PB82-126285

Effect of Simulated Sulfuric Acid Rain on Yield Growth, and Foliar Injury of Several Crops

(U.S.) Corvallis Environmental Research Lab., OR

1 Oct 80

229

TECHNICAL REPORT DATA
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1. REPORT NO. EPA-600/J-81-401	2. Journal Article	3. PB82-126285
4. TITLE AND SUBTITLE Effect of Simulated Sulfuric Acid Rain on Yield, Growth, and Foliar Injury of Several Crops		5. REPORT DATE 1981 October 1981
		6. PERFORMING ORGANIZATION CODE 310028
7. AUTHOR(S) Jeffrey J. Lee, Grady E. Neely, shelton C. Perrigan, Louis C. Grothaus		8. PERFORMING ORGANIZATION REPORT NO.
9. PERFORMING ORGANIZATION NAME AND ADDRESS Environmental Research La boratory, Office of Research and Development, U.S. Environmental Protection Agency, Corvallis, Oregon 97333		10. PROGRAM ELEMENT NO.
		11. CONTRACT/GRANT NO.
12. SPONSORING AGENCY NAME AND ADDRESS same		13. TYPE OF REPORT AND PERIOD COVERED
		14. SPONSORING AGENCY CODE EPA/600/02

15. SUPPLEMENTARY NOTES

Published in Environmental and Experimental Botany, Vol. 21, No. 2, pp 171-185, 1981

16. ABSTRACT

This study was designed to reveal patterns of response 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 (pH5.6). At harvest, the weights of the marketable portion, total aboveground portion and roots were determined for 28 crops. Of these, marketable yield production was inhibited for 5 crops (radish, beet, carrot, mustart greens, broccoli), stimulated for 6 crops (tomato, green pepper, strawberry, alfalfa, orchardgrass, timothy), and ambiguously affected for 1 crop (potato). In addition, stem and leaf production of sweet corn was stimulated. Visible injury of tomatoes might have decreased their marketability. No statistically significant effects on yield were observed for the other 15 crops. The results suggest that the likelihood of yield being affected by acid rain depends on the part of the plant utilized, as well as on species. Effects on the aboveground portion of crops and on roots are also presented. 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 related to effects on yield. However, foliar injury of swiss chard, mustard greens and spinach was severe enough to adversely affect marketability.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group

18. DISTRIBUTION STATEMENT Release to public	19. SECURITY CLASS (This Report) Unclassified	21. NO. OF PAGES
	20. SECURITY CLASS (This page) Unclassified	22. PRICE

EPA Form 2220-1 (9-73)

Rcvd 2-1-83

EPA-600/J-81-401
Journal Article

Environmental and Experimental Botany, Vol. 21, No. 2, pp. 171-185, 1981
Printed in Great Britain

0098-8472/81/020171-15 $02.00/0
Pergamon Press Ltd

EFFECT OF SIMULATED SULFURIC ACID RAIN ON YIELD, GROWTH AND FOLIAR INJURY OF SEVERAL CROPS*

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(*Received* 24 *June* 1980; *accepted in revised form* 1 *October* 1980)

LEE J. J., NEELY G. E., PERRIGAN S. C. and GROTHAUS L. C. *Effect of simulated sulfuric acid rain on yield, growth and foliar injury of several crops*. ENVIRONMENTAL AND EXPERIMENTAL BOTANY **21**, 171-185, 1981.—This study was designed to reveal patterns of response 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 weights of the marketable portion, total aboveground portion and roots were determined for 28 crops. Of these, marketable yield production was inhibited for 5 crops (radish, beet, carrot, mustard greens, broccoli), stimulated for 6 crops (tomato, green pepper, strawberry, alfalfa, orchardgrass, timothy), and ambiguously affected for 1 crop (potato). In addition, stem and leaf production of sweet corn was stimulated. Visible injury of tomatoes might have decreased their marketability. No statistically significant effects on yield were observed for the other 15 crops. The results suggest that the likelihood of yield being affected by acid rain depends on the part of the plant utilized, as well as on species. Effects on the aboveground portion of crops and on roots are also presented. 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 related to effects on yield. However, foliar injury of swiss chard, mustard greens and spinach was severe enough to adversely affect marketability.

