REPORT
on the
CROP RESPONSE WORKSHOP
of the
NATIONAL ACID PRECIPITATION ASSESSMENT PROGRAM

April 17-18, 1986
Chicago, Illinois

Sponsored by

The Interagency Task Force on Acid Precipitation
722 Jackson Place, N.W.
Washington, D.C. 20503

Organized by

Argonne National Laboratory
9700 S. Cass Avenue
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SUMMARY

The Workshop was convened to evaluate the state of knowledge on the impact of acidic deposition and associated oxidants on agricultural crops in order to determine future research needs to fulfill NAPAP policy objectives. To provide background information, the exposure-response relationships for major crops exposed to acidic rain, ozone (O_3), sulfur dixoide (SO_2), nitrogen oxides (NO_x) and their combinations were summarized. Additionally, significant findings from the most recently completed research on crop effects from acidic rain were presented by the principal investigators.

Information gaps were identified for three areas:

1.) Dose-response relationships;
2.) Mechanisms; and
3.) Interactions

Although the research completed to date does not indicate important effects of acidic deposition on crop systems, there are some critical and unexplained features in the body of data that suggest the possibility of impact under certain conditions. Increased knowledge in crop effects could also provide direction to investigations regarding the mechanisms for effects of both acids and oxidants in other terrestrial ecosystems (e.g., forests).

Workshop participants identified four critical areas for future research efforts:

1. <u>Determine the biochemical and physiological changes in the plant that lead to a response to acidic deposition and associated oxidants.</u>

   These studies will provide the information needed to explain and support observations which have:

   - demonstrated clear response differences among species and cultivars to given concentrations of O_3 and possible sensitivity to acidic rain for one cultivar of soybean;

   - indicated site-to-site and year-to-year differences in the yield response function for wheat and other crops exposed to O_3 and for a possibly sensitive soybean cultivar exposed to simulated rain; and

   - suggested that O_3 and acidic rain dose-response functions are modified by soil moisture status.

Studies should emphasize resource allocation during specific plant growth stages which will identify the step(s) in carbon-cycling that translate acidic deposition and O_3 stresses into yield loss.

2. Identify other stresses which may be enhanced by or which affect plant response to acidic deposition and/or oxidants.

   - Available research data (such as the year-to-year and site-to-site differences in response) suggest that the magnitude of acidic rain and oxidant effects are controlled by the environmental conditions to which a plant is exposed.

   - Preliminary studies have indicated a synergistic effect of acidic rain and drought in reducing the yield of a field corn hybrid previously considered insensitive to acidic rain.

   - Preliminary evidence suggests that soil moisture conditions may affect root/shoot carbon allocation in soybeans exposed to O_3.

   - Research has also shown that acidic rain affects leaf surface characteristics such as buffering ability and wettability. This suggests that acidic rain may enhance the uptake of phytotoxicants (such as O_3) and weaken the barrier to plant pests (e.g. insects, bacteria).

3. Identify the components of acidic deposition and O_3 exposure dynamics that are important in affecting plant response.

   - Ozone has been studied more with regard to crop effects than any other pollutant and yet the effect of different exposure dynamics (such as total dose vs dose rate) is not well understood even for this pollutant.

   - Wet and dry acidic deposition consists of multiple variables relating to chemical (e.g. H^+, SO_4^{-2}, NO_3^-), physical (e.g. fogs vs. thunderstorms) and temporal (e.g. duration, frequency) characteristics. Different combinations of these variables have not been examined.

   - Evidence suggests that the length of "recovery" periods in conjunction with stage of plant development can affect the magnitude of damage from exposures to O_3. Similiar results have been obtained in preliminary studies with acidic rain. The influence of concentration peaks and exposure duration is also believed to be important in affecting response to both acidic deposition and O_3.

4. Broaden the scope of knowledge regarding the sensitivity to acidic deposition and oxidants of regionally important crops in areas currently receiving high exposure rates.

- The establishment of techniques for short-term screening experiments capable of establishing the relative sensitivity of a crop to yield damage would be most valuable in light of the species and varietal differences to acidic rain and O_3 exposure which have already been documented.

- There are inadequate data for effects on forage crops which are under low levels of management. Their perennial nature suggests potential for longer-term effects on both plant and soil productivity.

- Tree fruit and other crops which have significant value on a regional basis have received little or no investigation of pollutant sensitivity.

Well designed experiments could address nearly all these questions on a first-order level by 1990 if an aggressive research program is implemented for the 1987, 1988, and 1989 field seasons. As an added benefit, such a program will provide valuable information on mechanisms and interactions which may be occurring in the forest plant community as a result of pollutant exposure.

REPORT OF THE NAPAP CROP RESPONSE WORKSHOP

I. Introduction

The workshop was convened by the National Acid Precipitation Assessment Program (NAPAP) to evaluate the status of scientific knowledge on the impact of acidic deposition and associated oxidants on agricultural crops and to determine future research needs in this area in order to meet NAPAP policy objectives. The workshop was directed toward obtaining an understanding both of what we now know and also of what we need to know about the effects on crops from acidic substances and associated oxidants acting either alone or in combination. This knowledge is necessary in order to determine whether there is a significant problem of crop damage in the U.S. which is caused by current levels of exposure to acidic substances. The problem is considered significant if there are statistically verified direct or indirect effects of acidic substances and associated oxidants on agricultural systems which could result in declines in the quantity and quality of the marketable yield of crops considered economically important in a particular region. Three major needs are identified to aid in addressing this problem:

1. Establish exposure-response relationships for acidic deposition and related oxidants with the yield of major agricultural crops.

2. Provide information on the mechanisms by which damage occurs in sensitive systems, to support exposure-response models and to justify extrapolations.

3. Provide data which will contribute to the information needed to extrapolate research results to other exposures, plants, climates and soils.

II. Background Summary of Crop Response to Air Pollutants

A. Acidic Deposition

Corn, soybeans, wheat and hay are the four most important crops in terms of value and acreage harvested in the United States. The reliable but limited scientific evidence based on simulated rain exposures in experimental settings (replicated field studies of 15 crop varieties among nine crop species) suggests that for the most part there is no detectable effect on yield from current growing-season levels of precipitation acidity (pH 4.2 in the eastern U.S.). However, one soybean cultivar ('Amsoy') appears to have some sensitivity to precipitation acidity. Several investigations of the 'Amsoy' soybean cultivar have demonstrated highly variable results. In other field investigations, the yields of 'Williams' soybean, two cultivars of field corn and one each of wheat, clover, timothy, potato, tobacco, oat, and snap bean were reported to be unaffected by current levels of rainfall acidity in comparison to rain with no strong acids. The results from the most recently completed field studies are discussed in Section III of this document.

Greenhouse-grown radish plants have been observed to be negatively affected by rain acidity at pH levels < 4.0, whereas no such effect has been reported for field-grown radish, suggesting that environmental conditions play a role in sensitivity. Some greenhouse studies have shown that the sensitivity of radish to acidic rain stress may be related to plant growth stage and length of time between last rain event and harvest. Plants exposed during the intermediate stage of development (when growth is most rapid) had the greatest reduction in yield (from rain pH $\leq$ 4.2). Longer recovery periods and longer intervals between exposures gave the smallest reductions in dry mass from acidic rain. Furthermore, it has been demonstrated that a few highly acidic rain events (pH 2.9) interspersed over the growing season among less acidic events may temporarily reduce chlorophyll content of soybeans compared to the same amount of H+ deposition from rain at a constant, moderate acidity level. These results with radish and soybean suggest that exposure dynamics may play a role in affecting the sensitivity of plants to acidic rain.

Some studies have reported that the $SO_4^{-2}:NO_3^-$ ratio in simulated rain may affect plant response, while other investigations have reported no such effect. Soil fertility is one factor that may influence the response. In fact, sulfur and nitrogen deposition may result in nutritional benefits to plants growing at low levels of fertility.

Finally, preliminary studies suggest that acidic rain may increase the severity of some biotic plant diseases and decrease the severity of others. The overall effect appears to be dependent on the temporal sequence of rain events relative to initial and secondary infections, the type of pathogen, (obligate or facultative parasite) and environmental conditions.

B. Ozone

Because of its high level of phytotoxicity and the distribution of elevated concentrations over broad geographic areas, ozone is viewed as the most critical air pollutant that affects vegetation in the United States. The majority of agricultural land in the U.S. receives seasonal 7-hr daily mean O_3 concentrations $\geq$ 0.04 ppm with significant areas receiving $\geq$ 0.05 ppm. Foliar injury from O_3 is one of the easiest impacts to detect, but effects on plant growth and yield are not necessarily proportional to the visible injury observed. Diverse experimental methods and designs have been used to assess these impacts in the field. Comparisons of plant growth and yield in charcoal-filtered or nonfiltered air and the use of chemical protectants have shown that ambient levels of ozone are sufficiently elevated to induce foliar injury and reduce the growth and yield in numerous plant species. Ozone studies have been conducted in open-top field exposure chambers to develop the exposure-response functions needed to evaluate the economic impacts on agriculture. The response functions relating plant yield to ozone concentrations have been developed in the field using open-top chambers to which various concentrations of ozone were added. Exposure-response functions have been developed for several legume, grain, fiber and horticultural crops.

