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Sulfuric Acid Rain Effects on Crop Yield and Foliar Injury

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SULFURIC ACID RAIN EFFECTS ON CROP YIELD AND FOLIAR INJURY

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DISCLAIMER

One of the principal reasons for the preparation of this report for the Environmental Protection Agency was to supply scientifically valid information which could be incorporated into the EPA SO_2-Particulate Matter Criteria Document, presently in the final stages of preparation. A strict requirement pertaining to that document is that any scientific information used there must be published (or at least in press) by January 1, 1980. Because of this demanding time constraint, it was necessary that the authors prepare this report in a shorter time than would ordinarily be attempted, and that it be published by EPA without undergoing peer review. We feel that early publication of these results in order to stimulate the broadest scientific discussion prior to completion of the criteria document justified waiving our normally more rigorous prepublication review requirements. Publication, however, does not signify that the contents necessarily reflect the views and policies of EPA, nor does mention of trade names or commercial products constitute endorsement or recommendation for use.

FOREWORD

Effective regulatory and enforcement actions by the Environmental Protection Agency would be virtually impossible without sound scientific data on pollutants and their impact on environmental stability and human health. Responsibility for building this data base has been assigned to EPA's Office of Research and Development and its 15 major field installations, one of which is the Corvallis Environmental Research Laboratory.

The primary mission of the Corvallis Laboratory is research on the effects of environmental pollutants on terrestrial, freshwater, and marine ecosystems; the behavior, effects and control of pollutants in lakes and streams; and the development of predictive models on the movement of pollutants in the biosphere.

This report describes the effects of simulated sulfuric acid rain on the yields of several crops. Data on foliar injury are also presented. This study was undertaken as part of an evaluation of the effects of acid rain on agro-ecosystems.

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ABSTRACT

A study was undertaken to determine the relative sensitivity of major United States crops to sulfuric acid rain. Potted plants were grown in field chambers and exposed to simulated sulfuric acid rain (pH 3.0, 3.5, or 4.0) or to a control rain (pH 5.6). At harvest, the fresh and dry weights of the marketable portion were determined for 28 cultivars. Of these, yield production was inhibited for 5 cultivars, stimulated for 6 cultivars, and ambiguously affected for 2 cultivars. The results suggest that the likelihood of yield being affected by acid rain depends on the part of the plant utilized.

Plants were regularly examined for foliar injury associated with acid rain. Of the 35 cultivars examined, the foliage of 31 was injured at pH 3.0, 28 at pH 3.5, and 5 at pH 4.0. Foliar injury was not generally correlated with effects on yield.

This report covers work performed from February through November, 1979.

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TABLES

SECTION 1

INTRODUCTION

Acid precipitation occurs over a large area of the United States. The increased concentrations of sulfuric and nitric acids in precipitation are derived primarily from the air pollutants sulfur doxide (SO_2) and oxides of nitrogen (NO_x). All states east of the Mississippi River and some western states regularly receive precipitation which is more acidic than the expected value of pH 5.6 for carbonic acid rain which is formed by dissolution of atmospheric CO_2.[1-8] In the northeastern United States, pH 3.5 is typical of summer rains, although more acidic rains do occur.[5] With the increasing use of fossil fuels, precipitation will probably be at least as acidic in the future.

The regions impacted or susceptible to acid rain encompass vast acreages of fertile farmland. The potential effect on crops has been identified as a major concern.[9,10] Although some studies have been performed,[11-21] there is little documentation of acid rain effects on crop foliage or yield. Specifically, it is not known whether response to acid rain is common or rare among crops; whether this response is generally stimulatory or inhibitory in terms of yield; or what plant characteristics might correlate with differences in yield response. To provide partial answers to these questions, we conducted an experimental survey to provide a comparison of the relative foliar and/or yield sensitivities of several crops to simulated sulfuric acid rain.

In this paper, we present the results on yield and on foliar injury ratings. Future papers will discuss findings on other growth parameters and present photographs showing the characteristics of foliar injury caused by simulated sulfuric acid rain.

SECTION 2

CONCLUSIONS

Data from a single growing season on the effects of simulated sulfuric acid rain on the yield of potted plants suggest the following tentative conclusions.

1. The yield of dicotyledons is more likely to be adversely affected by acid rain than the yield of monocotyledons.

2. Among dicotyledons, the yields of root crops are most likely to be adversely affected, followed by leaf, cole, and tuber crops. Legumes and fruit crops may be stimulated by acid rain.

3. Grain crops are unlikely to be affected, while monocotyledenous forage crops may be more productive under acid rain conditions.