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 dioxide (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.[1,11,12,18-23] In the northeastern United States, half of the summer rain events are at pH 4.0 or lower; occasional events are between 3.0 and 3.5.[19] With the increasing use of coal, precipitation will probably be at least as acidic in the future.

Since the regions impacted or susceptible to acid rain encompass vast acreages of fertile farmland, the potential impact on crops is a major concern.[3,10] Although some studies have been performed,[2,4-9,13-16,24] there is little

*Technical Paper Number 5344 of the Agricultural Experiment Station, Oregon State University.

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 be related to differences in yield response. To provide partial answers to these questions, we conducted an experimental survey to compare the relative foliar, growth, and/or yield sensitivities of several crops to simulated sulfuric acid rain.

The main interest of this study was to reveal patterns of acid rain response applicable to broad classes of crops. Thus, while data on specific crops are presented, the emphasis is on interpreting the data set as a whole. One result is a tentative classification scheme for crop responses to acid rain; this scheme is subject to modification as further experimentation is conducted. A validated classification scheme would be a valuable tool in regional or national assessments of crop effects. In the short-term, it will be useful for suggesting the underlying mechanisms of observed responses.

MATERIALS AND METHODS

Sandy loam soil was obtained from the floodplain of the Willamette River, Oregon. The low nitrogen (LN) mix was produced by mixing a portion of this soil with peat moss (7.7 kg/m^3 of soil) and 6–20–20 (N–P_2O_5–K_2O) fertilizer (624 g/m^3 of soil). The high nitrogen (HN) mix was produced by mixing another portion of the soil with peat moss (7.7 kg/m^3 of soil) and 10–20–20 fertilizer (624 g/m^3). After the soil was pasteurized by exposure to aerated steam (75°C for 40 min), plastic pots were filled with the mixes. Averaged results of chemical analyses of samples of the amended and unamended soils are given in Table 1. Supplemental fertilizer applications were made for several crops (Table 5).

For one group of crops, seeds were sieved into 3 size classes and the most common-sized seeds were planted in 6 l. plastic pots. Two potato pieces each containing two eyes were planted in 15 l. pots. In most cases, plants in this group were first exposed to simulated rain treatments

Table 1. Chemical analysis of soil mixes used in 1979

Soil mix	Salts (mmhos/cm)	Organic matter (%)	Total N (%)	P (ppm)	SO_x-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	51.9	0.20	204	10.9	5.6	0.27	21.2	17.0	5.8

within one day of planting. Crops in a second group were germinated in a greenhouse and transplanted to 6 l. plastic pots for exposure to simulated rain treatments.

Crops were grown in one of three types of exposure chambers (Table 2) situated at Oregon State University's Schmidt Research Farm, near Corvallis. All chambers were covered on top and sides to exclude ambient rain. Openings between the side and ground, and between the side and top, of each large round chamber provided for convective air exchange; these openings were covered with insect screening. The small round chambers and the square chambers were equipped with blowers which provided one ambient air exchange per minute. Although not measured during 1979, ambient concentrations of SO_2 during the previous 4 growing seasons were below detection limits (approximately 3 pphm). During the same period, an O_3 concentration of 14 pphm was measured on just one occasion; no other events above 10 pphm were observed. Thus, the ambient air entering the chambers was not filtered to exclude gaseous polutants.

All plants of any given crop were grown in the same type of 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.

Simulated rain was applied with stainless steel nozzles (Delavan Co., "Rain Nozzles"*) at an average rate of 6.7 mm/hr, 1.5 hr per day, 3 days per week, for a total of 30 mm/week. The simulated rain in each chamber contained a stock solution consisting of deionized water to which had been added 11 μeq/l Ca^{2+}, 12 μeq/l Na^{+}, 2 μeq/l K^{+}, 5 μeq/l Mg^{2+}, 11 μeq/l SO_4^{2-}, 12 μeq/l NO_3^{-}, and 12 μeq/l Cl^{-}. These concentrations were an approximation of non-acid rain based on a 7-yr average from a site in the northeastern United States, after eliminating estimated sulfuric and nitric acid components.[17] The control chambers received rain containing only the stock solution equilibrated with atmospheric CO_2 to approximately pH 5.6. In the treatment chambers the rain consisted of the stock solution with 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. 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.