The data indicate that response to O_3 may vary by cultivar within a species and from year-to-year for a particular cultivar (Fig. 1.c.) although some response functions can be considered homogeneous (Fig. 1.d.). Yield suppression of 10% was predicted for several crop species when the 7-hr seasonal mean concentration exceeded 0.04 to 0.05 ppm compared to yields in charcoal-filtered air. For specific cultivars of wheat, kidney bean and soybean, 10% yield reductions occurred at 7-hr mean concentrations of 0.028 to 0.033 ppm.

Although various statistics have been used to characterize pollutant exposures, the most frequent is the mean concentration. However, use of the mean concentration does not distinguish between low-level long-term exposures and short-term high-concentration ones. Use of the mean ignores the observation that at high O_3 concentrations a dose over a short period causes a different effect than when the same dose is applied over a long period. On the other hand, continuous, low concentrations of O_3 may be more damaging than episodic exposures because there are no recovery periods. An additional deterrent to understanding O_3 effects is that ambient concentrations of pollutants do not easily relate to the amount that actually enters the plant (i.e. the absorbed concentration or "effective" dose). Four hypotheses have been proposed to explain the proximal cause of yield loss from O_3: increased senescence, decreased photosynthesis, altered translocation/allocation and other metabolic disturbances, and reduced pollen germination/seed set.

Plant response to ozone is influenced by various climatic and edaphic factors as well as by the presence of other pollutants. The magnitude and mechanisms for these interactions are not understood. Preliminary field studies at Argonne National Laboratory suggest that soybeans respond differently to O_3 depending on soil moisture conditions. Fine root mass of moisture-stressed soybeans was significantly greater than that of irrigated plants, however, root mass of moisture-stressed plants was negatively affected by O_3 whereas no effect was observed on plants in irrigated plots (Fig. 2). Shoot weight (leaves and stems) was suppressed by O_3 in well-watered plots and unaffected by O_3 in the moisture-stressed plots (Fig. 3).

Recent studies using exposure response functions developed in open-top chambers have attempted to assess both the regional and national (U.S.) economic consequences of ozone effects on agriculture. A number of cultivars and species have been analyzed using linear and non-linear response functions. Results showed some year-to-year variation (e.g. Fig. 1a. 1c.). In general, as O_3 levels increase, crop yield decreases,

Figure 1. Actual yield and response function for soybeans and wheat exposed to O_3 over two years. Figure from D. Tingey.

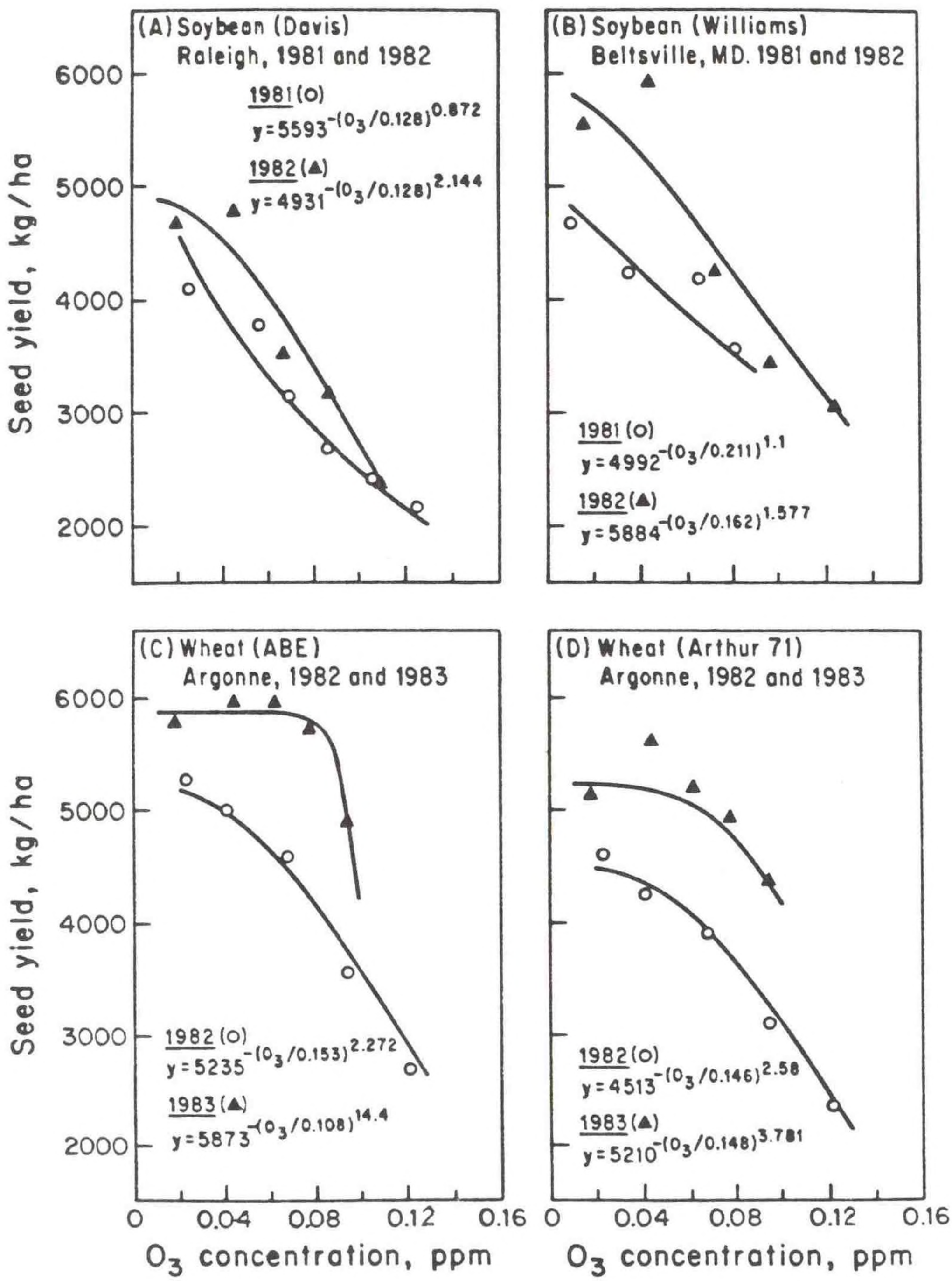


Figure 2.

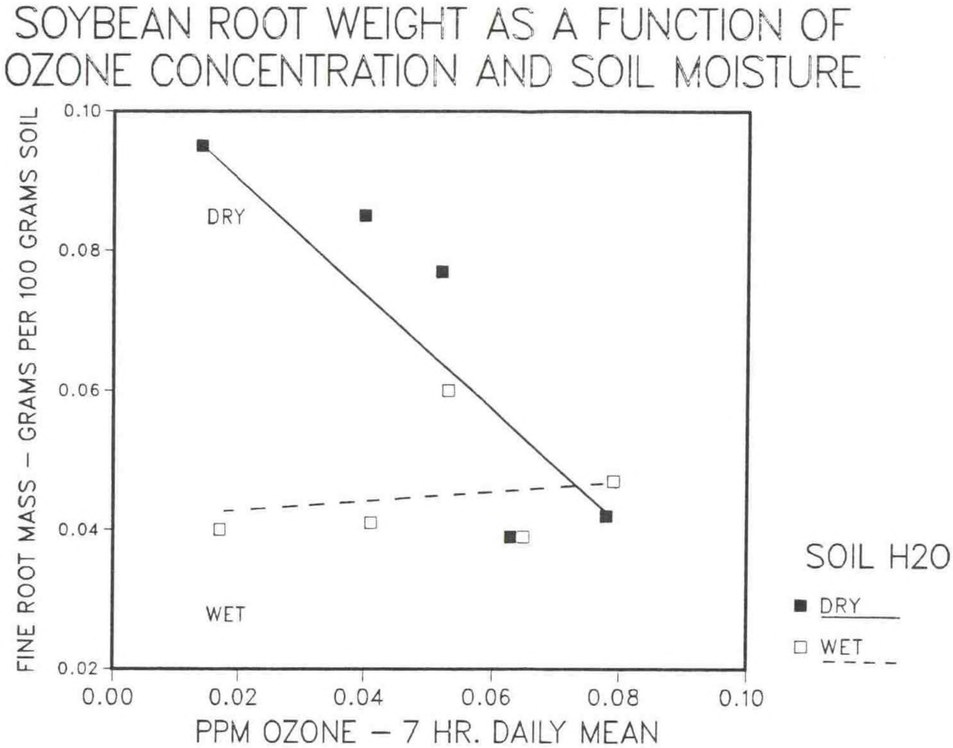
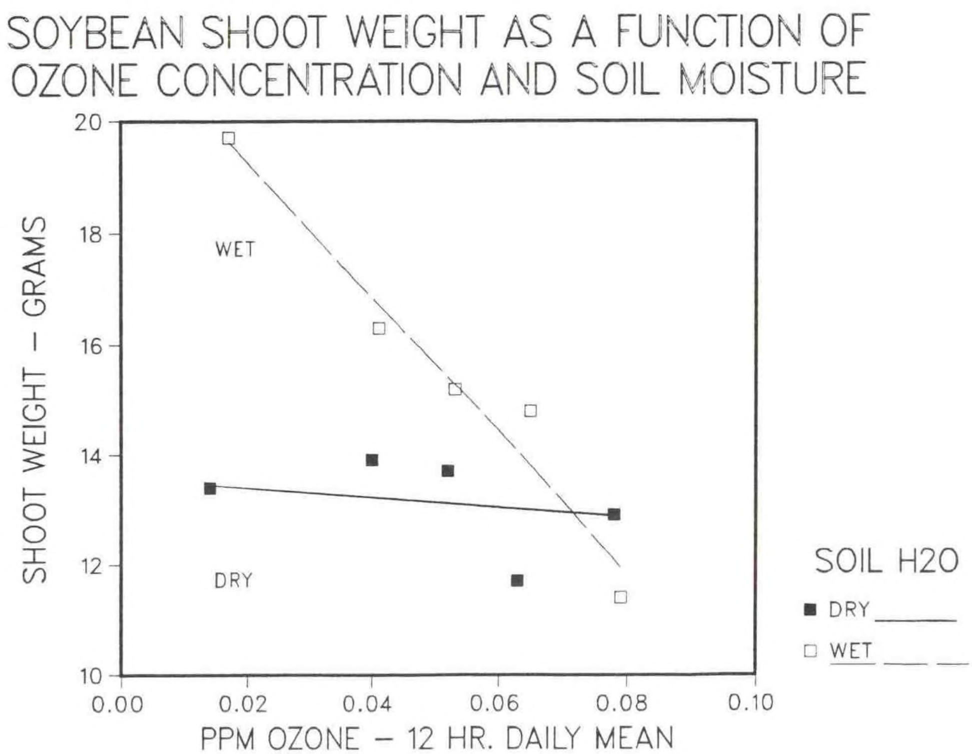