4. Foliar injury is not correlated with yield effects.

RECOMMENDATIONS

Interpretations of the data in this report should be regarded as unproven hypotheses. Additional comprehensive experimental studies under laboratory, greenhouse, and field conditions are necessary before the effects of acid rain on crops can be accurately assessed.

SECTION 3

EXPERIMENTAL PROCEDURES

Sandy loam soil was obtained from the floodplain of the Willamette River, Oregon. The low nitrogen, or LN, mix was produced by mixing a portion of this soil with peat moss (7.7 kg per cubic meter of soil) and 6-20-20 fertilizer (624 grams per cubic meter of soil). The high nitrogen, or HN, mix was produced by mixing another portion of the soil with peat moss (7.7 kg per cubic meter of soil) and 10-20-20 fertilizer (624 grams per cubic meter). After the soil was pasteurized by exposure to aerated steam (75°C for 40 minutes), plastic pots were filled with the mixes. The results of chemical analyses of samples of the amended and unamended soils are given in Table 1.

For one group of crops, seeds were sieved into 3 size classes and the most common-sized seeds were planted in 6-liter plastic pots. Two potato pieces each containing two eyes were planted in 15-liter pots. In most cases, plants in this group were first exposed to simulated rain treatments within one day of planting. A second group of crops was germinated in a greenhouse and transplanted to 6-liter plastic pots for exposure to simulated rain treatments.

Crops were grown in three types of exposure chambers (Table 2). All plants of any given crop were grown in the same type chamber. To check for seasonal variation, radishes were planted at different times during the growing season. Possible differences associated with chamber type were investigated by growing radish crops in all chamber types simultaneously.

Stainless steel nozzles were used to apply simulated rain at the average rate of 6.7 mm/hr, 1.5 hours per day, 3 days per week, for a total of 30 mm/week. The simulated rain in each chamber contained a stock solution containing 11 μeq/l Ca^{++}, 12 μeq/l Na^{+}, 2 μeq/l K^{+}, 5 μeq/l Mg^{++}, 11 μeq/l $SO_4^{=}$, 12 μeq/l NO_3^{-}, and 12 μeq/l Cl^{-}. These concentrations were an approximation of non-acid rain based on a 7-year average from a site in the northeastern United States, after elimination of estimated sulfuric and nitric acid components.[23] The control chambers received rain containing only the stock solution equilibrated with atmospheric CO_2 to approximately pH 5.6. Acid rain chambers received rain consisting of the stock solution to which had been added sufficient H_2SO_4 to lower the pH to 4.0, 3.5, or 3.0. Supplemental irrigation with well water was provided according to individual pot needs, as determined visually. Thus, soil moisture content was similar among pots. Water volumes applied to each pot were recorded. A chemical analysis of irrigation water is given in Table 3.

Crops were harvested according to various criteria (Table 4). For most crops, the fresh weight of the marketable portion was determined at time of harvest. The dry weights of the roots, tops and marketable portions also were measured. Data on the non-yield portions will be presented in future papers.

All crops in acid treatment chambers were regularly examined for acid rain injury. If noticeable injury was present, control plants were checked for the same characteristics. When only plants in the acid treatment chambers showed a particular type of injury, we attributed the injury to acid rain. The date on which injury was first noticed on a particular crop was recorded, as was the date on which more than half the plants in a particular chamber had acid injury on at least 10% of the leaf area. Just prior to havest, the fraction of leaf area showing acid rain injury was estimated for each plant. Area was estimated in graduations of 5%; therefore, the presence of any injury was always recorded as at least 5%. For some crops, leaf senescence and/or yellowing prevented these final estimates. For fescue, ryegrass, and bluegrass, extremely slow regrowth toward the end of the growing season resulted in insufficient tissue for accurate injury rating at the final harvest; thus, injury ratings refer to the first of several harvests.

Details of the experimental conditions used for each crop are summarized in Table 5.

Table 1. Chemical Analysis of Soil Mixes

Soil Mix	Salts mmhos/cm	Organic Matter %	Total N %	P ppm	SO_4-S ppm	B ppm	K ppm	Ca meq/ 100 g	Mg meq/ 100 g	Na meq/ 100 g	CEC meq/ 100 g	Free $CaCO_3$ %	pH
Unamended	0.43	0.81	0.06	13	5.7	0.16	99	13.6	6.2	0.29	20.2	16.7	6.3
Low Nitrogen (LN)	1.35	1.46	0.07	29	48.9	0.20	179	10.8	5.4	0.26	20.5	16.8	5.8
High Nitrogen (HN)	1.80	1.76	0.08	29	54.9	0.20	204	10.9	5.6	0.27	21.2	17.0	5.8

Table 2. Chambers Used in Crop Survey

Type	Diameter or Length Meters	Height Meters	Covering	Total Number	Number per Treatment	Pots per Crop per Treatment
Large Round (LR)	4.6	2.4	Krene	4	1	14[a]
Small Round (SR)	3.0	2.4	Krene	8	2	14
Square (SQ)	2.4	2.1	Teflon	20	5	25

[a]10 pots per treatment for potato.

