Effects of Simulated Sulfuric and Sulfuric-Nitric Acid Rain on Crop Plants: Results of 1980 Crop Survey

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EFFECTS OF SIMULATED SULFURIC AND SULFURIC-NITRIC ACID RAIN ON CROP PLANTS

RESULTS OF 1980 CROP SURVEY

AUTHORS: C.J. Cohen, L.C. Grothaus, and S.C. Perrigan are research assistants in the Crop Science Department.

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ABSTRACT

A series of experiments was performed to determine the sensitivity of a variety of crops to simulated sulfuric acid (H_2SO_4) and to sulfuric-nitric acid (H_2SO_4-HNO_3) rain. Treatments consisted of three 1.5-hour rains weekly at pH 5.6 (control) or at pH 3.0, 3.5, or 4.0. Six crops were grown in field plot experiments in a slightly acid soil, and 13 were grown in pots containing neutral to slightly alkaline soil in plastic chambers.

Yields of 7 of 15 crop cultivars were not affected by either H_2SO_4 or H_2SO_4-HNO_3 rain treatment in either field or chamber studies. Both stimulatory and inhibitory yield responses occurred in the remaining crops. In the field H_2SO_4 rain studies, no significant effects on yields of radish, mustard greens, or spinach occurred, but yields of alfalfa and tall fescue were stimulated. In the field H_2SO_4-HNO_3 rain studies, yields of alfalfa, tall fescue, radish, and spinach were not significantly affected, but yield decreases in corn and mustard greens occurred. However, corn yield was reduced at pH 4.0 because of reduced numbers of ears per plant, but no effect occurred at pH levels 3.0 and 3.5. Only root crops (radish, beet, and carrot) and leaf crops (lettuce and mustard greens) showed significant yield responses in chamber experiments. Root crops showed both yield stimulation and depression, but leaf crops showed only depression. Root sensitivity of crops was similar to yield sensitivity except for forage grasses. Foliar injury generally was minimal with mean injury rarely exceeding 1 to 2 percent of total leaf area. Most indicators of forage quality were not consistently affected by either H_2SO_4 or H_2SO_4-HNO_3 rain treatment.

These results support the conclusion from a similar crop survey in 1979 (which studied sulfuric acid rain and chamber-grown plants) that acid rain treatment does not appear to either generally stimulate or depress crop productivity. However, the variation seen in yield responses of several crops with acid rain type and growth environment does underscore the need to conduct multi-year field studies before the response of a given crop can be characterized with confidence.

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INTRODUCTION

Literature dealing with the effects of acid precipitation on crop plants has been reviewed previously (Cohen et al., 1981). Perhaps the most striking feature of this summary was the paucity of available information. Since only a limited number of crop species previously had been experimentally subjected to acid rain, a crop growth survey was initiated in spring, 1979, at the Schmidt Farm Research Station of Oregon State University at Corvallis. Productivity of 28 crop cultivars grown in pots in closed-top chambers and exposed to simulated sulfuric acid (H_2SO_4) rain treatments was determined, and quality characteristics of several of these cultivars were examined. Since yield of approximately two-thirds of the crops surveyed was not affected by simulated H_2SO_4 rain treatment and equal numbers of the remaining crops exhibited stimulatory and inhibitory yield responses, we concluded that acid rain treatment did not appear to either generally inhibit or stimulate crop productivity (Cohen *et al*., 1981).

The work described in this report was conducted as an extension of the initial crop growth survey effort. The crop survey approach was continued to provide additional information on the sensitivity of several important crop species to simulated H_2SO_4 rain. In addition, the survey was extended to study responses to a combination sulfuric-nitric acid rain [H_2SO_4-HNO_3, 2:1 H^+ equivalent-basis ratio, as reported for acid rain in the northeastern United States (Cogbill and Likens, 1974)]. The survey was also extended to study the growth of several crops in field plots as well as in chambers. Objectives of these experiments were to determine: (1) whether simulated H_2SO_4 and H_2SO_4-HNO_3 rain treatments affected the productivity and/or quality characteristics of the crop species examined and (2) whether qualitative responses of several selected crops to the two acid rain types differed.

Several ancillary experiments were conducted to study possible mechanisms of acid rain effects suggested by 1979 survey results. First, sulfur and nitrogen fertilization levels were varied in chamber grown alfalfa to investigate whether the stimulation of top dry matter production which occurred at intermediate pH levels in 1979 might have been caused by so-called "acid rain fertilizer effect". Second, rhizocylinder pH of radish grown in the field and in chambers was examined to investigate whether the greater relative reductions in root growth compared to top growth of root crops studied in 1979 may have occurred as a direct effect of acid rain on root growth through reduced pH of soil adjacent to roots. A large reduction in rhizocylinder pH would indicate possible toxic effects on the root through increased aluminum and/or manganese availability. Finally, potato seed piece sprouting and tuber yield of potatoes grown from transplants were studied separately in chambers to differentiate acid rain effects on stem number and tuber yield. Reductions in tuber number and yield in 1979 were associated with a reduction in stem number, one of the determinants of tuber number and, consequently, yield.

The field and chamber studies are discussed in separate sections of this report because they were conducted as independent studies under distinct growth conditions and results from these studies cannot be compared directly. In addition to environmental differences associated with growth in field plots versus growth in pots in stationary chambers, soil pH was different in the field and chamber studies. Soil pH was slightly acid in the field (mean pH of 6.2) but was neutral (alfalfa) to slightly alkaline (all other crops, mean pH of 7.9) in the chamber studies. The alfalfa studies are discussed as a subsection of the chamber studies, because of their complexity and the fact that a different soil was used for alfalfa.

FIELD STUDIES

Materials and Methods

Yield responses of five and six crop cultivars to simulated H_2SO_4 and H_2SO_4-HNO_3 rains, respectively, were studied in field experiments. Crops grown in both rain types were exposed to acidic simulants at pH levels 4.0, 3.5, and 3.0 and to control simulant at approximately pH 5.6. While alfalfa (Medicago sativa), tall fescue (Festuca arundinacea Schreb.), mustard greens (Brassica japonica), radish (Raphanus sativus), and spinach (Spinacia oleracea) were exposed to both rain types in concurrent experiments, corn (Zea mays) was exposed only to the H_2SO_4-HNO_3 rain type.

Rain simulants were prepared using a stock solution of deionized water to which 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^{-} were added. These concentrations were derived from precipitation data averaged over seven years from a site in the northeastern United States after subtraction of estimated acidic components and, therefore, approximated ionic concentrations of non-acid rain (J.J. Lee, personal communication). Control rain consisted of the stock solution equilibrated with atmospheric CO_2 to approximately pH 5.6. Acid rain treatments were prepared by adjusting the pH of control rain to the appropriate pH levels with additions of 3.6 N H_2SO_4 and 1.8 N HNO_3 prepared from reagent grade acid. The H_2SO_4 rain treatments were acidified with additions of H_2SO_4 only. The combination H_2SO_4-HNO_3 rain treatments were acidified with additions of both acids in a 2:1 H^{+} equivalent ratio of H_2SO_4:HNO_3.

Rain treatments were delivered through stainless steel nozzles at the average rate of 6.7 millimeters/hour, 1.5 hours/day, 3 days/week, for a total of 30 millimeters/week. The pH of rain solutions was checked at the beginning of each rain event using an Orion 901 Research Microprocessor Ionalyzer. This instrument was calibrated before each rain event using pH 4.01 and 7.0 standard buffer solutions. Rain delivery nozzles were calibrated for spray distribution pattern and delivery rate.

Experiments were conducted using randomized complete block designs. For each rain type, 16 plots per study were used with the four pH treatments assigned at random to plots within each of four replicate blocks. For the five crops exposed to both rain types, the 16 H_2SO_4-HNO_3 rain study plots were arranged in one strip planted east-to-west, and the 16 H_2S_4O rain study plots were planted in a second strip one meter to the south. Sixteen open-top, portable chambers were placed over plots of a rain type only during individual rain event applications. These chambers were covered with Monsanto 602 plastic and measured 3 meters in diameter and 2.4 meters in height. (Chambers were moved on and off 1.3-meter high stationary extensions in the corn experiment when corn plants reached approximately two meters in height so rain delivery nozzles remained above the crop canopy. Calibration checks indicated this did not significantly alter distribution.) The four chambers within each replicate block were rotated with respect to both treatment plot and nozzle position at successive rain events to reduce variation in plant response that might have been associated with chamber or nozzle variation.

The soil at Schmidt Farm is a Willamette silt loam with a well-drained surface layer about 60 centimeters thick overlying a silty clay loam subsoil. Pre-study characteristics of this soil are listed in Table 1. Initial field preparation consisted of plowing, discing, and harrowing and a paraquat herbicide application to eliminate standing weeds. Plots were then rototilled and raked to provide an extremely uniform seedbed.