Figure 3.



although there is an indication of a threshold effect for some crops at low doses. The year-to-year variation has not been adequately explained or quantified, but cultivar, soil moisture, dose characteristics, and other environmental differences are probable causes. These studies indicate that elevated ozone concentrations may be costing the agriculture producers and consumers several billion dollars annually, although further studies are needed to substantiate these estimates.

C. Sulfur Dioxide and Nitrogen Oxides

Sulfur dioxide (SO_2) and nitrogen oxides (NO and NO_2) are considered primary pollutants because they are formed during combustion and processing operations of fossil fuels and ores and released directly into the atmosphere. Nitrogen dioxide plays a major role in the atmospheric reactions that produce photochemical oxidants (such as O_3). The precursors of sulfuric and nitric acids in acidic rain are conversion products of SO_2 and NO_2.

1. Sulfur dioxide

Plant metabolism is affected by SO_2 in a variety of ways. Sulfur dioxide may act as a fertilizer by providing needed sulfur. Sulfur dioxide has been shown to stimulate phosphorous metabolism and reduce foliar chlorophyll concentration. Carbohydrate levels have been increased by low concentrations of SO_2 and decreased by higher concentrations. The mechanisms of action of SO_2 on plants have been studied by comparing susceptible versus resistant cultivars of the same species, or by comparing susceptible and resistant species. Differences in sensitivity are often related to SO_2 uptake and thus to stomatal activity. Differential leaf sensitivity has also been explained by metabolic processes resulting in the formation and loss of hydrogen sulfide (H_2S): resistant leaves lose H_2S more rapidly than susceptible leaves.

From morphological and physiological studies it has been suggested that differences in acute injury may be due primarily to avoidance (stomatal control), while differences in response to chronic injury may have other biochemical mechanisms. However, plant physiological and biochemical processes are probably more important controllers of plant resistance to SO_2 (tolerance) than is control of gas entry via the stomates (avoidance).

Plant species are known to adapt to SO_2 stress. For example, plants in a population of Lepidium virginicum having reproduced for over 75 years near a SO_2 source, were more resistant to SO_2 than plants further from the source. Perennial ryegrass populations from areas with high SO_2 concentrations also have been found to exhibit greater resistance to SO_2 than those from areas with low SO_2.

Interactions between climatic or biotic factors and SO_2 on plant response are known to occur, but are poorly understood. Generally, plants are more sensitive to SO_2 as light intensity, windspeed, temperature, and humidity increase while elevated CO_2 levels protect plants. Freezing may increase plant sensitivity and low soil moisture tends to make plants more resistant to SO_2. Obligate fungal parasitism is generally inhibited by SO_2, while diseases caused by some facultative parasites may be increased. Usually effects are indirect, acting through the host.

Effects of low SO_2 concentrations on carbon translocation and partitioning, and on plant growth and yield have been determined. The results support the contention that plants are more sensitive to low SO_2 concentrations (< 0.10 ppm), when exposed continuously, than has been supposed. Periods without SO_2 exposure may be critical to the recovery potential of plant systems following exposure to elevated levels of SO_2.

The role of short-term fluctuations in SO_2 may be particularly important where impacts of point sources are of concern. Here concentrations may fluctuate widely during exposure, and damage to vegetation may be most closely associated with short-term averages (1-hr) or even briefer peak concentrations.

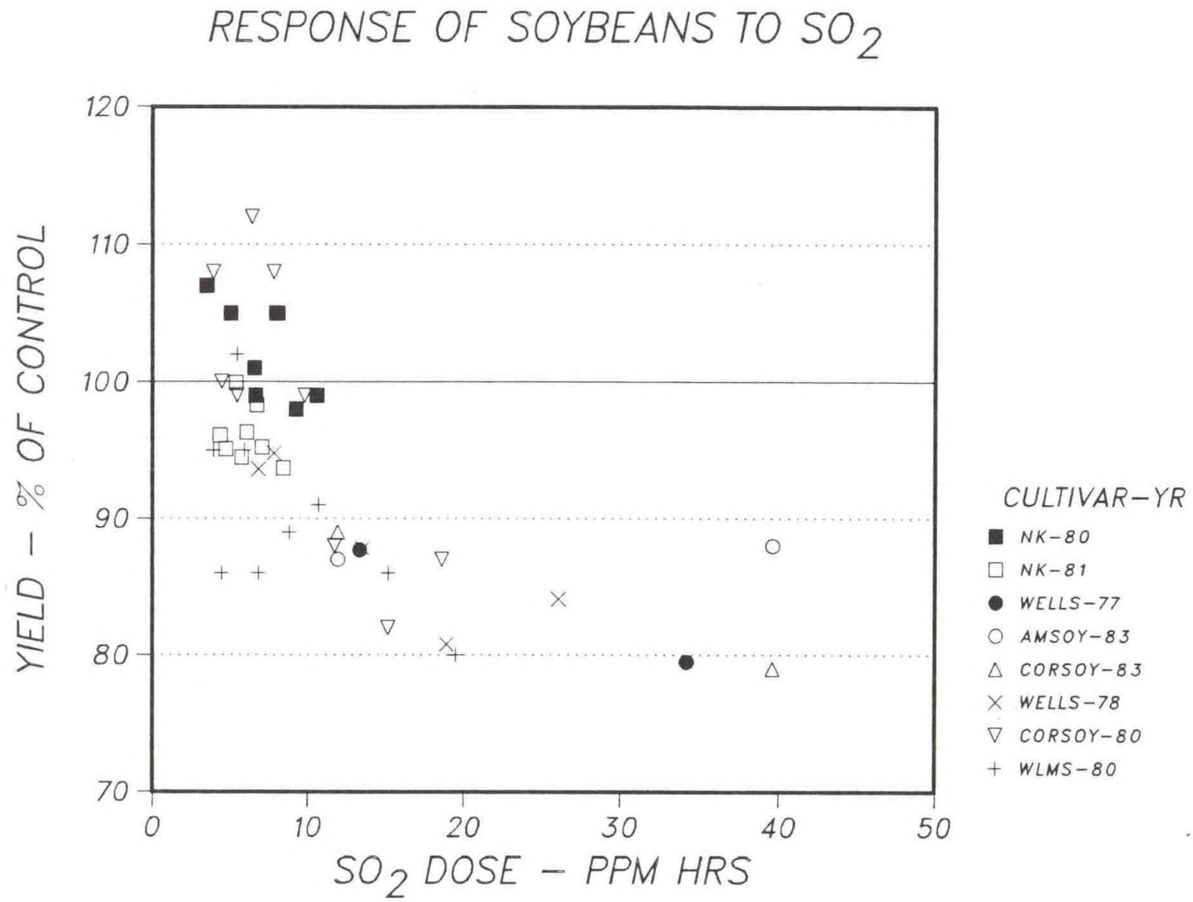
Sulfur dioxide concentrations in most agricultural areas of the U.S. rarely exceed 0.01 ppm for extended periods of time. Daily 4- or 7-hr exposures of cotton, tomato, or soybeans in open-top chambers throughout the growing season have demonstrated that in contrast to O_3, SO_2 concentrations likely to occur regionally in the United States do not suppress yield. Other studies of forage crops, winter wheat, alfalfa and potato support this conclusion. However, on a local rather than regional basis, concentrations of SO_2 near point sources (<200 km) can cause decreased yield in some crop species.