Table 3. Chemical Analysis of Irrigation Water

pH	7.46
Calcium	19.0 mg/l
Magnesium	6.1 "
Sodium	9.2 "
Potassium	1.7 "
Phosphorus	0.25 "
Kjeldahl-Nitrogen	0.07 "
Nitrate-Nitrogen	2.20 "
Cobalt	0.39 "
Copper	0.02 "
Iron	0.23 "
Molybdenum	0.20 "
Zinc	0.16 "
Aluminum	0.15 "
Silica	31.2 "

Table 4. Harvest Criteria

1. Maturity or senescence of control plants.

2. Size or maturity of marketable portion of control plants.

3. Multiple harvests as marketable portions of plants became mature and/or marketable.

4. Predetermined periodic harvests.

5. Premature harvests without usable measurement of yield.

Table 5. Experimental Conditions of Crops Surveyed

Crop	Cultivar	Chamber Type[a]	Seed or Transplant[b]	Plants per Pot	Soil Mix[c]	Supplemental Fertilizer[d] g/pot	Pesticide Used[e]	Planting Date	Date of First Exposure	Harvest Criteria[f]	Final Harvest Date
Radish 1	Cherry Belle	LR	S	3	HN	0.5 Urea		4/19	4/20	2	5/21
Radish 2	Cherry Belle	SR	S	2	HN		D	5/25	5/26	2	6/21
Radish 3	Cherry Belle	LR	S	3	HN			9/26	9/26	2	10/31
Radish 4	Cherry Belle	SR	S	3	HN			9/26	9/27	2	10/31
Radish 5	Cherry Belle	SQ	S	3	HN			9/26	9/27	2	10/31
Beet	Detroit Dark Red	SQ	S	2	HN		D	7/26	7/26	2	9/25
Carrot	Danvers Half Long	SQ	S	2	HN	1.0 Urea	D, M	7/26	7/26	1	11/01
Mustard Green	Southern Giant Curled	SR	S	2	HN			5/25	5/26	2	6/26
Spinach	Improved Thick Leaf	SR	S	2	HN			5/25	5/26	2	6/29
Swiss Chard	Lucullus	SR	S	1	HN	0.5; 4.1	D	5/25	5/26	2	8/07
Bibb Lettuce	Limestone	LR	T	1	HN			8/31	9/14	2	11/03
Head Lettuce	Great Lakes	LR	T	1	HN			8/31	9/14	5	11/15
Tobacco	Burley 21	LR	T	1	HN	2.0 Urea		5/02	6/13	1	8/08
Cabbage	Golden Acre	LR	T	1	HN	1.0 Urea	D	2/21	4/20	2	7/17
Broccoli	Italian Green Sprouting	LR	T	1	HN	0.5 Urea	D	2/21	4/20	3	6/10
Cauliflower	Early Snowball	LR	T	1	HN	1.0 Urea	D	2/21	4/20	3	6/11
Potato	White Rose	LR	E	2	HN	1.2 Urea	D	4/19	4/20	1	8/15
Green Pea	Marvel	LR	S	2	LN			4/19	4/20	2	6/22
Peanut	Tennessee Red	SQ	S	1	LN		D	7/26	7/26	5	9/26
Soybean 1	OR-10	SQ	S	1	LN		D	7/26	7/26	5	10/24
Soybean 2	Hark (G-1)	SQ	S	1	LN			9/05	10/02	5	-----
Soybean 3	Norman (G-00)	SQ	S	1	LN			9/05	9/11	5	-----
Soybean 4	Evans (G-0)	SQ	S	1	LN			9/05	9/11	5	-----
Alfalfa	Vernal	SR	S	2	LN	0.5 0-20-20	D	5/25	5/26	2	10/03
Red Clover	Kenland	SR	S	2	LN	4.1 0-10-10	D	5/25	5/26	2	10/02
Tomato	Patio	LR	T	1	HN	0.5; 4.1; 2.1		5/16	6/29	3	10/25
Cucumber	5116 Cresta	LR	S	1	HN	0.5; 4.1		7/17	7/18	5	10/01
Green Pepper	California Wonder	SR	T	1	HN	0.5; 0.0; 2.1	D	5/16	6/28	1	9/24
Strawberry	Quinalt	LR	T	1	HN	1.0 Urea	D	(g)	4/20	3	10/16
Oats	Cayuse	LR	S	3	HN			4/19	4/20	1	8/06
Wheat	Fieldwin	LR	S	3	HN			4/19	4/20	1	7/31
Barley	Steptoe	LR	S	3	HN			4/19	4.20	1	7/31
Corn	Golden Midget	LR	S	1	HN	0.5; 4.1		7/23	7/23	5	9/05
Onion	Sweet Spanish	LR	S	2	HN	2.0; 4.1		4/19	4/20	1	9/17
Fescue	Alta	SR	T	3	HN	0.5; 4.1	D	6/14	7/07	4	11/20
Orchardgrass	Potomac	SR	T	3	HN		D	6/14	7/07	2	9/25
Bluegrass	Newport	SR	S	3	HN	1.0; 8.2	D	5/25	5/26	2	11/07
Ryegrass	Linn	SR	T	3	HN		D	6/14	7/07	4	11/16
Timothy	Climax	SR	T	3	HN			6/14	7/07	2	9/19

