations can assume the role of a fertilizer and be a source of necessary nitrogen for the plant. Investigators have reported increases in plant growth and yield with low concentration NO_2 exposures, with plants grown in both nitrogen-deficient soils and those with optimum nitrogen nutrition. Concentrations of 0.05 ppm of NO_2 maintained continuously can cause small reductions in growth and yield for sensitive agricultural species.

Most of the studies conducted on the effect of NO_2 on growth and yield have been at high concentrations (more than 1.0 ppm). This is in part because many agricultural species may have only slight changes in growth and yield at concentrations as high as 1.0 ppm when plants are exposed to NO_2 alone. Acute exposures appear more injurious. Decreases in growth and yield at NO_2 concentrations less than 1.0 ppm have been observed.

Ozone has been proven to reduce growth and yield of many agricultural species. For O_3, the lowest limit for injury follows several hours of exposure to a concentration range of 0.02 to 0.05 ppm for the most sensitive species under general conditions.

Hydrogen sulphide is the most phytotoxic of the gases reviewed. At concentrations commonly found in the ambient air, however, the actual risk posed to plants by H_2S is much lower than the risk from the other gases. For most species investigated in this review there were either no effects or increases in yield with long-term exposures at a concentration of 0.10 ppm; but with a concentration of 0.30 ppm, decreases in yield were quite evident. For more sensitive species, yields were reduced at concentrations as low as 0.03 ppm.

Gaseous pollutants can affect plant reproduction in two ways. First, they can have a direct effect on reproductive structures and processes, and secondly, they can have an indirect effect on the plant when the reproductive structures compete with vegetative structures for metabolic assimilates, causing adverse effects on flower and fruit development. For agricultural fruit, seed, and nut crops, these effects on plant reproduction become quite important economically.

Sulphur dioxide exposure can affect plant reproduction in both the flowering and fruiting stages. Several researchers have reported losses of fruit and seeds due to SO_2 exposure. Pollen germination can also be reduced due to SO_2 exposure.

It has been known for several years that NOx causes detrimental effects on flowering and fruiting of vegetation. Decreases in yield of fruits and seeds have been observed at concentrations as low as 0.1 ppm in long-term exposures.

Ozone has caused detrimental effects on reproduction via decreases in grain, seed yield, or floral yield, as number and weight of fruit, and as delayed fruit setting. Both pollen germination and pollen tube growth can be inhibited by exposure to O_3.

Hydrogen sulphide has been observed to cause changes in plant reproduction by depression of seed germination.

From the research conducted on the effects of various pollutants on agricultural crops, it is useful to classify these crops by their sensitivity to each pollutant.

The relative ranking of plant sensitivities to SO_2 was analyzed for forages and grains because they occupy approximately 75% of the acreage of improved land in Alberta. Red clover was calculated as the most sensitive species followed by the winter grains, wheat, and rye; next in sensitivity are other grains, barley, spring wheat, and oats; at the less sensitive end of the scale is alfalfa; the most resistant of the species studied is canola. Alfalfa has been determined by other investigators to be very sensitive to SO_2. Perennial grasses are more sensitive to SO_2 than is alfalfa. Annual grasses seem to be significantly less sensitive than alfalfa to SO_2.

Forage, grain, and grass species can be ranked for relative sensitivities as follows:

clover > winter grains > spring grains > alfalfa > canola

and

winter grasses > alfalfa > other grasses

The position of alfalfa in the first ranking is not definite.

The relative sensitivity of many agricultural crops to NO_2 is as follows: Of the field crops and grasses, the leguminous forage crops and some grains (barley and oats) are the most sensitive. Also sensitive are several garden or "truck" crops including a bulb crop (leek), a root crop (carrot), a leafy crop (lettuce), and a stem crop (celery). Truck crops considered to be of intermediate sensitivity are a fruit crop (tomato) and the same stem crop (celery). Also of intermediate sensitivity are an annual grass (bluegrass), other grains (wheat, corn, and rye), and a tuber (potato). Considered resistant are a perennial grass (Kentucky bluegrass), truck crops consisting of two cole crops (cabbage and kohlrabi), the same root crop (carrot), and another stem crop (asparagus).

The relative sensitivity of many agricultural crops to O_3 is as follows: Leafy vegetables are the most sensitive in all cases and perennials and woody species are the most resistant. For the sensitive and resistant plant types, grasses and legumes are more sensitive than oats (a grain); but for intermediate plant types, wheat (a grain) is more sensitive than the grasses which in turn are more sensitive than legumes and clover.