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 rather than to insects or disease. 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

Table 2. Chambers used in 1979 crop survey

Type		Diameter or length (m)	Height (m)	Covering	Total No.	No. of chambers per treatment	Pots per crop per treatment
Large round	(LR)	4.6	2.4	Krene	4	1	14*
Small round	(SR)	3.0	2.4	Krene	8	2	14
Square	(SQ)	2.4	2.1	Teflon	20	5	25

*10 pots per treatment for potato.

*Mention of trade names or commercial products does not constitute endorsement or recommendation for use.

Table 3. Chemical analysis of irrigation water (mg/l)

pH	7.46
Calcium	19.0
Magnesium	6.1
Sodium	9.2
Potassium	1.7
Phosphorus	0.25
Kjeldahl-Nitrogen	0.07
Nitrate-Nitrogen	2.20
Sulfate	23.0
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.

on at least 10% of the leaf area. Just prior to harvest, the fraction of leaf area showing acid rain injury was visually estimated for each plant. Area was estimated in gradations 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.

Radish, alfalfa and onion were also grown during the previous (1978) season. Experimental conditions and exposure regimes were essentially the same for these crops as for those grown in 1979. One square chamber (Table 2) was used for each pH treatment (pH 3.0, 3.5, 4.0 and control). Radish and onion were grown in 12 pots per treatment; alfalfa was grown in 16 pots per treatment. Fresh and dry weights of marketable portions were measured. These results were used for interseasonal comparison.

In the statistical analysis of fresh and dry weights, a one-way analysis of variance among the four experimental groups (pH 3.0, 3.5, 4.0 and control) was performed for each crop. Provided that the resulting F-statistic was significant at the 0.10 level, two-sided t-tests were used to determine whether treatment means were significantly different from the control. While this is a standard approach, it is somewhat less conservative than other approaches which could have been chosen. It is appropriate since t-tests were done only between pre-selected pairs (i.e. treatment vs. control, rather than treatment vs. treatment) and since this was an exploratory study.[17,25]

To make patterns of response clearer, the three treatment means and the standard error were divided by the control mean. This was done after the statistical analysis was carried out.

RESULTS

For each crop harvested in 1979, the fresh and dry weights of the marketable portions (yield) of plants are given on a per pot basis in Table 6. Dry weights of aboveground portions and of roots are given in Table 7. Marketable yield results for crops grown in 1978 are given in Table 8. In Tables 6-8, the mean weights of crops subjected to simulated acid rain are presented as ratios to the control mean, as are the standard errors.

Foliar injury results from 1979 are summarized in Tables 9 and 10. Maximum injury ratings, made for all crops during the growing season, are given in Table 9. Yellowing and/or senescence of control leaves of several crops prevented estimating the per cent leaf area exhibiting acid rain injury at harvest; results for those crops for which estimates could be made are given in Table 10. Since foliar

Table 5. Experimental conditions of crops surveyed in 1979

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[f]	Harvest criteria[g]	Final harvest date[f]
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	10/03
Head Lettuce	Great Lakes	LR	T	1	HN			8/31	9/14	3	11/15
Tobacco	Burley 21	LR	T	1	HN	2.0 Urea		5/02	6/13	1	8/08
Cabbage	Golden Acre	LR	T[h]	1	HN	1.0 Urea	D	2/21	4/20	2	7/17
Broccoli	Italian Green Sprouting	LR	T[h]	1	HN	0.5 Urea	D	2/21	4/20	3	6/10
Cauliflower	Early Snowball	LR	T[h]	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	3	9/26
Soybean 1	OR-10	SQ	S	1	LN		D	7/26	7/26	3	10/24
Soybean 2	Hark (G-1)	SQ	S	1	LN			9/05	10/02	3	—
Soybean 3	Norman (G-00)	SQ	S	1	LN			9/05	9/11	3	—
Soybean 4	Evans (G-0)	SQ	S	1	LN			9/05	9/11	3	—
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	3	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	[h]	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/[illegible]
Corn	Golden Midget	LR	S	1	HN	0.5; 4.1		7/23	7/23	3	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: Manch.
[f]All dates are 1979.
[g]See Table 4 for harvest criteria.
[h]Transplants obtained from commercial grower.