[a] See Table 2 for chamber specifications.
[b] S: Plants were grown from seed in pots used in exposure chambers. T: Plants were started in greenhouse and transplanted to pots used in exposure chambers. E: Potato eyes planted in pots used in exposure chambers.
[c] See Table 1 for soil specifications.
[d] Where more than one number is given, first number refers to grams of urea; second to 0-10-10; third to 10-20-20.
[e] D: Diazonon, M: Maneb.
[f] See Table 4 for harvest criteria.
[g] Transplants obtained from commercial grower.

SECTION 5

RESULTS AND DISCUSSION

The yield results are summarized in Table 6. For each crop, the fresh and dry weights of the marketable portions of plants receiving the pH 5.6 rain (the controls) are given on a per pot basis. The mean yields of crops subjected to simulated acid rain are presented as ratios to the control mean, as is the standard error. Provided that the F-test from a one way analysis of variance was significant at the 0.10 level, two-sided t-tests were used to determine which treatment means were significantly different from the control.

Foliar injury results are summarized in Tables 7 and 8. Injury ratings, made for all crops during the growing season, are given in Table 7. Yellowing and/or senescence of control leaves of several crops prevented estimating the leaf area exhibiting acid rain injury at harvest; results for those crops for which estimates could be made are given in Table 8. Since foliar injury was rated in discrete steps, a rating of 5% indicated that a plant showed some, possibly minute, acid rain injury.

DICOTYLEDONS

As a group, dicotyledons were more susceptible to foliar injury by simulated sulfuric acid rain than were monocotyledons. Although stimulation of yield was observed for both monocotyledons and dicotyledons, inhibition of yield was observed only for dicotyledons. The various groups of dicotyledons are discussed in descending order of adverse effects on yield and ascending order of positive effects.

Root Crops

All three root crops (radish, beet, carrot) had foliar injury associated with pH 3.0 treatments; radish and beet were also injured at pH 3.5 (Table 7). Since root crops frequently are marketed with leaves attached, this type of disfiguration could adversely affect marketability. For radish, injury at harvest ranged up to 25% of the leaf area; this was the crop most susceptible to foliar injury (Table 8). Beet showed less leaf injury at harvest (Table 8), but was one of only five crops injured at pH 4.0 (Table 7). Since all mature beet leaves developed a mosaic pattern which may have partially masked acid rain injury, the results in Table 8 for beet may be underestimates.

In terms of yield, carrot was the most sensitive root crop, followed by radish and beet (Table 6). Although there was no apparent acid rain foliar injury, the yield of carrots at pH 4.0 was, on average, only 73% of that of the control plants.

Radish was grown in five independent studies. Plants grown earlier in the year (Radish 1 and 2) were somewhat more susceptible to foliar injury than those grown toward the end of the growing season (Radish 3, 4, and 5 in Tables 7 and 8). These differences may have been associated with the high temperatures (up to 40°C) which occurred during the earlier period. No such temporal differences in effect on marketable yield were apparent.

In one radish study (Radish 5) plants in all five control chambers were heavily damaged by slugs and twelve-spotted beetles, while plants in the acid-treatment chambers were, at most, only slightly damaged. The yield of the control plants consequently might have been somewhat reduced, resulting in artificially high yield ratios for the acid-treatment plants. However, ratios among acid treatments (e.g., pH 3.0 to pH 3.5) in this study were similar to those for the other radish studies.