Response of the early-maturing hybrid field corn variety 'Pioneer 3992' to H_2SO_4-HNO_3 rain simulants was studied using plots three meters square. Corn was seeded by hand May 15 in 10 east-west rows 51 centimeters apart and was thinned after emergence to a within-row spacing of 30 centimeters. This planting arrangement provided a plant population of approximately 64,200 plants/hectare. The date of first treatment exposure was May 28. Data for top dry matter production and grain yield were collected from 24 plants within the central 1.8 meter square area of each plot. This was the area for which satisfactory portable-chamber nozzle calibration had been obtained. Material was oven dried at 60°C for at least 48 hours before dry weight determinations. Two rows east and west and three rows north and south of the four-row calibrated spray area per plot were borders rows. The 16 plots in the 48.7-meter long study strip were contiguous. We believe the 2.5-meter distance separating study plants in adjacent plots sufficiently protected against rain simulants of different pH levels exerting effects in neighboring plots, as by lateral movement through the soil. Three additional border rows were planted at the east and west ends of the study strip. Pre-plant fertilization with 224-134-134-45-1 kilogram/hectare N-P_2O_5-K_2O-S-B was broadcast and incorporated. Soil pH at the end of the study averaged 6.4 (Table 2a). Pre-emergence herbicide applications of 1.7 and 2.2 kg/ha (active ingredient) of atrazine and alachlor, respectively, were made and additional manual weed control was provided as needed. Sprinkler irrigation with well water[1] provided approximately 25 centimeters of water, supplied in four applications from May 20 to August 16. In addition, 7.5 centimeters of natural rain fell from seedling emergence to harvest (period of acid rain treatment). Study plants were harvested at early dent stage on October 7.

Responses of two perennial forages, 'Vernal' alfalfa and 'Alta' tall fescue, to both rain types during their first season's growth were studied. The two east-west study strips for the H_2SO_4 and H_2SO_4-HNO_3 studies were separated by approximately one meter. Alfalfa and tall fescue were planted May 19 and May 20, respectively. Plots three meters square contained 10 handseeded rows at 15 centimeter row spacing of each species with the alfalfa rows planted north of tall fescue in both strips. Within the 1.8 meter square calibrated study area per plot, five study rows of each species were separated by one border row or each species. The remaining outer rows were border rows. Alfalfa was inoculated with Rhizobium meliloti before planting and was fertilized with 34-224-224-78-3 kg/ha N-P_2O_5-K_2O-S-B. Tall fescue was fertilized with 168-168-168-56 kg/ha N-P_2O_5-K_2O-S. Average study-end soil pH for alfalfa and tall fescue was 6.4 and 6.1, respectively (Table 2b). Pre-emergence carbon band and diuron sprays (2.2 kg/ha a.i.) were applied for weed control. Additional manual weed control was provided as needed, as was diazinon for insect control. Plots received first treatment exposure July 2. Sprinkler irrigation with well water provided approximately 36 centimeters of water in addition to the 6.1 centimeters of natural precipitation received between emergence and final harvest. Two harvests of top dry matter to a 7.6 centimeter stubble height were made for each species separately. Alfalfa was harvested at approximately 10 percent bloom stage. Tall fescue was harvested

[1]Average chemical composition (concentrations in μeq/ℓ): SO_4^{-2} = 486; NO_4 = 243; NH_4 = 0.04; Ca^{+2} = 761; Mg^{+2} = 603; K^+ = 416; Na^+ = 494; Cl^- = 148. pH = 7.4.

when we judged sufficient forage growth (or regrowth) had accumulated. Harvest dates for the alfalfa H_2SO_4 and H_2SO_4-HNO_3 rain studies, respectively, were July 23 and 25 (H1) and September 8 and 9 (H2). For tall fescue, they were July 22 and 24 (H1) and September 4 and 5 (H2). A subsample at each alfalfa harvest of 50 stems was separated into leaf plus petiole and stem fractions. Percent leafiness, one indicator of alfalfa forage quality, was calculated, and the two fractions were recombined for further quality analysis. Alfalfa and tall fescue tissue samples were analyzed for concentrations of nitrogen (N), acid detergent fiber (ADF), neutral detergent fiber (NDF), total sulfur (S), and 10 other elements: potassium (K), phosphorus (P), calcium (Ca), magnesium (Mg), manganese (Mn), iron (Fe), copper (Cu), boron (B), zinc (Zn), and aluminum (Al). Two samples per pH treatment per rain type of each species at both harvests were obtained for analysis by randomly combining two plots from different blocks into one sample at each pH. Dry tissue was ground to pass through a 0.5 millimeter screen. Crude protein (CP) was calculated by multiplying percent N by 6.25. Neutral detergent fiber primarily contains cellulose, lignin, and hemicellulose residues and is correlated with forage intake, while ADF primarily contains cellulose and lignin residues and is used as an indicator of forage digestibility (Matches, 1973). The Forage Analytical Service, Oregon State University, determined N using a standard Kjeldahl procedure (AOAC, 1975) and ADF and NDF using the methods of Goering and Van Soest (1970). The Plant Analysis Laboratory, Oregon State University, determined total S using a Leco Sulfur Analyzer as described by Jones and Issac (1972) and the 10 other elements using direct reading emission spectrometry as described by Chaplin and Dixon (1974).

Responses of the cool-season crops 'Cherry Belle' radish, 'Southern Giant Curled' mustard greens, and 'Improved Thick Leaf' spinach to both rain types were studied. The two east-west study strips for the H_2SO_4 and H_2SO_4-HNO_3 rain simulants were separated by approximately one meter. Plots three meters square contained six, four, and six rows of mustard greens, spinach, and radish, respectively (moving from north to south), of which two rows per crop were study rows. Three mustard and three radish border rows were planted north and south, respectively, of the 1.8-meter square calibrated spray area. One border row of each crop was planted between adjacent crop study rows within the calibrated area. Mustard greens and spinach were seeded by hand

May 8 and thinned after emergence to a 20 centimeter equidistant planting pattern which provided 15 study plants per crop per plot on average. Radish was seeded May 8 and thinned to 7.6 centimeter spacing within rows 15 centimeters apart which provided 38 study plants per plot on average. Radish was fertilized with 112-224-224-78-1 kg/ha of N-P_2O_5-K_2O-S-B and mustard greens and spinach with 168-224-224-78-1 kg/ha. All three crops were first exposed to treatments May 16. Soil pH at the end of the study averaged 6.0 (Table 2a). Manual weed control and insect control with diazinon were provided as needed. Irrigation, in addition to the 4.6, 2.3, and 4.2 centimeter natural rain received during the period of acid rain treatment of mustard greens, radish, and spinach, respectively, was not necessary. Radish, spinach, and mustard greens were harvested June 12, June 19, and June 24, respectively, when the marketable portions had reached commercially harvestable size (before bolting in spinach and while leaves were still tender in mustard greens).

The relative amounts of natural and simulated rainfall in the field studies are summarized in Table 3. The impact of natural rainfall on the pH of simulated acid rain treatments was negligible (Table 3). Volume weighted average pH increased from only .05 to .10 pH units after the inclusion of natural rainfall. The amounts of natural rain which fell on days of simulated rain treatment were also computed (Table 3). Since these amounts were only 2 to 9 percent of total simulated rainfall, it is unlikely that natural rain diluted or washed off simulated acid rain from foliage to any significant degree. Natural rainfall was measured starting when seedlings emerged from the soil since simulated rain treatments did not begin until this time.

A one-way analysis of variance (ANOVA) was used to compare treatments in the field studies. When the resulting pH-treatment F value was significant at the 5 percent level of probability ($P \leq 0.05$), two-sided t-tests were used to determine which acid rain treatment means differed significantly ($P \leq 0.05$) from the control. Data are expressed as plot means unless otherwise indicated.

Table 1. Pre-study field soil characteristics [a]

	Lime	ppm						%		meq/100 g			
pH	req. [b]	P	K	B	SO_4-S	NO_3-N	NH_4-N	Total N	OM	Ca	Mg	Na	CEC
6.9	6.7	38	233	1.11	3.37	0.88	4.58	0.15	3.29	15.0	1.4	0.09	17.3

[a] Mean values before fertilizer additions are listed.
[b] SMP buffer test.