Table 6. Yield of marketable portion of crops grown in 1979

Crop	Fresh weight of yield per pot: Control mean[a] (g/pot)	Fresh: Ratio of treatment mean[a] to control mean, pH 3.0[b]	Fresh: pH 3.5[b]	Fresh: pH 4.0[b]	Fresh: S.E.[c]	Fresh: F-test sign level[d]	Dry weight of yield per pot: Control mean[a] (g/pot)	Dry: Ratio of treatment mean[a] to control mean, pH 3.0[b]	Dry: pH 3.5[b]	Dry: pH 4.0[b]	Dry: S.E.[c]	Dry: F-test sign level[d]
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	0.001‡
Radish 3	47.74	0.24‡	0.73‡	1.14*	0.06	0.000‡	2.53	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[g]	0.59	1.41	1.56	—[g]	—[g]	1.08[g]	0.64	1.40	1.52	—[g]	—[g]
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	0.328	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	0.627
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	0.517
Alfalfa[e]	—	—	—	—	—	—	28.72	0.94	1.31‡	1.17	0.05	0.000‡
Red Clover[e]	—	—	—	—	—	—	31.05	0.99	1.03	1.02	0.04	0.911
Tomato[e]	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[e]	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[f]	—	—	—	—	—	—	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[e]	—	—	—	—	—	—	25.25	0.96	1.07	0.92	0.03	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[e]	—	—	—	—	—	—	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] Sample size per mean: for SR and ER chambers, 14 pots; for SQ chambers, 25 pots (see Table 5 for chamber types).
[b] Significance of difference between acid rain treatment mean and control mean determined by two-sided t-test.
[c] Standard error of the mean (computed using error mean square from analysis of variance), divided by mean control yield.
[d] Significance level of F-test from one-way analysis of variance among four experimental groups.
[e] Seasonal total of multiple harvests.
[f] For corn, data refer to total aboveground (stem plus leaves) weight.
[g] Unreliable data for control; see text.
* Significant with $p \leq 0.10$.
† Significant with $p \leq 0.05$.
‡ Significant with $p \leq 0.01$.