Although the reason for different degrees of pest damage is not clear, it does suggest varying responses of faunal populations to different levels of rain acidities. Less slug damage to acid-treated crops was also observed a year earlier with radish and onion. Control chambers were in different locations during the two seasons, thus eliminating chamber location as a possible cause for slug damage.

Leaf Crops

The foliage of Swiss chard, mustard greens, and spinach was injured by acid rain to the extent that marketability was affected. Lettuce (bibb and head) and tobacco were less severely affected. Cabbage was the least sensitive to acid rain (Tables 7 and 8). The only crop to have less yield due to exposure to acid rain, as measured by weight of foliage, was mustard greens (Table 6). However, Mohamed[11] found that acid rain at approximately pH 4 inhibited potted lettuce plants.

Cole Crops

Acid treatments of pH 3.0 and pH 3.5 caused foliar injury of broccoli and cauliflower. Cabbage leaves were injured only at pH 3.0 (Tables 7 and 8). Only radish was more extensively injured than cauliflower at pH 3.0 (Table 8). The waxy foliage of these cole crops afforded, at most, partial protection from acid rain injury.

Only broccoli showed significant yield effects; at pH 3.0 yield was lower than the control (Table 6). In a field study in New York State, Mohamed found that cabbage (cv. King Cole) was inhibited by exposure to acid rain (pH 3.0) during the first week after seedling emergence.[11]

Tuber Crop

The one tuber crop studied (potato) had a mixed response to simulated acid rain. Foliar injury was observed for the pH 3.0 and 3.5 treatments (Table 7). Yield, however, was inhibited by pH 3.0 rain, and simulated by pH 3.5 and 4.0 rain; the stimulatory effects at pH 3.5 and 4.0 were, however, significant only for fresh weight (Table 6).

Legumes

Acid rain treatments of pH 3.0 and pH 3.5 injured the foliage of all eight legume cultivars (Table 7). Of the three legumes grown to harvest (green pea, alfalfa, and red clover), only alfalfa yield was affected by acid rain; the yield of alfalfa plants receiving treatments of pH 3.5 and pH 4.0 was greater than the yield of control plants (Table 6).

The yield responses of red clover and alfalfa were consistent among the successive harvests (Table 9). Although not statistically significant, alfalfa yields tended to be lower at pH 3.0. Greater yields at intermediate pH values (Table 9) suggest competition between stimulatory and inhibitory effects of acid rain.

Fruit Crops

Acid rain severely injured the leaves of tomato, cucumber, and green pepper at pH 3.0; less severe injury occurred at pH 3.5 (Table 7). Although the leaves of green pepper were also injured at pH 4.0 (Table 7), this injury was not identifiable at final harvest (Table 8). Strawberry leaves sustained only minute injury (Table 7) which was not identifiable at final harvest (Table 8).

The yield of crops grown to harvest (that is, all except cucumbers) frequently was greater for plants receiving acid rain than for control plants. In no case did acid rain cause as ignificantly smaller yield than did control rain (Table 6). However, at pH 3.0 injury to tomato fruits was severe enough to adversely affect marketability. In contrast to our results, Mohamed[11] found yields lower than control for green peppers (cv. Stoddans Select) and tomatoes (cvs. Tiny Tim and New York) subjected to pH 3.0 simulated rain.

MONOCOTYLEDONS

Monocotyledons were generally less susceptible to acid rain injury of foliage than were dicotyledons. No significant adverse effects on yield were found. Groups of monocotyledons are discussed in increasing order of stimulatory effects on yield.

Grain Crops

Small grain crops (oats, wheat, barley) were the crops least sensitive to acid rain. The yields of grain (Table 6) were not affected by the acid treatments, and no foliar injury was apparent (Table 7).

Corn was harvested when the plants were tall enough to interfere with spray from the nozzles (approximately 1 m). Although the foliage was injured (Table 7), the total above ground weight (stems plus leaves) of plants receiving pH 3.0 rain was apparently larger than the control plants. The difference, however, was only marginally significant (Table 6).

Bulb Crop

Onion bulbs grown under acid treatments did not differ significantly from controls. There was, however, a suggestion of heavier bulbs for the acid-treated plants (Table 6); stimulation of these specialized leaves would be consistent with the results for corn, orchardgrass, and timothy. No foliar injury was identified (Tables 7 and 8).

Forage Crops

Acid rain at pH 3.0 and 3.5 caused foliar injury of fescue, orchardgrass, bluegrass, ryegrass and timothy. Bluegrass was only slightly injured at pH 4.0 (Tables 7 and 8).