Extensive dose-response studies with an open-air exposure system have been used at Argonne National Laboratory to simulate exposures of soybeans to SO_2 near point sources. Soybean yield was consistently decreased by periodic exposures of plants after flowering to total doses of approximately 10 to 15 ppm-hours of SO_2 (Fig. 4). The 10-15 ppm-hour dose statistics are products of mean exposure durations of 2.5 to 4.2 hours per event, mean concentrations of 0.12 to 0.31 ppm, and 19 to 25 exposure events. Doses in the 5 ppm-hour level ranged from no effect to stimulatory or inhibitory. Maximum peak to mean SO_2 concentration ratios were about 2.5. In contrast to soybean, two field corn cultivars examined in similiar studies were reported to be resistant to acute SO_2 exposures.

2. Nitrogen oxides

Of the various nitrogen compounds only nitric oxide (NO) and nitrogen dioxide (NO_2) reach concentrations that may be phytotoxic. Reports on the direct effects of NO_x on vegetation are usually associated with areas near specific industrial sources. For example, vegetation

Figure 4.


RESPONSE OF SOYBEANS TO SO_2
YIELD – % OF CONTROL
120
110
100
90
80
70
0
10
20
30
40
50
SO_2 DOSE – PPM HRS
CULTIVAR–YR
NK–80
NK–81
WELLS–77
AMSOY–83
CORSOY–83
WELLS–78
CORSOY–80
WLMS–80

injury has been observed near nitric acid factories and arsenals. There are no published reports on vegetation injury in the field due to regional concentrations of NO_2 or other oxides of nitrogen.

The response of vegetation to NO_2 stress shows considerable variation. This variation ranges from leaf chlorosis and necrosis to subtle alterations of leaf metabolism and premature senescence. These responses can be explained by the physiological processes affecting NO_2 uptake into the leaf, pollutant toxicity at target sites, and cellular repair capacity. Interactions between environmental and genetic factors probably explain dissimilar plant responses to NO_2 exposures.

According to the Environmental Protection Agency's Air Quality Criteria for nitrogen oxides, the concentrations and exposure frequencies of NO_2 that produce measurable injury to crop plants are higher than those that normally occur in the U.S. (yearly U.S. ave. = 0.001 ppm; 1-hr peaks from 0.06-0.5 ppm). Even with plants considered sensitive to NO_2, a 30-min acute exposure of 6-10 ppm or an 8-hr exposure of 2-5 ppm NO_2 was required to produce a foliar injury level of 5% (i.e. 5% of the leaves exhibited injury). Episodic exposure to NO_2 as high as 11.5 ppm-hr (400 ppb for 28 hrs. distributed over a 2 month period) has had no effect on yield of field-grown soybeans. Ambient levels of NO , however, may be deleterious in combination with other pollutants even though independent NO_2 effects are not noted until concentration levels reach 1.0 ppm, an order of magnitude greater than common ambient concentrations.

D. Pollutant Combinations

Potential interactive effects between acidic precipitation and gaseous air pollutants have been the subject of considerable speculation, but little experimental verification of suggested interactions has been reported. More data are needed on physiological mechanisms of potential interactions, on sequential and co-occurrence of acidic precipitation and other air pollutants, and on dose-response relationships between crop growth and yield and exposures to pollutant combinations under field conditions.

Because of the spatial co-occurrence and sequential exposures of ozone and acidic rain, interactions between the two are possible. Ozone is widespread in eastern North America and areas of high O_3 coincide with areas of high rainfall acidity. The highest concentrations coexist in the Los Angeles area where local situations involving acid fog, O_3, and NO_x, occur in crop growing regions.

There is sound theoretical support for suspecting that acidic rain and O_3 may have additive or greater-than-additive effects on plants. Potential mechanisms of interaction include the following:

1. ozone-induced reductions in photosynthesis predispose plants to further stress from effects of acidity on leaves or soil;

2. ozone-induced disruption of cellular membranes leads to nutrient leakage which reduces the capacity of foliage to buffer or neutralize acidity in precipitation; or

3. acidity in precipitation alters the stomatal mechanism, leading to an increased flux of gaseous pollutants and greater water loss from leaves.

The small number of experiments reported to date fail to support or show very weak evidence for interactions between acidic precipitation and ozone on growth, yield, or physiological responses of alfalfa, lettuce, radish, or soybeans. Only one field experiment has been performed on acid rain/SO_2 combinations and no significant interaction on soybean yield was observed. One study of soybeans and one of a grass-sorghum hybrid indicated that the presence of O_3 diminished a stimulatory effect of rain acidity on yield of these crops. However, the paucity of data for crop species and pollutant combinations that have been tested, particularly in the field, preclude definitive conclusions on the potential for interactive effects between acidic precipitation and gaseous air pollutants.

Synergistic effects on soybean yield have been observed to be caused by exposure to combinations of SO_2 and NO_2 at concentrations causing no effect when the pollutants were applied individually. A synergistic depression of the root/shoot ratio, was observed for 0.4 ppm of SO_2 and NO_2.

Results have not indicated consistent trends in the response of plants to combinations of SO_2 and O_3. Additive, synergistic, and antagonistic responses have been reported for these pollutants and the reasons for the varied response are not known. Recent, well-designed field studies have not indicated interactive effects from O_3 and SO_2. In a field study of 'Davis' soybean using open-top chambers for pollutant exposure, neither SO_2 nor O_3 altered the dose-response relationships for the other except at high concentrations (0.125 ppm O_3 and 0.367 ppm SO_2) where the effects were less than additive. Another study reported no indication of an interactive effect of O_3 and SO_2 on the yield of 'Amsoy-71' and 'Corsoy-79' soybeans.

III. Summary of Significant Findings from the 1985 Acid Rain-Crop Effects Research

A. Soybean (Glycine max) - Yield Studies

1. Brookhaven National Laboratory

Replicated field studies of soybean with similiar experimental design have been performed for 3 years at Brookhaven. The response of 'Amsoy 71' soybean is highly variable (Fig. 5, solid lines) but generally indicates a negative effect from simulated acidic rain. An individual means comparison of seed yield (kg ha^{-1}) in 1985 indicates that plants in the control (pH 5.6) plots yielded higher than all other plots, however there were no significant differences for yield in plots receiving pH 4.4, 4.1 or 3.3 simulated rain. The results for 1985 are similar to those for 1984 in that yields in the pH 5.6 treated plots were approximately 12% higher than in the pH 4.4, 4.1 and 3.3 treated plots. No physiological explanation is available for the large yield decrease between pH 5.6 and pH 4.5 without further information. In 1983, yields from plots treated with pH 2.7 simulated rain were significantly lower than from plots treated with 4.1 and 5.6 simulated rain.

There were no significant differences in yield among treatment groups (pH 5.6, 4.4, 4.1 or 3.3) for 'Asgrow', and 'Hobbit' soybeans in 1985. For 'Corsoy', yields in plots treated with pH 4.4 and 3.3 but not 4.1, simulated rain were significantly lower than in plots treated with pH 5.6 simulated rain. These results are different from those of 1984 in which significant quadratic and linear responses were reported. Overall seed yields (kg ha^{-1}) were approximately 10% greater and plant population (or density) was about 12% lower in 1985 (as a result of planting differences) than in 1984. It is unclear whether these differences played a role in the year-to-year variation observed.

2. University of Illinois

The response of 'Amsoy 71' soybeans to acidic rain was examined for 3 years at the University of Illinois at Urbana. Results in 1985 suggested greater seed yields with increased acidity of simulated rain. These results are in contrast with those in 1983 in which rain acidity had a negative effect ($p = 0.006$ for linear effect) on yield and with those in 1984 in which acidity had no effect on yield (Fig. 5, dashed lines). There were no differences in experimental design to account for the differences in results, thus environmental conditions may explain the differences in response of Amsoy to acidity.

The yield results of Amsoy averaged over 3 years for Illinois and over 2 years for Brookhaven (the 1983 treatments were not at the same pH levels and are not included) indicate a different overall response for the two sites (Fig. 6), even though concentration and total deposition of acids were approximately the same for both sites over all years. Such averaging may be useful in determining a net effect, but will mask differences which may help to explain the mechanism of action of acidic rain. Important differences between the two sites include soil texture,

Figure 5.