Table 7. Dry weights of aboveground portions and roots of crops grown in 1979

Crop	Total aboveground portions: Control mean[a] (g pot)	Ratio of treament mean[a] to control mean: pH 3.0[b]	pH 3.5[b]	pH 4.0[b]	S.E.[c]	*F*-test sign level[d]	Roots: Control mean[a] (g pot)	Ratio of treatment mean[a] to control mean: pH 3.0[b]	pH 3.5[b]	pH 4.0[b]	S.E.[c]	*F*-test sign level[d]
Radish 1	1.94	0.81†	0.94	1.07	0.05	0.019†	2.66	0.45‡	0.79‡	0.86†	0.04	0.000‡
Radish 2	1.65	0.88	0.96	0.99	0.06	0.461	2.51	0.47‡	0.83†	0.86*	0.06	0.001‡
Radish 3	2.00	0.66‡	0.84‡	0.92	0.04	0.000‡	2.54	0.31‡	0.77‡	1.15*	0.05	0.000‡
Radish 4	1.55	0.86*	1.02	0.86*	0.05	0.066*	1.71	0.42‡	1.01	0.87	0.08	0.000‡
Radish 5	1.29[e]	1.12	1.19	1.11	—[e]	—[e]	1.08[e]	0.64	1.40	1.52	—[e]	—[e]
Beet	10.03	0.90†	1.08	1.00	0.03	0.015†	10.58	0.55†	1.03	1.10	0.11	0.012†
Carrot	8.39	0.67‡	0.69*	0.82	0.07	0.002‡	13.36	0.54‡	0.57‡	0.69‡	0.08	0.000‡
Mustard Green	7.30	0.69‡	0.90	0.86*	0.05	0.002‡	2.06	0.86	0.90	1.05	0.08	0.334
Spinach	4.23	0.95	1.06	1.02	0.08	0.818	1.63	0.86	0.99	1.09	0.15	0.740
Swiss Chard	16.66	0.98	1.04	1.03	0.06	0.827	13.35	0.98	0.99	0.96	0.11	0.996
Bibb Lettuce	6.13	1.05	0.97	1.07	0.03	0.087*	1.33	0.78‡	0.88	0.94	0.06	0.074*
Tobacco	44.12	0.96	1.00	1.03	0.01	0.585	9.10	1.13	1.12	1.18	0.07	0.358
Cabbage	72.96	0.95	0.90	0.89	0.05	0.308	14.16	1.17	0.83	0.91	0.12	0.297
Broccoli	35.74	0.95	1.09	0.97	0.06	0.400	12.27	1.20	0.85	0.81	0.10	0.036‡
Cauliflower	30.92	1.10	1.10	1.12	0.05	0.391	6.29	1.18	1.12	1.04	0.08	0.362
Potato	11.14	0.97	1.27‡	1.24‡	0.06	0.001‡	3.71	0.68‡	0.81†	0.98	0.07	0.005‡
Green Pea	24.81	0.96	1.01	1.02	0.02	0.242	2.23	1.06	0.97	0.91	0.05	0.202
Alfalfa	33.83	0.94	1.30‡	1.16†	0.05	0.000‡	19.72	1.00	1.17‡	1.02	0.04	0.008‡
Red Clover	37.04	1.00	1.04	1.04	0.04	0.824	7.37	1.05	1.03	1.11	0.05	0.394
Tomato[f]	34.49	1.04	1.12‡	1.11‡	0.03	0.026†	5.06	0.85‡	1.01	0.98	0.04	0.029†
Green Pepper[f]	9.26	0.89*	1.14‡	1.08	0.04	0.000‡	5.70	0.92	1.02	1.09	0.05	0.111
Strawberry[f]	40.01	1.17‡	1.21‡	1.13†	0.04	0.001‡	36.17	0.86†	0.79‡	0.99	0.06	0.016†
Oats	63.29	0.96	1.02	1.00	0.04	0.817	3.78	1.16	1.60‡	0.97	0.16	0.022†
Wheat	69.73	0.98	0.94	0.98	0.05	0.850	11.45	0.64‡	0.53‡	0.71‡	0.07	0.000‡
Barley	63.81	1.04	1.09	1.01	0.05	0.484	6.35	0.88	0.96	1.13	0.08	0.164
Corn	35.56	1.13*	0.95	0.99	0.05	0.085*	6.36	1.12	0.97	1.03	0.07	0.430
Onion	15.54	1.30‡	1.08	0.94	0.07	0.007‡	—	—	—	—	—	—
Fescue	30.58	0.95	1.05	0.93	0.03	0.049†	21.48	0.82‡	1.01	0.85†	0.05	0.005‡
Orchardgrass	22.47	1.23†	1.10	1.00	0.07	0.097*	14.74	1.36‡	1.00	0.68‡	0.09	0.000‡
Bluegrass	16.43	0.96	0.91	0.96	0.04	0.530	6.48	0.92	0.85	0.75	0.10	0.330
Ryegrass	26.69	1.01	1.03	0.98	0.02	0.580	37.38	0.86†	0.84†	0.86‡	0.05	0.099*
Timothy	21.07	1.24†	1.09	0.86	0.07	0.003‡	13.26	1.16	0.95	0.88	0.09	0.133

[a]Sample size per mean: for SR and LR chambers, 14 pots; for SQ chambers, 25 pots (see Table 5 for chamber types).
[b]*Significance of difference between acid rain treatment mean and control mean determined by two-sided t-test.*
[c]Standard error of the mean (computed using error mean square from analysis of variance), divided by mean control weight.
[d]Significance level of *F*-test from one-way analysis of variance among four experimental groups.
[e]Unreliable data for control; see text.
[f]Aboveground portion does not include weight of fruit.
*Significant with $p \leq 0.10$.
†Significant with $p \leq 0.05$.
‡Significant with $p \leq 0.01$.