Although injured by acid rain, orchardgrass and timothy were significantly more productive under the pH 3.0 treatment than under the control rain. While not significantly different from the control, the results at pH 3.5 also suggested higher productivity (Table 6). In contrast, Crowther and Ruston[12] found that adding dilute sulfuric acid at pH values above 2.0 to soil had no effect on the productivity of timothy during the first year of exposure; in the third season productivity was inhibited at pH 3.4 and lower.

Acid rain effects on yield were indicated for fescue, although no treatment produced significant differences. No effects were found for bluegrass or ryegrass productivity (Table 6).

Summary of Results on Foliar Injury and Yield

A total of 35 cultivars, including 4 soybean cultivars, was examined for foliar injury associated with acid rain. Of these, 31 were injured at pH 3.0, 28 at pH 3.5, and 5 at pH 4.0 (Table 7).

Data on both foliar injury and on yield were obtained for 28 crops, resulting in 84 crop-treatment combinations (28 crops times 3 acid treatments). Table 10 shows the results of classifying these combinations by effects on foliar injury and effects on yield.

Of the 84 crop-treatment combinations, 32 showed no effect on either yield or foliar injury. Foliar injury without yield effects was found for 30 combinations and yield effects without foliar injury for 6 combinations. Yield effects with foliar injury occurred for 16 combinations.

Foliar injury was observed on a total of 46 of the 84 combinations. All but 5 of these were at pH 3.0 or 3.5. Yields higher than the control were found for 7 of these 46 crop-treatment combinations, and lower yields for 9 of 46 (Table 10). Thus, apparent foliar injury was not necessarily indicative of lower yield.

In 11 of the 84 crop-treatment combinations (6 at pH 3.0; 3 at pH 3.5; 2 at pH 4.0), the acid-treated plants had lower yields than the controls. For another 11 crop-treatment combinations (5 at pH 3.0; 3 at pH 3.5; 3 at pH 4.0), the yields of acid-treated plants were higher than the controls. The numbers of combinations having foliar injury were similar for both the stimulated and inhibited groups (Table 10). Therefore yield could be affected without apparent foliar injury. Moreover, acid rain effects could not be characterized as generally stimulatory or generally inhibitory of yield. However, results of this study indicate this is a possibility for specific groups of crops, as discussed above.

Caution should be used in drawing conclusions from these data. They were obtained by subjecting potted plants to simulated sulfuric acid rain in field exposure chambers, rather than to ambient rain under field conditions. The results pertain to a single growing season, a particular soil, and a particular location; thus, reproducibility of results has yet to be demonstrated. Interactions with air pollutants, other contaminants, or various environmental factors could affect the results. Interpretations of the data should be viewed as hypotheses to be tested under different conditions.