Table 2a. Study-end field soil analysis results [a]

Study	Treatment pH	Soil pH	ppm SO_4-S	ppm NO_3-N	ppm NH_4-N
Corn					
H_2SO_4-HNO_3 rain	3.0 B1	6.5	17.7	1.20	2.50
	3.0 B2	6.3	16.1	3.00	2.97
	3.0 B3	6.4	16.3	1.80	2.50
	3.0 B4	6.4	17.7	1.80	2.50
	5.6 B1	6.5	12.2	1.20	3.91
	5.6 B2	6.4	11.0	1.80	2.97
	5.6 B3	6.4	12.6	1.20	3.44
	5.6 B4	6.2	13.7	1.80	2.50
Must-Spin	3.0	6.0	18.1	21.5	4.13
H_2SO_4 rain	3.0	6.1	18.8	25.0	6.11
	5.6	6.1	17.2	20.8	4.83
	5.6	6.0	18.3	22.2	5.12
Mustard	3.0	6.4	17.3	8.26	3.56
H_2SO_4-HNO_3 rain	3.0	6.4	17.4	6.55	3.84
	5.6	6.2	15.5	11.2	3.56
	5.6	6.2	14.3	11.7	3.28
Radish	3.0	5.7	16.8	25.5	3.28
H_2SO_4 rain	3.0	5.6	18.3	22.9	4.69
	5.6	5.6	13.2	22.7	4.27
	5.6	5.7	14.2	22.1	5.40
Radish	3.0	6.1	19.5	25.4	6.11
H_2SO_4-HNO_3 rain	3.0	6.0	19.8	22.2	5.12
	5.6	6.0	16.8	24.2	6.25
	5.6	5.8	17.0	25.1	10.5

[a] Corn soil samples were collected from each block (B). Each radish and H_2SO_4-HNO_3 rain mustard sample was a composite of soil from two blocks, but H_2SO_4 rain mustard-spinach samples were composites of two blocks of each species.

Table 2b. Study-end field soil analysis results [a]

Study	Treatment pH	Soil pH	Lime req.[b]	ppm			Meq/100 g				%		ppm		% Free
				SO_4-S	P	K	Ca	Mg	Na	CEC	OM	Total N	NO_3-N	NH_4-N	$CaCO_3$
Alfalfa	3.0	6.4	6.6	10.3	48	195	11.4	1.5	0.08	17.1	3.78	0.16	6.21	1.71	0.69
H_2SO_4-HNO_3 rain	3.0	6.2	6.6	16.0	47	191	10.9	1.5	0.09	17.7	3.70	0.16	8.35	3.00	0.59
	5.6	6.4	6.7	8.19	40	179	10.6	1.4	0.08	17.8	3.30	0.16	6.43	3.64	0.74
	5.6	6.5	6.8	9.84	43	201	11.9	1.5	0.08	17.9	3.85	0.16	6.00	3.86	0.83
Alfalfa	3.0	6.3	6.6	14.3	45	199	11.0	1.5	0.12	18.4	3.13	0.16	5.78	6.21	0.79
H_2SO_4 rain	3.0	6.3	6.5	15.7	50	183	11.1	1.5	0.12	17.4	3.54	0.15	6.68	3.21	0.74
	5.6	6.5	6.6	9.52	41	172	11.1	1.4	0.12	17.1	3.44	0.16	4.93	1.93	0.64
	5.6	6.3	6.5	7.95	47	179	10.0	1.4	0.11	17.7	3.44	0.16	6.64	4.28	0.64
Tall fescue	3.0	6.3	6.6	12.1	43	164	10.7	1.5	0.10	17.1	3.54	0.16	1.71	3.21	0.74
H_2SO_4-HNO_3 rain	3.0	6.3	6.6	13.2	40	148	10.2	1.4	0.10	15.3	3.43	0.16	2.36	2.78	0.94
	5.6	6.2	6.5	8.96	40	160	10.4	1.5	0.09	17.6	3.59	0.16	1.29	2.57	0.49
	5.6	6.3	6.6	7.70	43	164	9.9	1.4	0.08	17.5	3,54	0.15	2.36	3.64	0.84
Tall fescue	3.0	6.0	6.5	16.5	47	191	9.3	1.4	0.09	17.1	3.54	0.16	1.71	3.21	0.84
H_2SO_4 rain	3.0	5.9	6.4	16.5	50	183	8.6	1.4	0.09	16.3	2.72	0.16	1.08	3.86	0.64
	5.6	6.0	6.5	9.45	43	168	9.5	1.6	0.10	16.8	3.54	0.16	0.96	3.96	0.54
	5.6	6.2	6.2	7.81	48	191	8.9	1.4	0.10	16.4	3.59	0.16	1.61	3.11	0.74

[a] Each sample was a composite of soil from two blocks.

[b] SMP buffer test.

Table 3. Summary of natural and simulated rainfall in field studies

Study	Natural Rainfall: From Emergence to Harvest[1] (cm)	Natural Rainfall: On Same Days as Simulated Rainfall[2] (cm)	Total Simulated Rainfall (cm)	Average[3] pH of Natural[4] plus Simulated Rainfall, Treatment pH 3.0	3.5	4.0
Corn	7.5	2.9	57	3.05	3.55	4.04
Alfalfa	6.1	0.6	30	3.08	3.57	4.06
Tall fescue	6.1	0.6	28	3.08	3.58	4.06
Radish	2.3	0.7	12	3.08	3.58	4.07
Mustard greens	4.6	1.5	17	3.10	3.59	4.07
Spinach	4.2	1.3	15	3.10	3.59	4.07

1 Includes all natural rain from the date seedlings emerged from soil until harvest. [Simulated rainfall did not begin until emergence or afterwards (alfalfa and tall fescue)].

2 Includes only natural rain which fell on days when simulated rain was applied.

3 Volume weighted average (computed using emergence to harvest natural rainfall).

4 pH was 5.59 for the 9.3 cm of natural rain which fell from May 8 to October 7 excluding the week of June 10 to June 17. During this week, the pH was 4.14 for 1.9 centimeters of rain because of secondary eruption of Mt. St. Helens. Average pH was 4.84 for entire 11.2 centimeters of rain which fell from May 8 to October 7.

Results and Discussion

Corn

Grain yield of 'Pioneer 3992' field corn was reduced by H_2SO_4-HNO_3 rain treatment at pH 4.0, but not significantly affected by pH levels 3.5 and 3.0 (Table 4). Grain dry weight at pH 4.0 was 9 percent lower than the control (pH 5.6) but was within 4 and 1 percent of the control at pH levels 3.5 and 3.0, respectively.

Although this corn hybrid generally produces only one ear per plant at normal plant populations, it can produce more than one ear under favorable environmental conditions. Multiple ear production occurred in this study. However, 77 percent of the control plants produced two ears per plant, on average, but only 49, 52, and 58 percent of the plants did so at pH levels 4.0, 3.5, and 3.0, respectively. As a result, mean number of ears per plot were 16, 14, and 11 percent lower than the control at these pH's. Since within each treatment grain dry weight increased in proportion to ear number, it was the reduction in multiple ear production which caused the significant decrease in grain dry weight at pH 4.0. In fact, after adjustment for differences in ear number by covariance analysis, H_2SO_4-HNO_3 rain treatment had no significant effect on grain yield (means within ± 3 percent of control). Furthermore, since multiple ear formation is known to occur near the edges of large fields, this phenomenon may have been exaggerated by the use of plots arranged into a long, narrow strip.

Acid rain treatment did not affect fresh or dry weights of total above-ground biomass or stem height to tassel (Table 4). Treatment means for these characteristics were quite uniform with acid rain treatment means within 4 percent of the control.

Table 4. 'Pioneer 3992' corn grown in the field: effects of simulated sulfuric-nitric acid rain on grain yield, ear number, stem height, and top weight

Treatment	Grain dry wt.	Total top wt. Fresh	Total top wt. Dry	Stem height[a]	Ear number	Avg. grain dry wt. per ear
	kg	kg	kg	cm		g
5.6	3.71	21.65	9.93	226	42.5	87.9
4.0	3.38*	21.05	9.48	223	35.7	94.8
3.5	3.57	20.78	9.65	217	36.5	99.0
3.0	3.70	21.38	9.75	224	38.0	97.7
S.E.[b]	0.08	0.29	0.12	3	1.9	3.6
F[c]	*	NS	NS	NS	NS	NS

[a]Stem height to tassel was measured on a subsample of 6 plants per plot.

[b]Standard error of the mean.

[c]Significance level of the F-test from one-way analysis of variance (ANOVA) with * denoting $P \leq 0.05$.

*Symbol after the table value denotes significant difference from control mean with $P \leq 0.05$ for two-sided t-test.

Forage crops: alfalfa and tall fescue

Evidence of a stimulatory acid rain effect on 'Vernal' alfalfa yield was found, particularly in H_2SO_4 rain. While 'Alta' tall fescue forage production was stimulated by H_2SO_4 rain treatment, it was not affected by H_2SO_4-HNO_3 rain. Most indicators of forage quality were not affected by acid rain in either species.

Total alfalfa yield at pH 4.0 in H_2SO_4 rain was stimulated, but in H_2SO_4-HNO_3 rain, an early stimulatory effect at pH levels 4.0 and 3.0 was not maintained (Table 5). Total top dry weight summed across harvests was 9 percent greater than the control at pH 4.0 in H_2SO_4 rain. However, the 10 and 7 percent increases in top dry weight at this pH in the individual harvests were not statistically significant. In H_2SO_4-HNO_3 rain, harvest one (H1) top dry weight was 16 and 9 percent greater than the control at pH levels 4.0 and 3.0, respectively, but was comparable to the control at pH 3.5. Mean top dry weights at H2, however, were slightly lower than the control in these two treatments. Consequently, total dry weight summed across both harvests was within 5 percent of the control in all acid rain treatments.