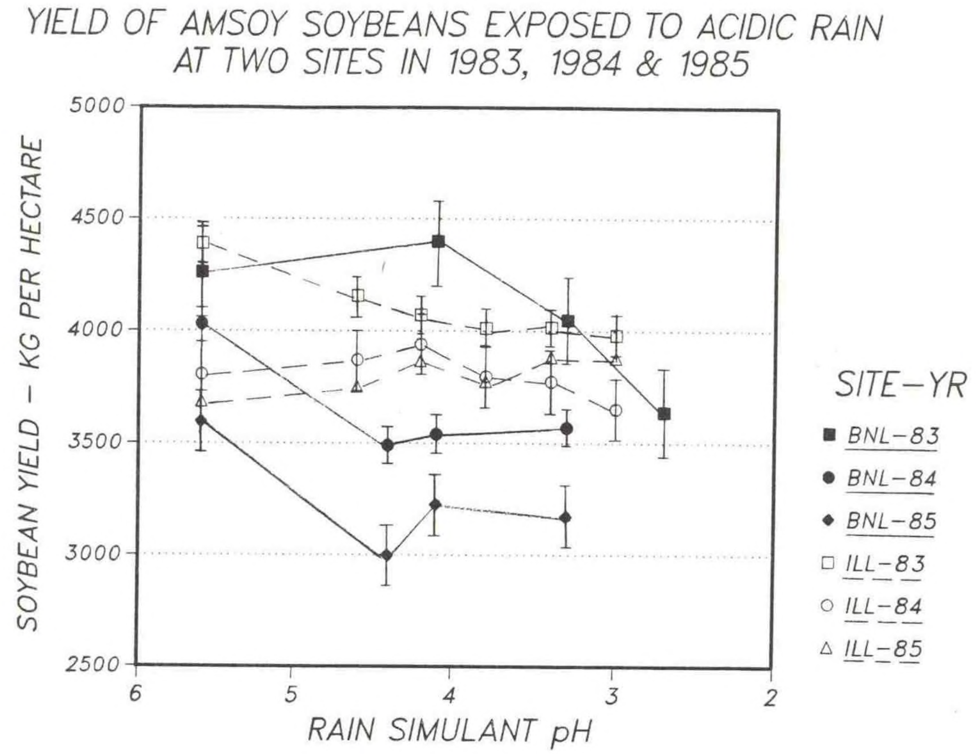
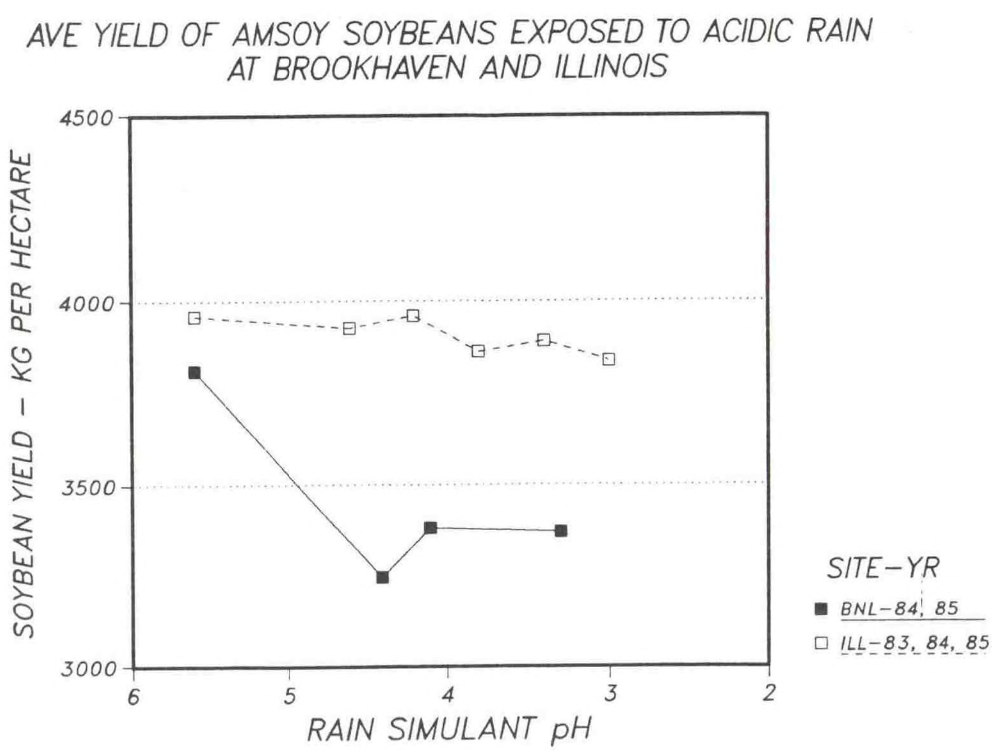


Figure 6.



time of rainfall simulation, and ambient O_3 levels. An interaction between acidic rain and one of these factors may account for the site-to-site differences in response.

'Williams 82' soybean also was examined for 3 years in Illinois to determine response to acidic rain. This cultivar has never exhibited an apparent negative response to acidic rain at pH levels similar to or less than ambient (pH $\geq$ 4.0). Results at Brookhaven and Illinois have been similar for this cultivar (Fig. 7). In studies at N. Carolina State University (NCS), the 'Forrest' cultivar has also been reported to be unaffected by rain acidity (Fig. 7).

The responses of Williams and Amsoy to acidic rain also were examined with regard to various amounts of applied rain at Illinois in 1985. Although lower quantities of rainfall resulted in decreased yield, acidity (pH 5.6 vs. 3.0) had no further effect on response.

A two-year screening study, in which 20 soybean cultivars from 5 maturity groups were exposed to pH 5.6 or 3.0 simulated rain, revealed no statistically significant effects of rain acidity on any yield parameters measured.

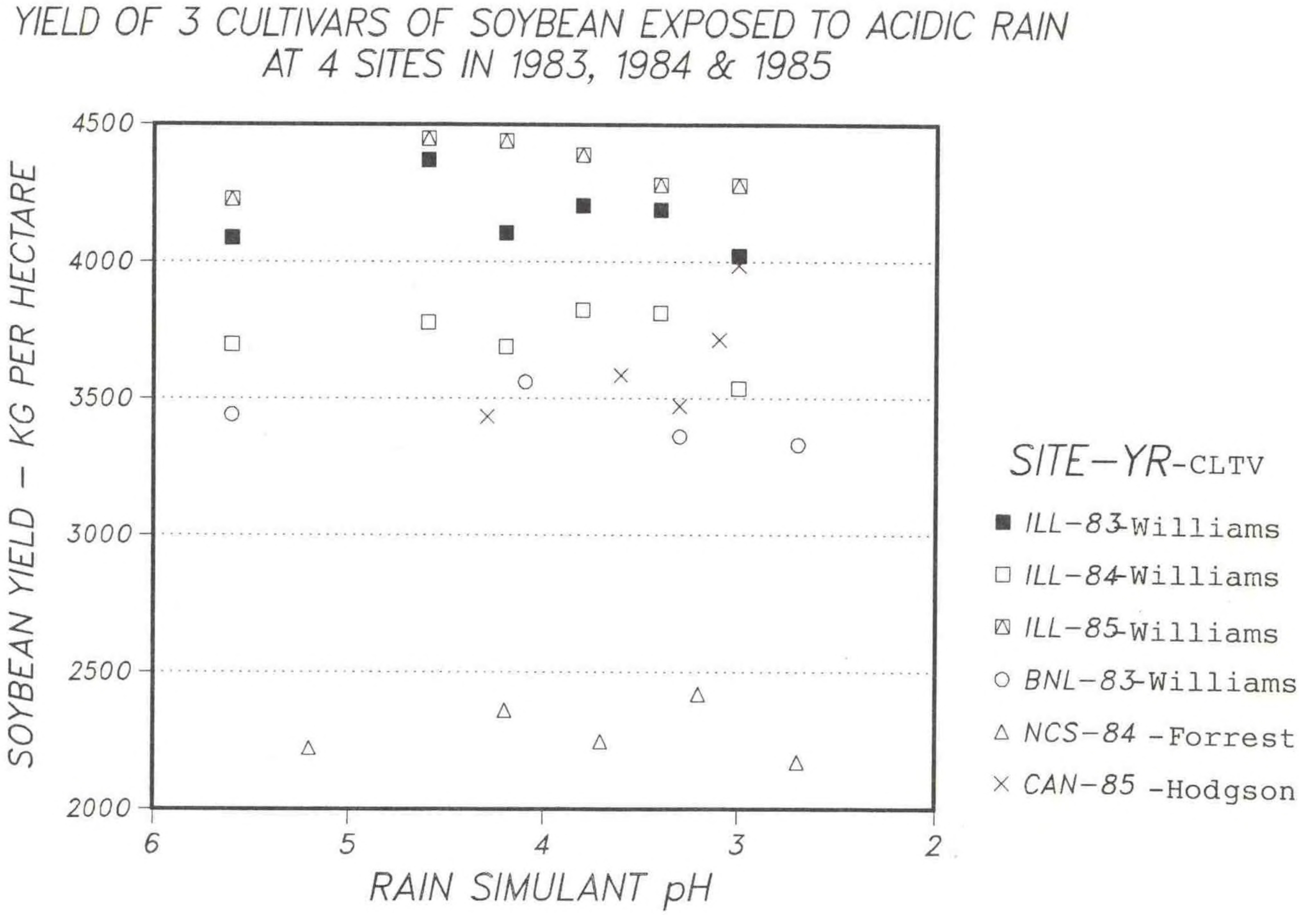
3. Canada

In a field study in which ambient O_3 was filtered from the experimental plots through use of open top chambers, Hodgson soybean exhibited yield stimulation by rainfall acidity in 1985 (Fig. 7) and no yield differences due to acidity in 1984. In contrast to the studies discussed above, this study did not include rain treatments with pH > 4.3.