Table 6. Yield of Marketable Portion of Crops

Crop	FRESH WEIGHT OF YIELD PER POT: From Control Plants g/pot	From Treatment Plants Ratio to Control Yield: pH 3.0	pH 3.5	pH 4.0	SE[a]	Sig'n[b] Level	DRY WEIGHT OF YIELD PER POT: From Control Plants g/pot	From Treatment Plants Ratio to Control Yield: pH 3.0	pH 3.5	pH 4.0	SE[a]	Sig'n[b] Level
Radish 1	43.23	0.44§	0.83§	0.92	0.04	0.000§	2.66	0.45§	0.79§	0.86†	0.04	0.000§
Radish 2	42.12	0.40§	0.81†	0.84*	0.06	0.000§	2.51	0.47§	0.83†	0.86*	0.05	0.000§
Radish 3	47.74	0.24§	0.73§	1.14*	0.06	0.000§	2.54	0.31§	0.77§	1.15*	0.05	0.000§
Radish 4	26.79	0.38§	1.03	0.86	0.09	0.000§	1.71	0.42§	1.01	0.87	0.08	0.000§
Radish 5	18.07[d]	0.59	1.41	1.56	----[d]	------[d]	1.08[d]	0.64	1.40	1.52	----[d]	-----[d]
Beet	55.07	0.57§	1.02	1.09	0.11	0.011†	10.38	0.55†	1.03	1.10	0.11	0.012§
Carrot	138.54	0.56§	0.55§	0.73†	0.08	0.001§	13.36	0.53§	0.57§	0.69§	0.08	0.000§
Mustard Green	59.28	0.70§	0.87*	0.83†	0.05	0.003§	7.30	0.69§	0.90	0.86*	0.06	0.002§
Spinach	32.33	0.85	0.99	0.90	0.07	0.388	3.58	0.93	1.03	0.98	0.08	0.871
Swiss Chard	99.72	0.90	1.04	0.94	0.07	0.561	16.66	0.98	1.04	1.03	0.06	0.827
Bibb Lettuce	129.97	1.01	1.02	1.03	0.04	0.932	6.13	1.05	0.97	1.07	0.03	0.087*
Tobacco	------	----	----	----	----	-----	27.64	0.97	0.97	1.03	0.03	0.443
Cabbage	240.81	0.91	1.47	1.01	0.17	0.131	29.89	0.87	1.19	0.92	0.13	0.378
Broccoli	44.63	0.75§	0.92	0.89	0.07	0.063†	6.07	0.75§	0.88	0.91	0.06	0.078†
Cauliflower	69.62	1.03	1.46	1.20	0.15	0.185	6.36	1.01	1.39	1.27	0.13	0.164
Potato	691.79	0.92§	1.11†	1.07*	0.03	0.001§	149.53	0.86§	1.05	1.05	0.03	0.000§
Green Pea	21.55	1.04	0.98	1.05	0.04	0.674	4.21	1.06	0.97	1.06	0.06	0.547
Alfalfa	------	----	----	----	----	-----	28.72	0.94	1.31§	1.17§	0.05	0.000§
Red Clover	------	----	----	----	----	-----	31.05	0.99	1.03	1.02	0.04	0.911
Tomato	302.88	1.31§	1.01	0.95	0.07	0.001§	------	----	----	----	----	-----
Green Pepper	193.12	1.05	1.20†	1.05	0.06	0.103*	12.72	1.13	1.17†	1.06	0.06	0.207
Strawberry	113.04	1.72§	1.72§	1.51§	0.13	0.001§	------	----	----	----	----	-----
Oats	------	----	----	----	----	-----	31.41	0.92	1.00	1.00	0.05	0.500
Wheat	------	----	----	----	----	-----	29.30	0.97	0.98	0.98	0.06	0.976
Barley	------	----	----	----	----	-----	34.71	1.05	1.06	1.00	0.05	0.727
Corn[c]	------	----	----	----	----	-----	35.56	1.13*	0.95	0.99	0.05	0.085*
Onion	410.11	1.01	1.12	1.04	0.06	0.426	29.11	1.10	1.14	1.09	0.06	0.295
Fescue	------	----	----	----	----	-----	25.25	0.96	1.07	0.92	0.04	0.018†
Orchardgrass	------	----	----	----	----	-----	22.47	1.23†	1.10	1.00	0.07	0.097*
Bluegrass	------	----	----	----	----	-----	12.81	0.98	0.94	1.00	0.05	0.725
Ryegrass	------	----	----	----	----	-----	20.24	0.99	0.98	0.96	0.03	0.787
Timothy	------	----	----	----	----	-----	21.07	1.24†	1.09	0.86	0.07	0.003§

[a]Standard error of the mean, divided by mean control yield.
[b]Significance level of F-test for treatment effects.
[c]For corn, data refer to total above ground (stem plus leaves) weight.
[d]Unreliable data for control; see text.
*Significant effect with p ≦ 0.10 for two-sided t-test.
†Significant effect with p ≦ 0.05 for two-sided t-test.
§Significant effect with p ≦ 0.01 for two-sided t-test.

Table 7. Relative Ratings of Maximum Acid Rain Injury of Leaves

Crop	Acid Rain Injury by pH of Treatment		
	3.0	3.5	4.0
Radish 1	++	+	o
Radish 2	++	+	o
Radish 3	+	+	o
Radish 4	+	+	o
Radish 5	+	+	o
Beet	+	+	+
Carrot	+	o	o
Mustard Greens	++	+	o
Spinach	++	+	o
Swiss Chard	++	+	+
Bibb Lettuce	+	+	o
Head Lettuce	+	+	o
Tobacco	+	+	o
Cabbage	+	o	o
Broccoli	+	+	o
Cauliflower	++	+	o
Potato	+	+	o
Green Pea	+	+	o
Peanut	+	+	o
Soybean 1	+	+	+
Soybean 2	+	+	o
Soybean 3	+	+	o
Soybean 4	+	+	o
Alfalfa	+	+	o
Red Clover	+	+	o
Tomato	++	+	o
Cucumber	++	+	o
Green Pepper	++	+	+
Strawberry	+	o	o
Oats	o	o	o
Wheat	o	o	o
Barley	o	o	o
Corn	+	o	o
Onion	o	o	o
Fescue	+	+	o
Orchardgrass	+	+	o
Bluegrass	+	+	+
Ryegrass	+	+	o
Timothy	+	+	o

++ At least half the plants had 10% or more of leaf area injured by acid rain at some time during growth.