Acid rain treatment did not affect alfalfa percent leafiness or the concentrations of NDF and mineral elements at either harvest (Tables 5 and 6). The significant increases in H_2SO_4-HNO_3 rain H1 total N at pH 4.0 and total S at pH 3.0 reflect the increases in top dry matter production which occurred rather than increased N or S concentration (Table 6). The concentration of ADF was 5.7 percent greater than the control, on average, in the H_2SO_4 rain treatments at H1 but was not affected by H_2SO_4 rain in H2 (Table 6). In H_2SO_4-HNO_3 rain, ADF concentration was not affected in H1 but was 5.8 percent greater than the control at pH 3.5 in H2 (Table 6). The H2 effect on ADF at pH 3.5 is probably unimportant, however, since no effect occurred at pH levels 4.0 and 3.0.

In the H_2SO_4 rain tall fescue study, H1 mean top dry weight was 41, 35, and 18 percent greater than the control at pH levels 4.0, 3.5, and 3.0, respectively (Table 7). The increases for the 4.0 and 3.5 treatments were statistically significant. Although pH 4.0 and 3.5 treatment means continued to exceed the control in H2 (by 14 and 9 percent, respectively), differences were not significant. Summed across harvests, total top dry weights at pH levels 3.5 and 4.0 were 19 and 24 percent greater than the control. In the

H_2SO_4-HNO_3 study, no significant treatment differences occurred, and acid rain treatment means were within 5 percent of the control (Table 7).

None of the indicators of tall fescue forage quality (CP, NDF, ADF) was significantly affected by acid rain in H1 (Table 8). However, mean S concentration at pH 3.0 was much greater than the control in H_2SO_4 rain (0.46 versus 0.34 percent) but was less than the control at pH 3.5 and 3.0 in H_2SO_4-HNO_3 rain (0.27 and 0.22 versus 0.38 percent). Similar patterns in total S uptake occurred for both rain types. Although effects in H2 also were not statistically significant, H_2SO_4 rain treatment again appeared to increase percent S and total S. No decrease at H2 with H_2SO_4-HNO_3 rain, as in H1, was suggested, however. Significant increases in H2 ADF concentration occurred in all H_2SO_4 rain treatments (up 2.2 to 2.8 percent) and at pH 3.0 in H_2SO_4-HNO_3 rain (up 2 percent). A statistically significant decrease in H2 Ca concentration at pH 4.0 in H_2SO_4-HNO_3 rain probably was from chance, since little or no change occurred at pH 3.0 or 3.5.

Table 5. 'Vernal' alfalfa grown in the field: effects of simulated sulfuric and sulfuric-nitric acid rain on top dry matter production and percent leafiness at two harvests

Treatment	Harvest 1 Top dry wt.	Harvest 1 Percent leafiness[a]	Harvest 2 Top dry wt.	Harvest 2 Percent leafiness	Total top dry wt. H1 + H2
	— g —		— g —		— g —
Sulfuric acid rain					
5.6	342.9	55.4	472.8	50.8	815.8
4.0	378.4	53.7	508.2	49.6	886.6*
3.5	348.3	54.5	446.2	50.4	794.6
3.0	330.9	55.2	470.4	50.8	801.3
S.E.[b]	13.1	0.8	14.4	0.7	16.8
F[c]	N.S.	N.S.	N.S.	N.S.	**
Sulfuric-nitric acid rain					
5.6	358.5	57.6	402.5	55.8	760.9
4.0	414.6**	53.9	388.0	55.4	802.7
3.5	355.4	56.4	421.2	55.9	776.6
3.0	391.4*	56.1	393.6	55.8	785.0
S.E.	7.3	1.0	21.3	0.8	22.0
F	**	N.S.	N.S.	N.S.	N.S.

[a]Percent leafiness was calculated using subsamples at each harvest of 50 randomly selected tillers per plot which were divided into leaf-petiole and stem portions and is expressed on a dry-weight basis. Harvest dates for the H_2SO_4 and H_2SO_4-HNO_3 studies, respectively, were July 23 and 25 (H1) and September 8 and 9 (H2).

[b]Standard error of the mean.

[c]Significance level of the F-test from one-way ANOVA with ** denoting $P \leq 0.01$.

*, **Symbols after the table values denote significant differences from control means with $P \leq 0.05$ and 0.01, respectively, for two-sided t-test.

Table 6. 'Vernal' alfalfa grown in the field: effects of simulated sulfuric and sulfuric-nitric acid rain on total N and S uptake and concentrations of N, S, crude protein (CP), acid detergent fiber (ADF), neutral detergent fiber (NDF), and 10 mineral elements at two harvests [a]

Treatment	Total N	Total S	N	S	CP	ADF	NDF	P	K	Ca	Mg	Mn	Fe	Cu	B	Zn	Al
	g						%							ppm			
							Harvest 1										
Sulfuric acid rain																	
5.6	9.14	1.10	2.67	0.32	16.72	26.23	35.94	0.35	2.21	1.69	0.19	40	116	6	44	19	71
4.0	10.03	1.12	2.65	0.29	16.58	33.08**	36.95	0.33	2.46	1.80	0.17	42	149	8	55	25	77
3.5	9.04	0.97	2.60	0.28	16.22	31.69**	36.45	0.49	2.61	1.89	0.28	44	158	7	55	29	75
3.0	8.76	1.06	2.64	0.32	16.52	30.89**	35.33	0.33	2.61	1.76	0.19	44	142	8	59	25	95
$\bar{x}$	9.24	1.06	2.64	0.30	16.51	30.47	36.17	0.38	2.48	1.79	0.21	43	141	8	54	25	80
Sulfuric-nitric acid rain																	
5.6	9.94	1.02	2.77	0.28	17.34	27.07	35.11	0.31	2.42	1.71	0.17	35	125	7	49	22	65
4.0	11.34*	1.12	2.74	0.27	17.11	29.04	36.90	0.30	2.43	1.70	0.20	31	127	6	47	21	78
3.5	9.23	0.90	2.60	0.25	16.23	28.32	35.36	0.33	2.40	1.70	0.20	38	142	7	50	22	78
3.0	10.66	1.27*	2.72	0.32	17.01	29.86	36.58	0.32	2.36	1.68	0.18	36	135	7	47	21	68
$\bar{x}$	10.29	1.08	2.71	0.28	16.92	28.57	35.99	0.32	2.40	1.70	0.19	35	133	7	48	22	72
S.E.[b]	0.38	0.08	0.13	0.02	0.82	0.77	0.68	0.06	0.13	0.06	0.04	5	17	1	6	2	8
pH-F for sulfuric[c]	NS	NS	NS	NS	NS	**	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
pH-F for sul.-nitric	*	*	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
							Harvest 2										
Sulfuric acid rain																	
5.6	14.26	1.11	3.02	0.23	18.85	29.01	36.29	0.31	2.18	1.38	0.13	33	180	6	46	20	55
4.0	15.46	1.10	3.04	0.21	19.00	28.04	36.03	0.31	2.38	1.45	0.15	34	181	6	52	22	67
3.5	14.05	1.15	3.15	0.26	19.67	30.47	36.71	0.33	2.40	1.47	0.21	34	152	6	47	20	67
3.0	14.24	1.29	3.03	0.27	18.91	30.67	38.01	0.29	2.32	1.40	0.14	31	152	5	45	17	58
$\bar{x}$	14.50	1.16	3.06	0.25	19.11	29.55	36.76	0.31	2.32	1.43	0.16	33	166	6	48	20	62
Sulfuric-nitric acid rain																	
5.6	12.70	1.15	3.15	0.28	19.72	30.72	34.79	0.32	2.44	1.24	0.17	34	115	7	58	26	69
4.0	12.30	1.12	3.17	0.29	19.83	29.05	33.69	0.34	2.53	1.36	0.17	32	113	6	61	32	74
3.5	13.21	1.24	3.14	0.29	19.60	36.55*	33.74	0.35	2.66	1.36	0.17	36	121	6	64	31	73
3.0	12.12	1.14	3.08	0.29	19.25	28.01	35.33	0.31	2.36	1.19	0.16	33	173	7	58	29	74
$\bar{x}$	12.58	1.16	3.14	0.29	19.60	31.08	34.39	0.33	2.50	1.29	0.17	34	131	6	60	30	73
S.E.	0.69	0.08	0.03	0.01	0.19	1.69	0.60	0.03	0.14	0.14	0.02	4	25	1	7	5	8
pH-F for sulfuric	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
pH-F for sul.-nitric	NS	NS	NS	NS	NS	*	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS

[a]Concentrations are expressed on a dry-weight basis. Harvest dates for the H_2SO_4 and H_2SO_4-HNO_3 rain studies, respectively, were July 23 and 25 (H1) and September 8 and 9 (H2).