Table 8. Yield of marketable portion of crop grown in 1978

	Fresh weight of yield per pot						Dry weight of yield per pot					
		Ratio of treatment mean[a] to control mean						Ratio of treatment mean[a] to control mean				
Crop	Control mean[a] (g/pot)	pH 3.0[b]	pH 3.5[b]	pH 4.0[b]	S.E.[c]	*t*-test sign level[d]	Control mean[a] (g/pot)	pH 3.0[b]	pH 3.5[b]	pH 4.0[b]	S.E.[c]	*F*-test sign level[d]
Radish	69.83	0.75‡	0.86†	0.88*	0.05	0.011‡	4.04	0.79‡	0.87*	0.84†	0.05	0.022*
Alfalfa:												
Harvest 1	—	—	—		—	—	3.78	1.19*	1.16	0.89	0.07	0.019†
Harvest 2	—	—	—		—	—	6.10	1.12	1.12	1.09	0.09	0.757
Harvest 3	—	—	—		—	—	7.20	1.04	1.27†	1.29†	0.09	0.053†
Total	—	—	—		—	—	17.08	1.10	1.19	1.13	0.06	0.197
Onion	96.51	0.93	1.06	1.07	0.10	0.732	9.66	0.98	1.02	0.86	0.12	0.801

[a]Sample size per mean: for radish and onion, 12 pots; for alfalfa, 16 pots.
[b]Significance of difference between acid rain treatment mean and control mean determined by two-sided *t*-test.
[c]Standard error of the mean (computed using one-way analysis of variance), divided by mean control weight.
[d]Significance level of *F*-test from one-way analysis of variance among four experimental groups.
*Significant with $p \leqq 0.10$.
†Significant with $p \leqq 0.05$.
‡Significant with $p \leqq 0.01$.

Table 9. Relative ratings of maximum acid rain injury of leaves for 1979

Crop	Acid rain injury by pH of treatment 3.0	3.5	4.0
Radish 1	+ +	+	0
Radish 2	+ +	+	0
Radish 3	+	+	0
Radish 4	+	+	0
Radish 5	+	+	0
Beet	+	+	+
Carrot	+	0	0
Mustard Greens	+ +	+	0
Spinach	+ +	+	0
Swiss Chard	+ +	+	+
Bibb Lettuce	+	+	0
Head Lettuce	+	+	0
Tobacco	+	+	0
Cabbage	+	0	0
Broccoli	+	+	0
Cauliflower	+ +	+	0
Potato	+	+	0
Green Pea	+	+	0
Peanut	+	+	0
Soybean 1	+	+	+
Soybean 2	+	+	0
Soybean 3	+	+	0
Soybean 4	+	+	0
Alfalfa	+	+	0
Red Clover	+	+	0
Tomato	+ +	+	0
Cucumber	+ +	+	0
Green Pepper	+ +	+	+
Strawberry	+	0	0
Oats	0	0	0
Wheat	0	0	0
Barley	0	0	0
Corn	+	0	0
Onion	0	0	0
Fescue	+	+	0
Orchardgrass	+	+	0
Bluegrass	+	+	+
Ryegrass	+	+	0
Timothy	+	+	0

+ + = 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.

0 = No apparent acid rain injury on leaves.

Table 10. Estimated fraction of leaf area at final harvest showing injury associated with acid rain treatment for 1979

Crop	Acid rain injury % of leaf area by pH of treatment 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	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.

injury was rated in discrete steps, a rating of 5% indicated that a plant showed some, possibly minute, acid rain injury. For some crops, maximum per cent injury occurred well before harvest, sometimes early in the growing season.

Dicotyledons

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

Root crops. The yield of all three root crops (radish, beet, carrot) tended to be lower than control under acid rain treatment. Aboveground productivity was inhibited and foliar injury was common. Thus, root crops were considered to be the group most adversely affected by acid rain.

All three root crops had foliar injury associated with pH 3.0 treatments; radish and beet were also injured at pH 3.5 (Table 9). Since root crops frequently are marketed with leaves attached, disfiguration of leaves 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 10). Beet showed less leaf injury at harvest (Table 10), but was one of only five crops injured at pH 4.0 (Table 9). Since all mature beet leaves developed a mosaic pattern which may have partially masked acid rain injury, the results in Table 10 for beet may be underestimates.

In terms of marketable 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 (Table 6). Aboveground productivity of root crops was also inhibited, although not to the same degree as root productivity (Table 7).

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 9 and 10). No such temporal differences in effect on marketable yield were apparent (Table 6). The yield reductions observed in 1978 (Table 8) were similar to those for 1979 (Table 6).