\+ Acid rain injury noted, but at no time during growth did more than half of plants show 10% or more of leaf area injured by acid rain.

o No apparent acid rain injury on leaves.

Table 8. Estimated Fraction of Leaf Area at Final Harvest Showing Injury Associated with Acid Rain Treatment

	Acid Rain Injury Percent of Leaf Area by pH of Treatment			
Crop	3.0	3.5	4.0	Maximum
Radish 1	17.5	5.0	0.0	25
Radish 2	15.4	5.0	0.0	20
Radish 3	11.4	5.0	0.0	15
Radish 4	7.9	4.3	0.0	10
Radish 5	11.6	4.8	0.0	15
Beet	5.0	1.2	0.2	5
Carrot	0.0	0.0	0.0	0
Mustard Greens	10.4	4.3	0.0	15
Spinach	11.8	4.0	0.0	15
Bibb Lettuce	5.0	0.0	0.0	5
Head Lettuce	4.6	0.0	0.0	5
Cabbage	4.3	0.0	0.0	5
Broccoli	5.0	3.2	0.0	5
Cauliflower	14.6	0.4	0.0	30
Green Pea	5.0	5.0	0.0	5
Alfalfa	4.3	0.4	0.0	5
Red Clover	5.0	0.0	0.0	5
Green Pepper	5.0	0.0	0.0	5
Strawberry	0.0	0.0	0.0	0
Corn	5.0	0.0	0.0	5
Onion	0.0	0.0	0.0	0
Fescue[a]	7.9	5.0	0.0	10
Orchardgrass[a]	6.1	1.8	0.0	10
Bluegrass[a]	5.0	3.6	0.4	5
Ryegrass[a]	5.0	0.4	0.0	5
Timothy	4.3	1.4	0.0	5

[a]Estimates made at first of multiple harvests, when foliar material was most abundant.

Table 9. Yields from Successive Harvests of Red Clover and Alfalfa.

Crop	Harvest Date	From Control Plants g/pot	Dry Weight of Yield Per Pot From Treatment Plants Ratio to Control Yield				Sig'n[b] Level
			pH 3.0	pH 3.5	pH 4.0	SE[a]	
Red Clover	07/26	7.53	0.84*	0.99	1.11	0.07	0.046†
(planted 5/25)	08/17	7.09	1.04	1.03	0.92	0.05	0.267
	09/06	7.72	1.05	1.01	1.04	0.07	0.952
	10/02	8.71	1.04	1.10	1.01	0.05	0.567
	Total	31.05	0.99	1.03	1.02	0.04	0.911
Alfalfa	07/26	9.59	0.96	1.25§	1.12	0.06	0.004§
(planted 5/25)	08/27	8.51	0.81†	1.31§	1.06	0.06	0.000§
	10/03	10.61	1.03	1.36§	1.31§	0.07	0.001§
	Total	28.72	0.94	1.31§	1.17§	0.05	0.000§

[a]Standard error of the mean divided by mean control yield.
[b]Significance level of F-test for treatment effects.
*Significant effect with $p \leq 0.10$ for two-sided t-test.
†Significant effect with $p \leq 0.05$ for two-sided t-test.
§Significant effect with $p \leq 0.01$ for two-sided t-test.

Table 10. Classification of Results by Foliar Injury and by Yield. Entries are Number of Crop-Treatment Combinations in Each Category.

Foliar Injury:

- ++ At least half the plants had 10% or more of their leaf area injured by acid rain at some time during growth.
- \+ Acid rain injury noted, but at no time did half the plants have 10% or more of leaf area injured by acid rain.
- o No apparent acid rain injury on leaves.

Yield:

- \+ Yield of treatment plants greater than yield of control plants.
- o Yield of treatment plants not significantly different from yield of control plants ($p \leq 0.10$).
- \- Yield of treatment plants less than yield of control plants.

		Foliar Injury			
		++	+	o	Total
Yield	+	1	6	4	11
	o	4	26	32	62
	-	2	7	2	11
	Total	7	39	38	84

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16. ABSTRACT

A study was undertaken to determine the relative sensitivity of major U. S. crops to sulfuric acid rain. Plants were grown under controlled environmental conditions and exposed to simulated acid rain of three sulfuric acid concentrations (pH 3.0, 3.5, 4.0) or to a control rain (pH 5.7). Injury to foliage and effects on yield were common responses to acid rain. However, foliar injury was not a good indicator of effects on yield.

17. KEY WORDS AND DOCUMENT ANALYSIS

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