To correctly interpret experimental data, it is important to understand experimental design and how this design affects experimental results. Experiments testing the same hypothesis can have significantly different results by employing a different experimental design. Upon analyzing results from different experiments, what appear to be conflicting results could simply be the result of differences in experimental methods and procedures. The variety of different experimental designs makes comparison among experiments very difficult and ambiguous. Factors that may vary among experiments are pollutant type, method of pollutant exposure, plant species or variety, stage of plant development, edaphic factors, and climatological factors such as light, humidity, precipitation, and temperature. The environment of the experiment as influenced by the experimental apparatus is also important in that it may influence plant response. Different experimental types that may affect plant response are controlled environments, controlled field experiments, and natural field experiments.

The increased phytotoxicity of a given gaseous pollutant in the presence of another has become an important consideration when assessing the impact of pollutants on vegetation. Frequently, elevated concentrations of more than one pollutant exist as a result of atmospheric mixing, the emissions of a pollutant into already polluted air, the simultaneous emission of more than one pollutant, or the chemical conversion of different pollutants. Most pollution sources emit more than one pollutant. These mixed emissions may be simultaneous or sequential over time.

Interactive effects of pollutants in combination can be described as follows:

(1) The plant response to the pollutant mixtures is additive, and is similar to the summed effects of the individual pollutants.
(2) The plant response may be antagonistic (less than additive).
(3) The plant response may be synergistic (greater than additive).

In addition, in sequential exposures, plants may become sensitized or hardened to a pollutant by a previous exposure to a different pollutant. Changes in injury type may also occur in plants exposed to pollutant mixtures compared to single pollutants. Plant responses to pollutant combinations depend not only on the components of the mixtures and their temporal succession, but also on the same factors that influence plant response to single pollutant exposure.

Sulphur dioxide and O_3 are the two pollutants most frequently found in mixture in ambient atmospheres. Nitrogen dioxide is a third pollutant to consider in pollutant mixture studies and evaluations. The potential for synergistic responses from mixtures of NO_2 and SO_2 is considered to be the most important way that NO_2 reacts in the atmosphere reacts with vegetation.

In general, the foliar symptoms observed in plants exposed to a mixture of O_3 and SO_2 are the same as those that characterize O_3 injury. In some cases foliar symptoms are observed which are distinctive from those found on foliage after exposure to O_3 or to SO_2 alone. Foliar injury can be affected synergistically, additively, or in an antagonistic interaction. Most of the studies seem to show an antagonistic interaction between SO_2 and O_3 on foliar injury.

Various studies have shown that a synergistic response of decreased plant growth and yield can occur at low concentrations (at or below the threshold for visible injury) of SO_2 and O_3. This response is observed more often than an antagonistic response but less often than an additive one.

Researchers have reported a variety of interactions between SO_2 and NO_2, ranging from synergism to antagonism. Most of the experiments have reported additive or synergistic effects and few have observed antagonistic effects.

Symptoms of injury resulting from the pollutant mixture of SO_2 and NO_2 often resemble foliar injury caused by O_3. The visible injury threshold for the most sensitive agricultural species is between 0.05 ppm and 0.10 ppm for each gas when SO_2 and NO_2 are present together. Researchers have found synergistic, additive, and antagonistic interactions between these gases on visible foliar injury.

As with foliar effects, reductions in growth and yield due to SO_2 and NO_2 mixtures may be synergistic, additive, or antagonistic.

Limited data are available on the effects of SO_2 and NO_2 on reproduction. Pollen tube growth has been reported to be inhibited synergistically.

There have been few reports concerning the effects of NO_2 and O_3 in combination on all plant responses. Synergistic, additive, and antagonistic interactions have been observed in foliar injury caused by exposures to NO_2 and O_3 mixtures. Plants have been observed to be sensitized to O_3 by exposures to NO_2 with respect to responses in growth and yield. Synergistic to antagonistic interactions for effects on growth and yield due to mixtures of NO_2 and O_3 have been reported.

Pollutant combinations containing O_3, including the mixture of O_3, SO_2, and NO_2, cause foliar injuries similar to those seen when O_3 is present singly. An antagonistic response to foliar injury when these gases were present in equal concentrations has been observed.

Researchers have found that in nearly every instance, exposure to the three pollutants (O_3, SO_2, and NO_2) causes a greater loss in plant growth and yield than the single gases or the two pollutant mixtures. Studies conducted thus far have been important because they have shown that growth and yield responses to this mixture occur in the NO_2 concentration range of 0.05 to 0.30 ppm, well below the air quality standard for NO_2 and within ambient elevated NO_2 concentrations. The decrease in growth and yield caused by NO_2 in the presence of SO_2 and/or O_3 ranges from 5% to 20% at concentrations of NO_2 that cause little or no injury when the pollutant is present singly.