[b]Standard error of the mean of one pH for one rain type (sample size = 2).

[c]Significance levels of the F-tests from one-way analyses of variance, one for sulfuric and one for sulfuric-nitric acid rain, with * and ** denoting $P \leq 0.05$ and 0.01, respectively. At each harvest, a pooled estimate of error with 8 d.f. was used in the F-tests.

*, **Symbols after table values denote significant differences from control means with $P \leq 0.05$ and 0.01, respectively, for two-sided t-tests.

Table 7. 'Alta' tall fescue grown in the field: effects of simulated sulfuric and sulfuric-nitric acid rain on top dry matter production at two harvests[a]

Treatment	Top dry weight		
	H1	H2	Total
	g		
Sulfuric acid rain			
5.6	321.9	495.5	817.4
4.0	454.2**	563.2	1017.4**
3.5	434.0*	538.2	972.3*
3.0	379.9	482.7	862.6
S.E.[b]	25.1	25.3	38.7
F[c]	*	N.S.	*
Sulfuric-nitric acid rain			
5.6	448.5	526.6	975.1
4.0	436.0	542.0	978.1
3.5	411.0	538.1	949.1
3.0	457.1	476.4	933.5
S.E.	30.8	30.7	47.9
F	N.S.	N.S.	N.S.

[a]Harvest dates for the H_2SO_4 and H_2SO_4-HNO_3 rain studies, respectively, were July 22 and 24 (H1) and September 4 and 5 (H2).

[b]Standard error of the mean.

[c]Significance level of the F-test from one-way ANOVA with * denoting $P \leq 0.05$.

*,**Symbols after table values denote significant differences from control means with $P \leq 0.05$ and 0.01, respectively, for two-sided t-test.

Table 8. 'Alta' tall fescue grown in the field: effects of simulated sulfuric and sulfuric-nitric acid rain on total N and S uptake and concentrations of N, S, crude protein (CP), acid detergent fiber (ADF), neutral detergent fiber (NDF), and 10 mineral elements at two harvests [a]

Treatment	Total N	Total S	N	S	CP	ADF	NDF	P	K	Ca	Mg	Mn	Fe	Cu	B	Zn	Al
	g		%									ppm					
Harvest 1																	
Sulfuric acid rain																	
5.6	9.66	1.09	3.00	0.34	18.72	27.23	45.51	0.32	3.60	0.31	0.20	78	294	6	7	22	255
4.0	14.26	1.37	3.13	0.30	19.55	28.09	46.94	0.34	3.68	0.30	0.20	74	189	6	9	25	131
3.5	12.64	1.39	2.91	0.32	18.21	29.15	47.83	0.31	3.63	0.43	0.20	69	172	6	7	24	105
3.0	11.36	1.74	2.99	0.46	18.68	25.23	46.66	0.30	3.35	0.25	0.18	68	216	6	6	21	159
x̄	11.98	1.40	3.01	0.35	18.79	27.43	46.74	0.32	3.57	0.32	0.20	72	218	6	7	23	162
Sulfuric-nitric acid rain																	
5.6	14.04	1.73	3.15	0.38	19.68	24.95	45.75	0.26	3.32	0.30	0.24	65	166	3	3	18	110
4.0	13.66	1.58	3.25	0.40	20.33	24.68	45.95	0.33	3.54	0.31	0.21	73	182	6	9	23	102
3.5	12.51	1.11	3.08	0.27	19.23	25.20	47.26	0.29	3.26	0.29	0.21	65	145	4	3	21	81
3.0	13.87	1.03	3.04	0.22	19.00	25.96	48.46	0.31	3.37	0.29	0.19	69	169	7	8	22	95
x̄	13.52	1.36	3.13	0.32	19.56	25.20	46.86	0.30	3.38	0.30	0.22	68	166	5	6	21	97
S.E.[b]	1.18	0.20	0.26	0.07	1.61	1.20	1.63	0.03	0.12	0.05	0.02	5	41	2	3	3	45
pH-F for sulfuric[c]	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
pH-F for sul.-nitric	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
Harvest 2																	
Sulfuric acid rain																	
5.6	6.16	1.24	1.25	0.25	7.78	28.24	48.95	0.27	2.45	0.20	0.18	76	80	2	8	11	77
4.0	7.39	1.91	1.31	0.33	8.19	30.79**	49.52	0.27	2.63	0.19	0.19	79	84	2	5	13	89
3.5	7.45	1.64	1.38	0.30	8.64	30.49**	48.42	0.28	2.72	0.20	0.18	75	92	2	6	13	85
3.0	6.22	1.52	1.29	0.31	8.07	31.02**	48.97	0.27	2.58	0.16	0.15	78	86	3	6	15	83
x̄	6.81	1.58	1.31	0.30	8.17	30.14	48.97	0.27	2.60	0.19	0.18	77	86	2	6	13	84
Sulfuric-nitric acid rain																	
5.6	7.90	1.33	1.50	0.25	9.38	28.05	48.80	0.32	2.80	0.24	0.19	83	124	3	10	19	129
4.0	7.51	1.24	1.38	0.23	8.62	28.70	49.52	0.27	2.49	0.19*	0.18	76	77	3	5	13	65
3.5	7.95	1.39	1.44	0.25	8.99	28.96	49.02	0.30	2.78	0.24	0.21	87	94	2	8	14	91
3.0	6.97	1.45	1.47	0.30	9.21	30.00**	48.49	0.25	2.52	0.22	0.20	74	74	1	4	11	64
x̄	7.58	1.35	1.45	0.26	9.05	28.93	48.96	0.29	2.65	0.22	0.20	80	93	2	7	14	87
S.E.	1.15	0.24	0.08	0.03	0.48	0.32	0.59	0.02	0.15	0.01	0.01	5	12	1	3	3	17
pH-F for sulfuric	NS	NS	NS	NS	NS	**	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
pH-F for sul.-nitric	NS	NS	NS	NS	NS	*	NS	NS	NS	*	NS	NS	NS	NS	NS	NS	NS

[a] Concentrations are expressed on a dry-weight basis. Harvest dates for the H_2SO_4 and H_2SO_4-HNO_3 rain studies, respectively, were July 22 and 24 (H1) and September 4 and 5 (H2).

[b] Standard error of the mean of one pH for one rain type (sample size = 2).

[c] Significance levels of the F-tests from one-way analyses of variance, one for sulfuric and one for sulfuric-nitric acid rain, with * and ** denoting $P \leq 0.05$ and 0.01, respectively. At each harvest, a pooled estimate of error with 8 d.f. was used in the F-tests.

*, **Symbols after table values denote significant differences from control means with $P \leq 0.05$ and 0.01, respectively, for two-sided t-test.

Cool-season crops: mustard greens, radish, and spinach

Acid rain treatment reduced the yield of 'Southern Giant Curled' mustard greens in the H_2SO_4-HNO_3 rain study but had no significant effect on yields of 'Cherry Belle' radish and 'Improved Thick Leaf' spinach in either rain type.

Although decreases of 23 and 33 percent in mean top fresh weight of mustard greens at pH 3.0 occurred in the H_2SO_4 and H_2SO_4-HNO_3 rain studies, respectively, only the effect with H_2SO_4-HNO_3 rain was statistically significant (Table 9). The response pattern for H_2SO_4-HNO_3 rain was different than for H_2SO_4 rain, since a significant reduction in top growth at pH 4.0 (-31 percent) also occurred. Effects on root growth appeared to be similar to those on top growth, but differences were not significant.

No significant treatment differences in radish root or top growth occurred (Table 10). However, mean root fresh and dry weights at pH 3.0 were lower than the control by 5 and 7 percent in H_2SO_4 rain and by 14 and 9 percent in H_2SO_4-HNO_3 rain. In addition, mean root and top weights were greater than control means at intermediate pH levels in the H_2SO_4 rain study. For example, mean root fresh weights at pH levels 4.0 and 3.5 were 15 and 25 percent greater than the control, respectively ($P \leq 0.10$ at pH 3.5). It is unclear why a stimulatory effect at intermediate pH might occur in H_2SO_4 rain, but not in H_2SO_4-HNO_3 rain.

Neither H_2SO_4 nor H_2SO_4-HNO_3 rain treatment significantly affected leaf fresh weight or dry matter production of spinach (Table 11). Of the three cool-season crops grown in the field, spinach was the only one for which foliar injury from acid rain treatment was identified (Table 39). Although growth reductions were suggested by data for both greens and radish, none was for spinach. This apparent lack of association between the presence of foliar injury and observed growth response may be caused by the extremely low levels of injury that occurred (Table 39).