B. Corn (Zea mays) - Yield Studies

Effects of acidic rain on field corn have been examined for 3 years at the University of Illinois. No statistically significant effect on yield could be attributed to rain acidity for hybrid B73xMo17 for any of the three study years when normal rainfall amounts were applied (Fig. 8). It is interesting to note, however, that overall yields for B76xMo17 in 1983 were low compared to 1984 and 1985 (possibly due to higher evapotranspirational demand). Furthermore, yield at pH 3.0 in 1983 was lower (p= 0.014) than the average for all other treatments. A study was initiated in 1985 to examine the response of field corn to acidic rain as a function of total amounts of rainfall. When simulated rainfall amounts were reduced by 50% or 75% of the average rainfall amount, yield at pH 3.0 compared to pH 5.6 was reduced by 7.4% or 16.5%, respectively, for B76xMo17 (Fig. 9). The 'Pioneer' hybrid exhibited no interactive effects from moisture and acidity stress.

Figure 7.



Except for Hodgson, none of the differences for a particular cultivar are statistically significant.

Figure 8.

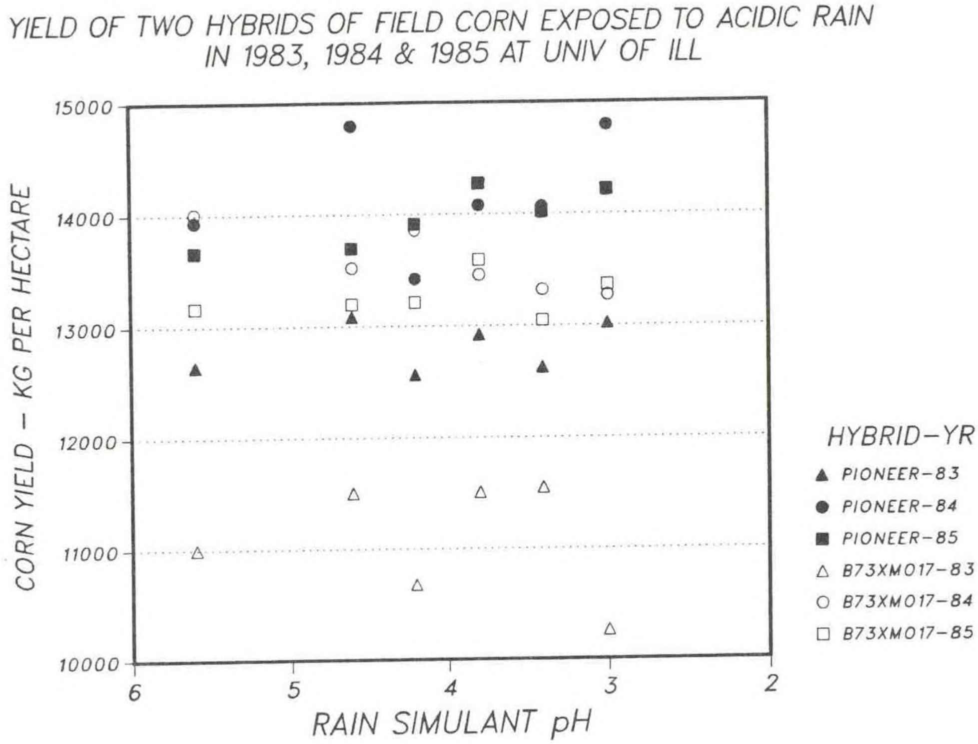
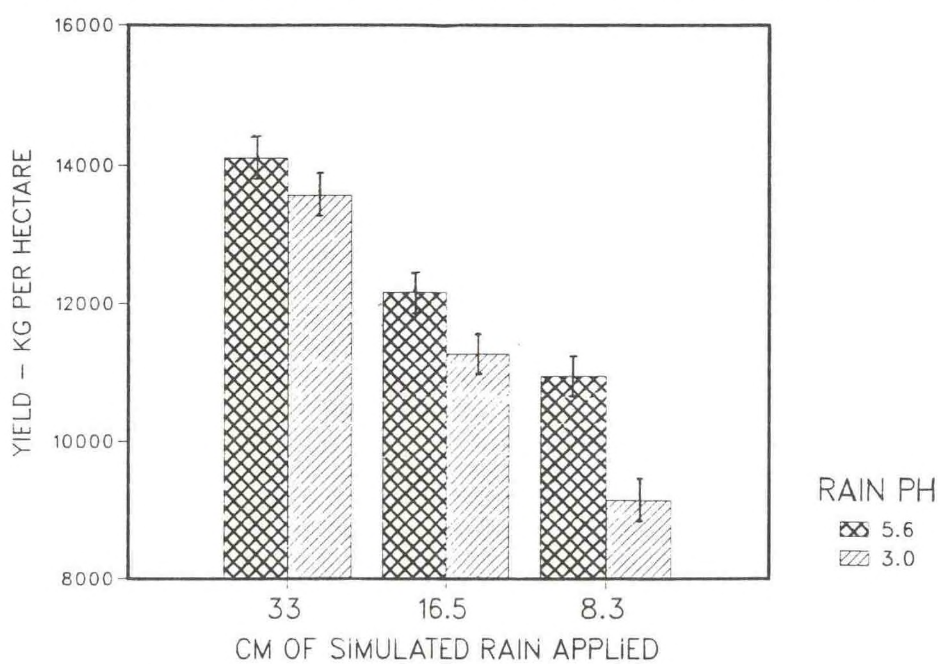


Figure 9. YIELD OF B73XMO17 FIELD CORN AS A FUNCTION OF AMOUNT AND ACIDITY OF SIMULATED RAIN



Research at the University of Massachusetts suggests that pollination in field corn may be reduced by acidity in rain when the plants are under stress (see part "D" below). This may be an explanation for the moisture stress/acidity interaction observed in Illinois. Another explanation is that moisture stress may reduce the buffering capacity of leaf surfaces (see part "D" below).

C. Oat (*Avena sativa*)-Yield Studies

No significant differences in the yield or productivity of field-grown oat plants ('Ogle') were observed as a result of simulated acidic rain treatments (pH 4.8, 4.2, 3.6, and 3.0) performed at Pennsylvania State University in 1985. The experiment has not been repeated.

D. Mechanistic and Screening Studies

Acute and chronic screening studies were conducted at North Carolina State University. These studies were designed to examine the potential predictive value of screening studies using acute acid rain exposures (one highly acidic rain event of pH 2.5) in which visible injury is measured. Results were compared to short-term growth responses from chronic exposures. The data suggest that an acute-type screening study is valid in indicating the qualitative sensitivity of crop species to acidic rain, but not in separating cultivars within a species. The chronic studies indicated that acidic rain (pH 3.5 and 3.0) had a significant effect on biomass accumulation in 3-week tomato plants, less of an effect on soybean and no effect on wheat plants. According to the acute screening studies, tomato, tobacco, and eggplant may be particularly sensitive to acidic rain during early stages of growth.

Preliminary studies with cotton and wheat suggest that the acidity of a single, 2-hr, highly acidic (pH=2.5) simulated rain treatment can adversely influence the fruit and seed production of exposed flowers. Another preliminary study suggested that pretreatment of the tassels and silk of one field-corn hybrid with pH 3.6 simulated rain may have a greater effect in reducing fertilization than pretreatment with pH 4.6 rain.

Two studies at Pennsylvania State University designed to examine the potential interaction between acidic rain and O_3 reported significant increases in ethylene emission from oats and suppression of biomass production of grasses after exposure to O_3. Effects from rain acidity and interactions were not observed in either study.

Studies at the University of Denmark have indicated large differences in the capacity of crop species to buffer acid solutions left on leaf surfaces after a rain event (pH 3.3). Plants which had been exposed to moisture stress showed decreased buffering capacity.

Other studies indicated increased wettability and enhanced uptake of phytotoxicants for plant leaves previously exposed to simulated acidic rain (pH< 4.0). This research suggests that acidic rain effects on leaf surface characteristics may predispose a plant to further stress from other agents. The work also suggests that environmental conditions that may influence leaf surface characteristics affect the degree of damage from acidic rain exposure.