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. Consequently the yield of the control plants 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(s) 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 in 1978 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. Although statistically significant inhibition of yield occurred for only one leaf crop, foliar injury, a quality factor, was observed on all five crops. Thus, adverse effects on leaf crops were ranked second to those on root 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 9 and 10). The only leaf crop to have less marketable yield due to exposure to acid rain, as measured by weight of foliage, was mustard greens (Table 6). Root productivity of bibb lettuce was inhibited at pH 3.0 (Table 7). MOHAMED[24] found that acid rain at approximately pH 4 inhibited total (aboveground plus root) productivity of potted lettuce plants.

Cole crops. Since adverse effects on marketable yield occurred only under the most acid conditions, this group was considered to be only slightly sensitive to acid rain.

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 9 and 10). Only radish was more extensively injured than cauliflower at pH 3.0 (Table 10). The waxy foliage of these cole crops afforded, at most, partial protection from acid rain injury.

Only broccoli showed significant marketable yield effects; at pH 3.0 yield was lower than the control (Table 6). No significant effects on aboveground or root productivity were found

(Table 7). 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.[24]

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 9). Marketable yield, however, was inhibited by pH 3.0 rain, and stimulated by pH 3.5 and 4.0 rain; the stimulatory effects at pH 3.5 and 4.0 were significant only for fresh weight (Table 6). Aboveground productivity was stimulated at pH 3.5 and 4.0; root production was less than control at pH 3.0 and 3.5 (Table 7).

Legumes. Acid rain treatments of pH 3.0 and pH 3.5 injured the foliage of all eight legume cultivars (Table 9). 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). Total aboveground weight (including stubble) of alfalfa was greater than control at pH 3.5 and pH 4.0, while that of clover was not affected. Root weight of alfalfa was greatest at pH 3.5 (Table 7).

The yield responses of red clover and alfalfa were consistent among the successive harvests (Table 11). Although not statistically significant, alfalfa yields tended to be lower than control at pH 3.0. Greater yields at intermediate pH values (Table 11) suggest competition between stimulatory and inhibitory effects of acid rain. The pattern of results from 1978 (Table 8) were consistent with results from 1979 (Table 11) at pH 3.5; however, there was no indication of lower yields at pH 3.0.

Fruit crops. Stimulatory effects were most

Table 11. Yields from successive harvests of red clover and alfalfa grown in 1979

		Dry weight of yield per pot					
			Ratio of treatment mean to control mean				
Crop	Harvest date	Control mean[a] (g pot)	pH 3.0[b]	pH 3.5[b]	pH 4.0[b]	S.E.[c]	F-test sign level[d]
Red Clover (planted 5 25)	07/26	7.53	0.84*	0.99	1.11	0.07	0.046*
	08/17	7.09	1.01	1.03	0.92	0.05	0.267
	09/06	7.72	1.05	1.01	1.04	0.07	0.552
	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 (planted 5 25)	07/26	9.59	0.96	1.25‡	1.12	0.06	0.003‡
	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]Sample size per mean was 14 pots.
[b]Significance of difference between acid rain treatment mean and control mean determined by two-sided t-test.
[c]Standard error of the mean (computed using one-way analysis of variance), divided by mean control yield.
[d]Significance level of F-test from one-way analysis of variance among four treatment groups.
*Significant with $p \leq 0.10$.
†Significant with $p \leq 0.05$.
‡Significant with $p \leq 0.01$.

general for fruit crops. The yield of crops grown to harvest (i.e. all except cucumbers) frequently was greater for plants receiving acid rain than for control plants. In no case did acid rain cause a significantly 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[24] 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.

For all three fruit crops, the greatest aboveground weights (not including fruit weights) were at pH 3.5. Top growth of strawberry was stimulated at pH 3.0 and 4.0, and at pH 4.0 for tomato. At pH 3.0 the mean aboveground weight of pepper plants was less than control. Root growth of tomato and strawberry was inhibited at pH 3.0; strawberry roots were also inhibited at pH 3.5 (Table 7).

Acid rain injured most leaves of tomato, cucumber and green pepper at pH 3.0; less severe injury occurred at pH 3.5 (Table 9). Although the leaves of green pepper were also injured at pH 4.0 (Table 9), this injury was not identifiable at final harvest (Table 10). Strawberry leaves sustained only minute injury (Table 9) which could not be identified at final harvest (Table 10).