Table 9. 'Southern Giant Curled' mustard greens grown in the field: effects of simulated sulfuric and sulfuric-nitric acid rain on top and root growth

Treatment	Top weight[a] Fresh	Top weight[a] Dry	Root dry wt.	Total dry wt.	Top percent water	Plant number
	g				%	
Sulfuric acid rain						
5.6	127.83	7.40	0.50	7.90	94.2	15.7
4.0	122.72	7.16	0.46	7.62	94.1	15.2
3.5	122.35	7.01	0.49	7.50	94.2	17.0
3.0	98.99	6.20	0.38	6.58	93.8	14.7
S.E.[b]	8.70	0.40	0.03	0.43	0.1	1.0
F[c]	N.S.	N.S.	N.S.	N.S.	N.S.	N.S.
Sulfuric-nitric acid rain						
5.6	139.00	8.05	0.50	8.56	94.2	16.5
4.0	96.02*	5.81	0.36	6.17	93.9	13.5
3.5	119.85	7.23	0.43	7.67	93.9	15.0
3.0	93.17*	6.30	0.38	6.68	93.1	16.5
S.E.	10.22	0.57	0.03	0.60	0.3	1.3
F	*	N.S.	N.S.	N.S.	N.S.	N.S.

[a]Data are presented on a weight-per-plant basis.

[b]Standard error of the mean.

[c]Significance level of the F-test from one-way ANOVA with * denoting $P \leq 0.05$.

*Symbols after the table values denote significant differences from control mean with $P \leq 0.05$ for two-sided t-test.

Table 10. 'Cherry Belle' radish grown in the field: effects of simulated sulfuric and sulfuric-nitric acid rain on root and top growth

Treatment	Root weight Fresh	Root weight Dry	Root percent water	Top dry wt.	Total dry wt.	Plant number
	g	g	%	g	g	
Sulfuric acid rain						
5.6	11.38	0.58	94.8	0.57	1.16	41.0
4.0	13.09	0.66	94.9	0.68	1.34	37.5
3.5	14.21	0.67	95.3	0.62	1.29	37.5
3.0	10.80	0.54	94.9	0.58	1.13	35.2
S.E.[b]	0.87	0.04	0.2	0.03	0.06	1.7
F[c]	N.S.	N.S.	N.S.	N.S.	N.S.	N.S.
Sulfuric-nitric acid rain						
5.6	13.06	0.64	95.1	0.63	1.26	39.2
4.0	12.88	0.66	94.9	0.66	1.32	37.2
3.5	13.03	0.65	95.0	0.64	1.30	38.2
3.0	11.26	0.58	94.8	0.64	1.22	38.0
S.E.	0.57	0.02	0.1	0.02	0.03	1.2
F	N.S.	N.S.	N.S.	N.S.	N.S.	N.S.

[a] Data are presented on a weight-per-plant basis.

[b] Standard error of the mean.

[c] Significance level of the F-test from one-way ANOVA.

Table 11. 'Improved Thick Leaf' spinach grown in the field: effects of simulated sulfuric and sulfuric-nitric acid rain on leaf fresh weight and dry matter production

Treatment	Leaf weight[a] Fresh	Leaf weight[a] Dry	Nonmarketable stem dry wt.	Root dry wt.	Total dry wt.	Leaf percent water	Plant number
	g					%	
Sulfuric acid rain							
5.6	36.43	2.46	0.31	0.14	2.92	93.2	14.0
4.0	34.07	2.31	0.29	0.12	2.72	93.2	14.7
3.5	33.98	2.44	0.27	0.13	2.83	92.8	13.0
3.0	33.07	2.55	0.29	0.13	2.97	92.3	15.5
S.E.[b]	2.87	0.17	0.03	0.01	0.20	0.3	0.5
F[c]	N.S.	N.S.	N.S.	N.S.	N.S.	N.S.	N.S.
Sulfuric-nitric acid rain							
5.6	56.51	3.84	0.39	0.20	4.43	93.1	15.0
4.0	47.97	3.43	0.36	0.18	3.97	92.8	14.7
3.5	52.36	3.71	0.39	0.17	4.28	92.9	14.0
3.0	51.90	3.82	0.43	0.20	4.45	92.6	15.0
S.E.	5.65	0.31	0.03	0.01	0.34	0.3	0.9
F	N.S.	N.S.	N.S.	N.S.	N.S.	N.S.	N.S.

[a]Data are presented on a weight-per-plant basis.

[b]Standard error of the mean.

[c]Significance of the F-test from one-way ANOVA.

CHAMBER STUDIES

Materials and Methods

Yield responses of 8 and 13 crop cultivars to simulated H_2SO_4 and H_2SO_4-HNO_3 rains, respectively, were studied in chamber experiments. Crops grown in both rain types were exposed to acidic simulants at pH levels 4.0, 3.5, and 3.0 and to control rain at approximately pH 5.6. The composition, average rate, duration, and frequency of rain applications were the same in chamber studies as in field experiments. The same procedures also were used to check rain solution pH during each rain event and to calibrate stainless steel nozzles.

Two types of stationary, closed-top chambers were used. Both were covered with vinyl (Krene or Roll-A-Glass) to exclude natural rain. Insect screening covered openings between the side and top and between the side and bottom. These openings provided convective air exchange between chamber and ambient air. Large round (LR) chambers measured 4.6 meters in diameter and 2.4 meters in height and were used in H_2SO_4-HNO_3 rain experiments. Small round (SR) chambers were 3.0 meters in diameter and 2.4 meters in height and were used in H_2SO_4 rain experiments. Two chambers per pH level, each containing seven pots per crop (five pots for potato and tomato) were used for each rain type.

Pots were assigned at random to treatments giving 14 pots per treatment per crop (10 for potato and tomato). Pots of each crop were placed in a wedge-shaped arrangement within chambers so that any unevenness in nozzle spray patterns was averaged across all pots. In addition, nozzles were rotated among nozzle positions (four and three to LR and SR chambers, respectively) after each rain event. These measures were taken to reduce variation in plant response that might have been associated with spray distribution variation.

Because of chamber design, convective cooling sufficiently controlled chamber temperature buildup during most of the growing season. Daily minimum and maximum chamber temperatures typically were 2-5°C higher than ambient temperatures and were comparable for both chamber types. No measures were employed to modify chamber environments, e.g., use of supplemental lighting or temperature control.

Crop species were chosen to represent diverse taxonomic groups, crop products, and previously observed responses to H_2SO_4 rain simulants in the 1979 survey. Plants were grown in six-liter plastic pots (except potato and tomato, which were grown in 15-liter pots). Pots contained sandy soil obtained from the flood plain of the Willamette River near Corvallis, Oregon, which was mixed with peat moss to improve water retention and soil aeration (3:1 soil:peat mix v/v), fertilizer, and lime before planting. Characteristics of this soil mix before fertilizer and lime additions are shown in Table 12. At planting, leguminous species were fertilized with 34-224-224-78 kg/ha of N-P_2O_5-K_2O-S, grasses with 56-168-168-56, onion and tomato with 56-224-224-78, radish with 112-224-224-78, and all others with 84-224-224-78 kg/ha. Legumes were inoculated with Rhizobia species immediately before seeding using standard techniques. Several species also received boron at planting and additional fertilizer during the study according to individual crop needs. Urea, potassium sulfate, triple superphosphate, diammonium phosphate, monoammonium phosphate, and boric acid fertilizer sources were used. Hydrated lime was added to the 3:1 soil:peat mix at the rate of 5.6 metric T/ha (20.6 grams/pot). Average soil pH was 7.9 at the end of the study (Table 13). Thus, chamber experiments involved study of the response to acid rain of crops grown at alkaline soil pH. Although the availability of several plant nutrients, especially micronutrients, decreases at such high pH, no evidence of nutrient stress was observed and plant growth generally was quite vigorous. Productive, non-saline soils having pH values in the range used in these studies (i.e., 7.4-8.2) are found in all western states, and crops grown in these mostly arid and semi-arid region soils under irrigation include all those surveyed (Soils of the Western United States, 1964). Crops were irrigated with well water according to individual pot needs, as determined by visual inspection. Pesticides for insect (diazinon) and disease (maneb) control were applied as needed. Protection against root maggot damage in cabbage, carrot, pea, and radish studies was provided by mixing diazinon granules with soil before seeding. Crop species and cultivar names; rain type(s) studied; total seasonal fertilizer application rates; and dates of seeding, first treatment exposure, and final harvest are listed in Table 14.

Most crops were first exposed to treatments several weeks after seeding because they were germinated in a greenhouse to provide uniform seedlings and later transplanted to study pots. In all cases, exposures to simulated rain continued until final harvest. Crops which were first exposed to rain simulants immediately after seeding received a Captan 5 percent dust seed pre-treatment to protect against seed decay and damping-off fungi and were later thinned to uniform seedling size. The number of plants per pot after thinning or transplanting is shown in Table 14.