IV. Important Gaps in the Information Available to Assess the Impact of Acidic Substances and Associated Oxidants on Crops

A. Dose-response Relationships

1. Dose

Ozone has been studied more with regard to crop effects than any other pollutant and yet the effect of different exposure dynamics is not well understood even for this pollutant. Peak concentrations and episodes of high and low levels of O_3 can have different effects on plant response than a constant exposure concentration when the averages are the same.

The "effective" dose, or that amount of pollutant actually taken up by the plant, is perhaps more meaningful than exposure <u>per se.</u> Uptake of gaseous pollutants can be controlled by many factors which affect stomatal conditions and plant metabolic rate. Some of the more obvious factors which may control uptake include plant water relations, light, temperature, nutrient conditions, and age of tissue. More information is needed concerning the role of peaks (concentration and frequency), the influence of respite times (when repair processes can occur), the dynamics of multiple pollutant exposures, and the relationship between plant phenology and exposure of O_3, SO_2, and NO_2.

Even less is known regarding exposure dynamics for acidic rain impacts. Acidic rain consists not only of H^+ but also SO_4^{-2}, NO_3^- and other rain components. Rain acidity can fluctuate by as much as $\pm$ 1 pH unit both within and among events and plant response may be dependent on these fluctuations. The effect of peak acidity events has not been well defined, although one study reported that peak acidity rain events may have a short-term impact on chlorophyll content of soybean leaves; this effect was less pronounced as the plants matured. The ratio of $SO_4^{-2}:NO_3^-$ has been reported to affect plant response in some preliminary studies and not in others. This aspect of dose also requires further examination, especially in light of control strategy options.

Another aspect of exposure dynamics that requires further investigation is the importance of plant developmental stage in affecting sensitivity to pollutant exposure, especially for pollutants that are episodic in nature. Recovery time (time between pollutant exposures) is known to be important for gaseous pollutant impacts and has been reported to be a factor for plant response to acidic rain in preliminary studies. Exposure dynamics with regard to length and rate of rain event, droplet size and duration of the rain-free interval are of unknown but possibly significant importance in affecting plant response.

2. Response

The National Ambient Air Quality Standards for gaseous pollutants are based on ambient concentrations. However, vegetation injury is the result of the absorbed dose of pollutants. Studies are needed to relate absorbed dose to the ambient concentration to provide meaningful response functions.

Grains, which are the most economically important crop commodity, have been studied more extensively than any other crop group for sensitivity to pollutants. Information on response of major crops to acidic rain and oxidants include results for soybean, corn, rice, cotton, sorghum, wheat, forage, and peanuts. Except for soybean, only one or two cultivars have been examined for most crops. Where multiple cultivars have been studied, the response to acidic rain and gaseous polluants was found to be variable. Thus, information is lacking for certain major crops, for regionally important crops (e.g. fruits and nuts), and for cultivars within a crop. Additionally, there is very little information available regarding acidic rain impacts on grassland and pastureland which are often under marginal levels of management and potentially more susceptible to impacts through the soil system.

One study at Argonne National Laboratory which examined the effects of rain acidity on poorly managed plant/soil systems reported that acidic rain resulted in increased acidity of the surface soil, although no negative effects on the soil microbiota were found. More research in this area is desirable since unmanaged grasslands constitute a major, relatively unstudied agricultural system. Most agricultural land is irrigated, fertilized, and protected by pesticides; unmanaged grasslands receive none of these stress-alleviating treatments. This type of ecosystem should be investigated in light of existing evidence indicating that acidic rain effects may be exacerbated by stressful conditions. A decrease in the carrying capacity of range and pastureland could have a potentially large economic effect if ameliorative management is not performed.

The dose-response data that exist for acidic rain impacts on crops generally demonstrate no significant trends in the ambient pH range (5.6 - 4.0), however, the experimental data within this range is inadequate for a complete quantitative assessment at this time. The mechanisms responsible for the year-to-year variation in the response of some crops to O_3 are unknown however it is believed that differences in environmental conditions may play a role. The same may be true for acidic rain impacts, and further study is needed in this area for both pollutants within the range of ambient concentrations. Extrapolations from crop species and crop cultivars which have been studied experimentally to others which have not involves additional uncertainty. This is also true for extrapolations from one geographic region to another due to different environmental factors. The lack of understanding of the mechanisms responsible for variability in the available data has limited the evaluation of acidic rain effects even for soybean which has been studied more than any other crop. Therefore, further experimental work is required to increase the accuracy for assessing the national impacts of these pollutants on crop productivity.

B. Mechanisms

An understanding of the biological mechanisms by which a pollutant affects a crop enables extrapolations to unstudied crops and environments to be made with a higher degree of confidence. Yield response functions are considered more valid if there is mechanistic information to support them and aid in interpretation.

A determination of the year-to-year and site-to-site environmental differences which affect the response of crops to acidic rain and associated oxidants could provide information relative to the mechanism(s) of action.

Currently, no general theories supported by research have explained the impacts of acidic rain on crops. One of the few studies to examine physiological responses indicated that acidic rain affected the marketable yield of radish (root & hypocotyl) through reductions in photosynthetic carbon production brought about by reduction of photosynthetically active tissue due to lesion development and reduced leaf expansion. Reasons, other than changed carbon allocation, for the reduced leaf expansion are unknown.

The effects of acidic rain on leaf surfaces also deserves further study, especially since research suggests that this is the route for further interactive effects. Mechanistic research can lead to an understanding of processes involved in yield effects and are critical to understanding and predicting effects. Research in this area may also be applicable to forest species and may aid in interpreting symptoms of forest decline.

C. Interactions

The greatest effect of acidic rain may be in interactions with other pollutants. To date, studies that have been completed have shown no synergisms. However, definitive studies which would rule out pollutant interactions are not available; so few species and pollutants have been tested that any conclusions based on the lack of findings to date are premature.

The body of knowledge on the amount, type, and effect of dry deposition on plants contains considerable uncertainties. Retained particles and gases adsorbed on plant surfaces are subject to cyclic dissolution and precipitation in periods between rain events. This has been demonstrated to result in SO_4^{-2} and NO_3^- concentrations in water droplets on leaves several times higher than in acidic rain. Thus, the dose to the plant from dry deposition is potentially much higher than might be expected from consideration of the relative mass removed from the atmosphere by dry processes. In addition, large amounts of alkaline dust may be present in some localities, neutralizing deposited acids and mitigating or entirely opposing the effects of acidic deposition. Dry deposition was not controlled in the studies presented in Fig. 1 and could be responsible for the different apparent response.

Acidic precipitation studies which exclude O_3 are particularly important to identify effects due solely to acidic rain. The majority of field studies done in the past were actually "interactive" studies in that they did not exclude O_3. Similiarly, field studies using controlled doses of O_3 have not generally excluded acidic rain.

Local climatic, edaphic, and biological parameters mediating crop response to acidic inputs and oxidants are unknown. These factors are likely to produce the between-year and between-site variations that make the generalization of experimental results so difficult. If the most important environmental parameters mediating plant response could be identified and used to explain experimental variation, then the generalization of results would be improved.

Some evidence suggests an interaction between acidic rain and drought stress on one field corn hybrid. This interaction must be explored further to determine its magnitude and the mechanism. An understanding of this possible interaction may aid in the evaluation of hypotheses to explain forest decline in some areas.

Acidic precipitation and oxidant effects on plant response to pests and disease have not been adequately studied. One study with field corn (FR632 X FR619 - a hybrid susceptible to northern corn leaf blight) indicated that disease incidence is higher ($p = 0.01$) in plants treated with pH 3.0 inoculum spray compared to pH 5.6. However, 70% fewer plants treated with pH 3.0 inoculum exhibited Goss' leaf blight compared to pH 5.6 inoculum. This study also suggested that pH 3.0 rain could reduce the pathogenicity of primary and secondary inoculum for bacterial blight of soybeans. In the short run, with respect to annual crops, the question of pollutant-parasite interactions is associated with mechanisms, since losses related to insect and disease stresses are incorporated into the overall yield loss measurement. However, for perennial crops and forests, the possibility of a long-term and gradual decrease in plant resistance to parasites is a very important potential effect of acidic precipitation and oxidants. Hence, the examination of this interaction in the more easily studied annual crop systems may be important in detecting mechanisms and causes applicable in other areas (e.g. forestry).

V. Research Needs

Although the research completed to date does not indicate important effects of acidic deposition on crop systems, there are some critical and unexplained features in the body of data that suggest the possibility of impact under certain conditions. Examination of these factors could also provide direction to investigations regarding the mechanisms for effects in other terrestrial ecosystems (e.g. forests). The critical research needs and the reasons for their importance follow. Controlled environment studies performed in the following categories should be supported or confirmed by research on yield effects in field studies.

1. Determine the biochemical and physiological changes in the plant that lead to a response to acidic deposition and oxidants.