Monocotyledons

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

Grain crops. Small grains (oats, wheat, barley) were the crops least sensitive to acid rain. The yields (Table 6) were not affected by the acid treatments, and no foliar injury was apparent (Table 9). However, root productivity of wheat was inhibited at all acid rain treatments, while the root growth of oats was stimulated at pH 3.5 (Table 7).

Corn was harvested when the plants grew tall enough to interfere with spray from the nozzles (approximately 1 m). Although the foliage was injured (Table 9), the total aboveground 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). No significant effect on roots was observed (Table 7).

Bulb crop. Onion bulbs grown under acid treatments did not differ significantly from controls in either 1978 (Table 8) or 1979 (Table 6). No foliar injury was identified (Tables 9 and 10): aboveground foliage at pH 3.0 was greater than control (Table 7).

Forage crops. Although foliar injury occurred on forage crops, no adverse effects on productivity were observed. Marketable yield was either not affected or greater under acid rain treatment.

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 9 and 10).

No effects on bluegrass or ryegrass productivity were found. 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[2] 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. Results for total aboveground weight (including stubble) were similar to those for yield (Table 7).

Root growth of ryegrass (pH 3.0, 3.5, 4.0) and of fescue (pH 3.0, 4.0) was inhibited. Mean root weight of orchardgrass was greatest at pH 3.0 and least at pH 4.0 (Table 7).

DISCUSSION

Marketable and non-marketable yields

Root growth tended to be inhibited by sulfuric acid rain. Inhibition was observed for 10 of 28 cultivars, while stimulation occurred for only 2 cultivars. In addition, mean root weight of orchardgrass was greater than control at pH 3.0 and smaller than control at pH 4.0. However, except for root crops, decreased root weight generally was not associated with decreased marketable yield. For example, at pH 3.0, the roots of tomato plants weighed 15% less than control; however, these plants produced fruit weighing a total of 31% more than control. Wheat roots at all acid rain treatments weighed much less than controls, and oat roots at pH 3.5 were heavier than controls; grain production was not affected for either crop.

Total aboveground weight was more closely associated with marketable yield. In no case was the direction of the effect on aboveground weight different from the direction of the effect on marketable yield. However, for broccoli (pH 3.0) and tomato (pH 3.0) marketable yield, but not top weight, was affected. Also, for tomato (pH 3.5 and 4.0) and onion (pH 3.0) top weight, but not marketable yield, was affected.

Stimulation of marketable yield at intermediate pH values occurred for 3 crops (potato, alfalfa, green pepper). Peaked responses also were observed for aboveground portions (potato, alfalfa, tomato, green pepper) and for roots (alfalfa, oats). This pattern suggests that the net effect of acid rain was the result of competing stimulatory and inhibitory effects. If this was generally true, then the optimum pH was greater than 4.0 for those crops which were consistently inhibited in this study, and less than 3.0 for those which were consistently stimulated. However, this might have been a sulfate effect rather than a pH effect.

Foliar injury and yield

In 1979, 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 9).

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 12 shows the results of classifying these combinations by effects on foliar injury and effects on yield.

On 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 12). 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

Table 12. Cross-classification of 1979 results on foliar injury and yield. Entries is number of crop-treatment combinations in each category

	Foliar injury			
	+ +	+	0	Total
Yield: Greater than crontrol	1	6	4	11
Not significantly different from control	4	26	32	62
Less than control	2	7	2	11
Total	7	39	38	84

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.
0 = No apparent acid rain injury on leaves.

controls. The yields of acid-treated plants were higher 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 numbers of combinations having foliar injury were similar for both the stimulated and inhibited groups (Table 12). 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 possibility for specific groups of crops, as discussed above.

CONCLUSIONS

Caution is essential 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. While some crops were grown during two seasons, the results pertain mainly to a single growing season, a particular soil, and a particular location; thus, for most crops, reproducibility of results has yet to be proven. 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. Hypotheses suggested by the results of this study include:

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

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

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

4. Foliar injury is not necessarily associated with marketable yield effects.

5. Effects on top weight, but not necessarily root weight (except for root crops), are correlated with effects on marketable yield.

6. Net effect of acid rain is the result of competing stimulatory and inhibitory effects; this implies the existence of an optimum rain pH or sulfate concentration for maximum productivity.

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