The types of data collected and harvest regimes used varied with crop species. For example, top dry weight at multiple harvests for clover and fruit fresh weight, number, and size class for tomato were determined. In addition to data for marketable crop portions, dry weights of the remaining plant parts were determined. Dry weight determinations were made after plant material was oven dried at 60°C for at least 48 hours. Tall fescue forage quality was also examined. Concentrations of N, CP, ADF, NDF, S, K, P, Ca, Mg, Mn, Fe, Cu, B, Zn, and Al were determined as described previously. All data from the chamber studies were subjected to standard analysis of variance procedures as in the field experiments.

Potato Seed-Piece Sprouting Experiments

The "potato flat" experiment was conducted to determine whether acidic rain simulants affected seed-piece sprouting and, therefore, stem number, a determinant of tuber number and, consequently, yield. One flat per chamber for both rain types was used and contained sandy soil fertilized with 56-168-168-56 kg/ha N-P_2O_5-K_2O-S. Apical halves of comparably-sized 'Russet Burbank' potato seed pieces (seed pieces weighed from 110 to 170 grams) were again cut in half, coated with Captan 5 percent dust, and planted at 6.4 centimeter depth in flats that measured 36.8 x 47.0 x 8.9 centimeters, 72 per flat. Flats were randomly assigned to treatment chambers. Data for stem number and dry weights of top and root portions per flat were collected after four weeks' growth.

Table 12. Pre-study chamber soil mix characteristics [a]

Description	Soil pH	Lime req.[b]	ppm						%		meq/100 g			
			P	K	B	SO_4-S	NO_3-N	NH_4-N	Total N	OM	Ca	Mg	Na	CEC
Soil before peat moss addition: used in potato flat studies	6.8	7.1	10	93	0.22	1.23	0.50	1.82	0.02	1.27	8.6	4.6	0.27	13.2
Soil: peat mix (3:1)	5.3	6.5	11	111	0.26	5.07	5.8	7.89	0.08	1.95	8.9	4.6	0.24	17.0

[a] Mean values before fertilizer or lime additions are listed.

[b] SMP buffer test.

Table 13. Study-end chamber soil analysis results [a]

Study	Treatment pH	Soil pH
Beet 2:1[b]	3.0	7.9
	3.5	8.1
	4.0	8.1
	5.6	7.7
Carrot 2:1	3.0	7.7
	3.5	7.8
	4.0	8.1
	5.6	8.0
Clover 2:1	3.0	7.8
	3.5	8.0
	4.0	7.9
	5.6	7.9
Tall fescue 1:0	3.0	7.5
	3.0	7.5
	3.5	7.8
	3.5	7.8
	4.0	7.7
	4.0	7.7
	5.6	7.7
	5.6	7.6
Tall fescue 2:1	3.0	7.6
	3.0	7.9
	3.5	7.8
	3.5	7.7
	4.0	7.7
	4.0	8.1
	5.6	8.0
	5.6	8.1
Lettuce 1:0	3.0	8.0
	3.5	8.2
	4.0	8.1
	5.6	8.1

Study	Treatment pH	Soil pH
Lettuce 2:1	3.0	8.1
	3.5	8.2
	4.0	8.0
	5.6	8.0
Mustard greens 1:0	3.0	8.1
	3.5	8.2
	4.0	8.3
	5.6	8.2
Mustard greens 2:1	3.0	8.1
	3.5	8.1
	4.0	8.1
	5.6	8.1
Onion 2:1	3.0	7.4
	3.5	7.8
	4.0	7.5
	5.6	7.6
Orchardgrass 1:0	3.0	7.5
	3.0	7.5
	3.5	7.7
	3.5	7.6
	4.0	7.9
	4.0	7.7
	5.6	7.8
	5.6	7.6
Orchardgrass 2:1	3.0	7.7
	3.0	7.6
	3.5	7.7
	3.5	7.7
	4.0	7.6
	4.0	7.5
	5.6	7.6
	5.6	7.5

Study	Treatment pH	Soil pH
Pea 2:1	3.0	8.0
	3.5	8.0
	4.0	7.9
	5.6	7.9
Potato 1:0	3.0	7.9
	3.5	7.9
	4.0	8.0
	5.6	8.0
Potato 2:1	3.0	7.9
	3.5	8.0
	4.0	8.0
	5.6	8.0
Radish 1:0	3.0	8.1
	3.5	8.1
	4.0	8.1
	5.6	8.2
Radish 2:1	3.0	8.0
	3.5	8.1
	4.0	8.1
	5.6	8.1
Tomato 1:0	3.0	7.7
	3.5	7.8
	4.0	7.8
	5.6	7.9
Tomato 2:1	3.0	7.7
	3.5	7.8
	4.0	7.9
	5.6	8.0

[a] All values were obtained for soil composited on a treatment basis, except for samples of tall fescue and orchardgrass which were composited on a chamber basis.

[b] 2:1 refers to H_2SO_4-HNO_3 rain type, and 1:0 refers to H_2SO_4 rain type.

Table 14. Crop cultivars, rain type(s) studied, total fertilizer application rates, dates of seeding, first treatment exposure, and final harvest, and number of plants per pot after thinning or transplanting for chamber studies

Crop	Cultivar	Rain types		Plant no. per pot	Total fertilizer application rate (kg/ha)[c]	Dates of		
		1:0[a]	2:1[b]			Seeding	First exposure	Final harvest
<u>Forage Legume Crop</u>								
Red clover *(Trifolium pratense)*	Kenland		✓	2	34-224-224-78-3	6/06	6/28	10/2
<u>Forage Grass Crops</u>								
Orchardgrass *(Dactylis glomerata)*	Potomac	✓	✓	3	168-168-168-56	6/06	7/03	9/16
Tall fescue *(Festuca arundinacea)*	Alta	✓	✓	3	168-168-168-56	5/16	7/01	9/29
<u>Root Crops</u>								
Beet *(Beta vulgaris)*	Detroit Dark Red		✓	2	224-448-448-157-6	4/15	5/13	7/07
Carrot *(Daucus carota)*	Danvers Half Long		✓	2	154-336-336-118-3	3/31	5/13	6/26
Radish *(Raphanus sativus)*	Cherry Belle	✓	✓	2	112-224-224-78-1	5/08	5/13	6/10
<u>Fruit Crop</u>								
Tomato *(Lycopersicon esculentum)*	Patio	✓	✓	1	168-448-448-157	d	7/10	10/31
<u>Leaf Crops</u>								
Lettuce *(Lactuca sativa)*	Summer Bibb	✓	✓	1	168-224-224-78-1	4/15	5/13	6/27
Mustard greens *(Brassica japonica)*	Southern Giant Curled	✓	✓	1	168-224-224-78-1	5/08	5/13	6/18
<u>Other Crops</u>								
Onion *(Allium cepa)*	White Sweet Spanish		✓	2	224-448-448-157	3/31	5/13	9/30
Pea *(Pisum sativum)*	Little Marvel		✓	2	34-224-224-78	4/15	5/13	7/08
Potato *(Solanum tuberosum)*	Russet Burbank	✓	✓	1	308-504-504-177-1	4/15	5/15	9/11

[a] 1:0 refers to H_2SO_4 rain type.

[b] 2:1 refers to H_2SO_4-HNO rain type.

[c] Fertilization rates are for kg/ha of N-P_2O_5-K_2O-S-B.

[d] Starts were obtained from a commercial nursery.

Results and Discussion

Forage legume: clover

No significant effect of H_2SO_4-HNO_3 rain on top dry matter yield of 'Kenland' clover was found (Table 15). A stimulatory effect at pH 3.5 was suggested, however. At pH 3.5, mean total top, leaf, and stem dry weights exceeded the control at each of the three harvests. Summed across harvests, mean total top dry weight was 17 percent greater than the control mean, mean leaf dry weight was 11 percent greater, mean stem dry weight was 38 percent greater ($P \leq 0.01$), and mean percent leafiness was 3 percent lower ($P \leq 0.10$, 77.1 versus 80.2 percent in the control). Since stem dry weight only constituted about 20 percent of total top dry weight across harvests and mean leaf dry weight did not increase as much as stem dry weight at pH 3.5, total top dry weight did not increase significantly at pH 3.5. The significant stimulation in stem dry weight across harvests at pH 3.5 appeared to be associated with an increase in stem weight, rather than number. For instance, H1 mean stem number was less that 1 percent greater than the control mean, but mean stem dry weight was 135 percent greater ($P \leq 0.10$). In H3, mean stem number at pH 3.5 was 3 percent lower, but mean stem dry weight was 49 percent greater.