'Amsoy' soybean has been reported to be sensitive to acidic rain under certain conditions, in contrast to the majority of crop cultivars. What are the reasons for its sensitivity? One field corn hybrid has exhibited an interactive effect on yield from acidic rain combined with drought stress while another has shown no interactive effect. Response differences among species and cultivars have also been noted for O_3 and SO_2. A close examination of the genetic, morphological, and biochemical characteristics of sensitive varieties compared to those which have been reported to be resistent to acidic rain and oxidants may provide insight to the biochemical changes leading to a response. Differences in leaf surface characteristics and buffering capacities should also be examined, as well as varietal differences in pollutant metabolism. Another valuable research area is an examination of resource allocation during specific plant growth stages which identify the step(s) in carbon-cycling that translate pollutant stress into yield loss. These studies may provide the evidence needed to explain the variable response observed and may allow extrapolations to other plant types (e.g. forest trees), exposures, and environmental conditions.

2. Identify other stresses which may be enhanced by or which affect plant response to acidic deposition and associated oxidants.

Preliminary studies have indicated that a plant growing under conditions of moisture stress may be more susceptible to acidic rain stress. The acidic rain-drought interactive effect appears to be species-dependent and may be related to changes in the surface characteristics and buffering ability of plant leaves. An O_3-drought interaction may involve root/shoot carbon allocation and stomatal relations. Preliminary studies have suggested that fine root mass is suppressed by O_3 in drought stressed soybean plants while shoot mass is suppressed in well-watered plants. During most growing seasons, crops are occasionally and sometimes frequently subjected to moisture stress. This important interaction needs to be investigated for other species and varieties in conjunction with mechanistic studies especially since it may provide valuable information regarding forest response to stress.

Research which has shown acidic rain effects on leaf surface characteristics and wettability suggests that it may predispose a plant to other stresses such as enhancing the uptake of phytotoxicants (e.g. gaseous pollutants, especially O_3) and weakening the barrier to plant pests (insects, fungus, bacteria, viruses). Several studies have demonstrated such interactions. The further influence of dry deposition (acids, alkalines, heavy metals) in affecting leaf surface characteristics should also be a priority. The fact that the response of some crops to O_3 and SO_2 in controlled studies has varied from year-to-year at a particular site suggests some type of interaction with environmental conditions. Similar differences have been observed in the response of 'Amsoy' soybean to acidic rain. Further research to identify the interacting factors will contribute to understanding mechanisms of response and estimating yield effects on a regional basis.

3. Identify the components of acidic deposition and O_3 exposure dynamics that are important in affecting plant response.

Exposure dynamics are known to affect the response of plants to gaseous pollutants yet little has been done to examine this aspect of acidic rain effects. For example, at high O_3 and SO_2 doses, peak concentrations may have more of an effect than a longer-term mean. Other work suggests that a constant low level of exposure may be more damaging than episodic exposures having the same total dose, possibly because recovery periods cannot occur during constant exposures. Only preliminary studies have been completed to address these issues.

Wet and dry deposition consists of multiple variables relating to chemical (eg. H^+, SO_4^{-2}, NO_3^-), physical (e.g. fogs vs thunderstorms) and temporal (e.g. duration, frequency) components. Evidence from O_3 studies suggest that length of "recovery" periods in conjunction with stage of plant development can affect the magnitude of damage from the O_3 exposures. Similiar results have been obtained in preliminary studies with acidic rain. These and other aspects of exposure dynamics (such as S and N input vs. fertility, and acid fog exposure) require further investigation because controlled studies to date have not encompassed many aspects of exposure.

4. Broaden the scope of knowledge regarding the sensitivity to acidic deposition and oxidants of regionally important crops in areas currently receiving high rates of deposition.

Species and varietal differences to O_3, SO_2, and NO_2 exposure have already been documented and are suspected for acidic rain, thus extrapolation of dose-reponse information to unstudied species would increase the uncertainty in assessments of impacts. Tree fruit and other crops with great regional economic importance have not been examined at all or only in preliminary studies. Preliminary data indicate that vegetable crops may be more sensitive to pollutants than the more extensively studied grain crops. Additionally, forage crops are of special significance because of their perennial nature and potential for longer-term impacts. Long-term effects on the soils of unmanaged rangeland are also unknown but potentially important. The establishment of techniques for short-term screening experiments capable of establishing the relative sensitivity to yield damage would be most valuable in this area.

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APPENDIX II
MEETING AGENDA

1986 NAPAP Crop Research Workshop
Ambassador West Hotel
Chicago, IL

J. L. Kulp, Chairman
Director of Research, NAPAP

AGENDA

Wednesday, April 16

8:00 AM - 5: PM   Registration - The Assembly - 1st floor

Thursday, April 17   THE GUILDHALL - 1st floor

8:15 AM   Introduction - P.M. Irving

8:20 AM   Statement of Purpose - J. L. Kulp

8:30 AM   Significant findings from 1985
Acid Rain - Crop Effects Research
(20 minutes each plus 10 minutes each for discussion)

Jay Jacobson - Moderator
- Wayne Banwart - University of Illinois
- Denis DuBay - North Carolina State University
- Lance Evans - Manhattan College
- Al Kuja - Ontario Ministry of Environment
- Eva Pell - Pennsylvania State University

10:00 AM   BREAK

10:15 AM   RESUME

11:15 AM   General Discussion - At this time, other researchers will have the opportunity to comment on their research results as they pertain to the Workshop objectives (10 min. max. each).

12:15 PM   LUNCH

1:30 PM   Business Meeting - Air Pollution Workshop (attendance not required)

2:30 PM   Air Pollution Workshop officially adjourns.

Thursday, April 17 (Continued):

2:35 PM — Panel Discussion - What are the exposure-response relationships of major crops to acidic rain, its precursors, associated pollutants, and combinations of these pollutants?

Dave Shriner - ORNL: Moderator

Panel members:

Lance Evans - Manhattan College: acid rain
David Tingey - EPA Corvallis: O_3
Walter Heck - North Carolina State University: SO_2, NO_2
Patrick Temple - U. of California: pollutant combinations

Each member will have 20 minutes to address the question, then 10 minutes each for discussion.

5:00 PM — Adjourn for dinner.

7:30 PM — KING'S ROOM - 2nd Floor

Panel discussion - Is there sufficient knowledge available to determine whether there is a significant problem of crop damage caused by current levels of acidic rain, its precursors and oxidants?

The question will be addressed on the basis of the information presented during the morning and afternoon sessions.

Moderators: Jacobson and Shriner

9:30 PM — ADJOURN

Friday, April 18 — THE KINGS ROOM - 2nd floor

8:30 AM — Review of highlights from panel discussions of the previous day. Session leaders will summarize major points of agreement from the discussions on Thursday.

9:00 AM — Participants will be split into smaller working groups (7-9 individuals) to thoroughly explore and critically discuss the three questions listed in the workshop objectives:

What are the important gaps in our knowledge of the impact of acidic substances and associated oxidants in the following areas:

1. Response to total dose and dose rate;
2. Extrapolation to other varieties and species

Friday, April 18 (Continued)

3. Physiological mechanisms
4. Influence of climate and soil

Discussion Leaders:

Jeff Brandt
Patricia Irving

12:00 PM LUNCH
(Buffet lunch as a group at the hotel)

1:00 PM Summary of Significant Gaps

Patricia M. Irving - Moderator

Participants will reconvene as a whole and each working group leader will summarize the discussions and conclusions of their group.

2:30 PM If significant gaps have been identified, participants will address the following:

What are the scientific priorities in obtaining additional knowledge relating to crops on the impact of acidic substances and associated oxidants pertaining to:

1. Dose/response relationships
2. Extrapolations
3. Mechanisms

3:30 PM ADJOURN

APPENDIX III: WORKSHOP OBJECTIVES

1986 NAPAP CROP RESEARCH WORKSHOP

BACKGROUND: The National Acid Precipitation Assessment Program (NAPAP) seeks to evaluate the status of scientific knowledge on the impact of acidic deposition and associated oxidants on agricultural crops, and decide future needs for research in this area for NAPAP policy objectives.

OBJECTIVES:

The workshop is directed toward obtaining an understanding on what we now know and what we need to know about the effects on crops from acidic substances and associated oxidants acting either alone or in combination. Important research results from the 985 field season will be reported so that an up-to-date evaluation can be made. Based on what is known, workshop participants will be asked to address relevant gaps in our scientific knowledge. The following is the key question of interest in research managers and policy makers:

> Is there a significant problem of crop damage in the U.S. which is caused by current levels of exposure of acidic substances and oxidants derived from SO_2, NO_x, and VOC?

In developing a response to this question, NAPAP would like to have three subsidiary questions addressed:

1. What are the exposure/response relationships (based on total dose, dose rate and concentration) of major agricultural crops to acidic substances and oxidants acting either alone or in combinations?

2. Can research results be extrapolated to other: exposures (higher and lower), plants (varieties, annual crops, perennial forage crops, trees), climates and soils?

3. What are the mechanisms responsible for net effects on growth and yield?

The first day of the workshop (Thursday) will be used to explore what is currently known about the effects of acidic substances on crops. The second day will be focused on identifying the existence and importance of gaps in our knowledge of the effects of acidic substances on crops.

The task of the moderator in each session will be to keep the discussion focused on the above three questions within the context of the key question.