Studies on the effects of combined exposures of wet acidic deposition and gaseous pollutants on plants are only in their initiation. These studies thus far generally show synergistic and additive interactions. The interaction between gaseous pollutants and wet acidic deposition is significant because these two pollutants usually occur concurrently.

Additive responses for foliar injury have been observed in mixtures of acidic precipitation and SO_2 and in mixtures of acidic precipitation and O_3. In addition, synergistic responses have been observed with the latter mixture.

Both synergistic and additive responses have been observed for yield reductions in plants exposed to mixtures of simulated acidic precipitation and O_3. An additive response has also observed in plants exposed to mixtures of simulated acidic precipitation and SO_2. An additive interaction between acidic precipitation and a gaseous mixture of SO_2 and O_3 has been reported for inhibition of plant growth.

9.2.1 Soil

Acidic deposition could significantly decrease soil fertility. The potential changes in Alberta soils as a result of acidic deposition are reviewed by Turchenek et al. (1987). Soil response will be greater in unmanaged soils than in agricultural soils, where amendments such as fertilizer have a dominant effect. The most likely changes in soil are a rise in the acidity of the soil solution, a rise in exchangeable aluminum, and a decrease in the base saturation capacity. Acidity is not directly toxic until the pH is below 3.0; aluminum toxicity is the most common cause of crop failure on acidic soils. Manganese toxicity and calcium deficiency are common problems. Toxicity and deficiency symptoms for other elements also occur. Under some conditions (e.g., sulphur-poor soils) plant growth may be stimulated by acidic deposition.

Tolerance for acidic soils varies among crop species. Tables 29 to 34 rank species according to their tolerance for different changes in the soil environment. Among species prominent in Alberta, oats are the most tolerant of acidic soils. Alfalfa, barley, and canola are the most sensitive. Because plants are not uniformly sensitive to all properties of acidic soils, only broad generalizations can be made about plant suitability for alkaline or acidic soils. Specific recommendations or warnings are best based on data from the field site, although general guidelines should be used in the absence of complete data.

Although the grasslands of Alberta have rich, well buffered soils, acidic deposition can affect them. There is potential for changes in reproduction, decreased productivity, or alterations in partitioning of photosynthate as a result of foliar exposure to acidic deposition. The threshold, in terms of pH of acidic wet deposition or total free-hydrogen deposition, has not been determined. The secondary effects can be lower tolerance of some environmental stresses (e.g., drought) and changes in species viability.

In managed agricultural systems, results of acidic precipitation are more likely to be lower productivity, lower marketable yield, and lower resistance to some environmental stresses (e.g., pathogens).

9.2.2 Pathogen

Acid deposition may affect plant-symbiont interactions through impact on the plant, the symbiont, or both. Acid deposition can alter the plant's quality as a host organism or decrease plant resistance to infection. Symbiotic organisms may be affected at different stages of their life cycle (e.g., reproductive phases).

Shriner (1980) concluded that acidic wet deposition is of greater significance than is dry deposition in affecting interactions between plants and their pathogens.

Changes in plant biochemistry produce significant changes in insect populations because of associated alterations in insect location, recognition, and acceptance mechanisms. Insect behaviour and viability are also affected by plant metabolites which may act as deterrents, antibiotics, or growth inhibitants. Pollutants may reduce the ability of the plant to produce defensive chemicals.

Sulphur dioxide may induce physiological changes similar to those occurring with natural maturation. Because some insects prefer consuming older plants, the effect of SO_2 may thus be to increase predation from those insects.

Plant-feeding insects are relatively unaffected by contact with gaseous pollutants such as O_3, but are significantly affected by water soluble pollutants, such as acidic sulphate aerosols.

Stimulation or inhibition of growth and reproduction due to acidic precipitation varies for bacteria, yeast, and fungi. Bacteria are the least resistant to acidity, while fungi are generally the most resistant. Diseases caused by obligate fungal parasites have been found, as a rule, to be restricted in development by air pollutants.

Most experiments on plants and pathogens used values at the extremes of ambient pH ranges (e.g., 2.5 and 6.0) and no control for ambient gaseous-pollutant levels. From these experiments it is not possible to identify the pH levels at which significant biological stress would be observed under ambient levels of pollution. More research is needed using pollutants of realistic composition and application, with appropriate pollutant-free controls. More research is also needed to determine whether lower acidity has similar effects in natural and experimental conditions.

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