Shoot-to-root ratios increased at pH levels 4.0 and 3.5 because of nonsignificant decreases in root dry weight (-21 and -17 percent at pH 4.0 and 3.5, respectively) and nonsignificant increases in total top dry weights. Stubble and total plant dry weights were not affected by acid rain treatment, with acid rain treatment means within 5 percent of the control. Nodule number was reduced by acid rain treatment at pH levels 4.0 and 3.0 by 17 and 23 percent, respectively. Nodule number at pH 3.5, however, was similar to the control (within 3 percent). It is not clear why a reduction in nodulation would occur at pH levels 4.0 and 3.0, but not at pH 3.5. It is also not known whether this decreased nodulation resulted in any decreased nitrogen fixation.

Table 15. 'Kenland' clover grown in LR chambers: effects of simulated sulfuric-nitric acid rain on forage production, percent leafiness, and stem number at three harvests, stubble, root, and total dry weights, shoot-to-root ratio (S:R), and nodule number [a]

Treatment	Harvest 1					Harvest 2					Harvest 3				
	Total top	Leaf	Stem	Stem no.	% Leaf	Total Top	Leaf	Stem	Stem no.	% Leaf	Total Top	Leaf	Stem	Stem no.	% Leaf
	g	g	g			g	g	g			g	g	g		
5.6	3.18	2.84	0.34	33.6	92.1	7.53	5.77	1.76	60.3	76.9	10.35	8.27	2.09	113.6	80.6
4.0	3.69	3.27	0.42	34.1	90.0	7.07	5.54	1.53	64.6	78.8	10.94	8.90	2.05	119.6	81.7
3.5	4.38	3.58	0.80	33.9	84.6	7.84	5.97	1.87	64.8	77.0	12.38	9.26	3.11	109.8	76.4
3.0	3.83	3.32	0.51	34.9	89.1	7.54	5.98	1.55	68.6	80.2	10.84	8.62	2.22	111.8	80.2
S.E.[b]	0.40	0.29	0.13	1.6	2.1	0.43	0.29	0.17	2.6	1.4	0.60	0.34	0.35	6.5	1.9
F[c]	N.S.	N.S.	N.S.	N.S.	N.S.	N.S.	N.S.	N.S.	N.S.	N.S.	N.S.	N.S.	N.S.	N.S.	N.S.

Treatment	Harvests 1-3				Stubble dry wt.	Root dry wt.	Total dry wt.	S:R	Nodule no.
	Total top	Leaf	Stem	% Leaf					
	g	g	g		g	g	g		
5.6	21.06	16.87	4.19	80.2	5.25	9.58	36.16	2.95	351.1
4.0	21.71	17.72	3.99	81.8	5.24	7.55	34.50	3.72*	291.8*
3.5	24.59	18.81	5.78**	77.1	5.50	7.96	38.05	3.96**	340.0
3.0	22.21	17.92	4.28	81.3	5.34	8.10	35.64	3.62	270.4**
S.E.	1.06	0.76	0.43	1.2	0.25	0.64	1.57	0.25	19.2
F	N.S.	N.S.	*	*	N.S.	N.S.	N.S.	*	**

[a]Forage was harvested at approximately 10% bloom stage to a 7.6 cm stubble height on August 12, September 4, and October 2.

[b]Standard error of the mean.

[c]Significance level of the F-test from one-way ANOVA with * and ** denoting $P \leq 0.05$ and 0.01, respectively.

*,**Symbols after table values denote significant differences from control means with $P \leq 0.05$ and 0.01, respectively, for two-sided t-test.

Forage grasses: orchardgrass and tall fescue

An early stimulatory but transitory effect of H_2SO_4-HNO_3 rain on 'Alta' tall fescue forage production was observed. No significant effects on tall fescue forage yield occurred in H_2SO_4 rain. Forage production of 'Potomac' orchardgrass was not significantly affected by either rain type.

Orchardgrass top dry weight was not significantly affected by acid rain treatment in either rain type (Table 16). In H_2SO_4 rain, acid rain treatment means were within 5 percent of the control. In H_2SO_4-HNO_3 rain, mean top dry weight at pH levels 4.0 and 3.5 was within 5 percent of the control, but was 15 percent greater than the control mean at pH 3.0 ($P \leq 0.10$). Root dry weight at pH 3.0 in H_2SO_4-HNO_3 rain was 28 percent greater than the control. This increase led to 20 percent greater total plant dry weight. Shoot-to-root ratios remained comparable, however, because mean top dry weight at pH 3.0 showed a similar, though statistically nonsignificant, increase.

Although top dry matter yield was not significantly different for acid rain treatments in either rain type, the yield components (tiller number and yield per tiller) were affected. In H_2SO_4 rain, tiller number at pH 3.5 was 19 percent greater than the control at harvest, and dry weight per tiller was 15 percent lower. Tiller number at pH 3.5 was not greater earlier in the season. A greater tillering rate from August 8 to September 16 ($P \leq 0.05$) produced a greater average tiller rate over the course of the season and resulted in greater tiller number at harvest. An opposite effect occurred in H_2SO_4-HNO_3 rain. Tiller numbers at harvest were from 15 to 20 percent lower in the three acid rain treatments, yield per tiller was 19 to 34 percent greater, and the lower seasonal tillering rates in these treatments were from decreased tillering rates from August 8 to September 16 ($P \leq 0.01$). It is not clear why the two rain types would produce opposite adjustments of the yield components tiller number and yield per tiller. Continued effects on yield per tiller in a field situation after stand establishment would be expected to have long-term consequences for forage production. However, since these experiments were conducted in pots, it would be difficult to extrapolate results to a field situation.

In the H_2SO_4-HNO_3 rain tall fescue study, H1 increases of 24 and 32 percent in top dry weight at pH levels 4.0 and 3.0, respectively, were significant, but a mean increase of 13 percent at pH 3.5 was not (Table 17). The increase at pH 3.0 continued in H2 (+35 percent). Differences in top dry weight at H3 and summed across harvests (H1-H3) were not significant, however, and acid rain treatment means for H1-H3 were within 7 percent of the control. While top dry weight was not affected by H_2SO_4 rain, stubble dry weight at pH 4.0 was significantly greater than the control by 13 percent (Table 17). Decreases of approximately 18 percent for root dry weight occurred, however, at pH levels 4.0 and 3.5 in H_2SO_4 rain and produced higher S:R ratios. Total plant dry weights did not differ significantly among treatments in either rain type and were fairly uniform; acid rain treatment means were within 9 percent of control means.

Increases in top dry matter production were associated with increases in the yield component tiller number, but not yield per tiller, in both rain types (Table 17). In H_2SO_4 rain, tiller numbers on July 31 (H1) were from 11 to 16 present greater in the three acid rain treatments (which had 10 to 17 percent greater mean top dry weight), but were comparable to control levels at subsequent harvests. In H_2SO_4-HNO_3 rain, tiller numbers exceeded the control at pH levels 4.0 and 3.0 on July 11, continued to be greater at pH 3.0 on July 11, continued to be greater at pH 3.0 at the first two harvests (July 31 and August 30), but were similar to the control in all three acid rain treatments at the final harvest (September 30). Apparently, the initial increases in tillering were not sustained throughout the season.

While calculated tillering rates for the period July 11 to July 31 were significantly greater than the control in H_2SO_4 rain at all three acid rain pH levels and in H_2SO_4-HNO_3 rain at pH 3.0 tillering rates for subsequent periods did not differ significantly among treatments in either rain type. The initially greater tillering rate at pH 3.0 in H_2SO_4-HNO_3 rain was responsible for the maintenance of higher tiller numbers in this treatment through H2, and the increase over the control remained relatively constant at 19 and 22 percent for the differential disappeared.

Since tiller rate (and number) is primarily influenced by the supply of photosynthate and mineral nutrients (Milthorpe and Moorby, 1974), it is possible that photosynthate supply to tiller buds was affected by acid rain treatment early in the season (e.g., through effects on photosynthetic rate or translocation) and/or that nutrient supply was affected (e.g., through effects on N and S nutrient availability, root absorption of minerals, or efficiency of utilization). In a field sward situation, however, increased initial tillering without increased yield per tiller would not be expected to be a long-term benefit, since a dynamic equilibrium between tiller formation and death is reached and maintained after stand establishment.

Several effects on tall fescue forage quality were found. At H1 in H_2SO_4-HNO_3 rain, total N increased by 23 to 36 percent in all acid rain treatments (Table 18). Since little change occurred in percent N, these increases were caused by increases in top dry weight. Nonsignificant increases in total S of similar magnitude also occurred and resulted from increases in top dry weight. Harvest One ADF at pH levels 3.5 and 3.0 in H_2SO_4 rain increased significantly by 2.5 to 3.4 percent. In addition, mean percent NDF increased by 2.8 to 4.9 percent in all H_2SO_4 rain treatments, but differences were not statistically significant. The erratic fluctuation from pH to pH seen for Mn and Cu in the H_2SO_4-HNO_3 rain study strongly suggests that the statistically significant effects which occurred were caused by chance variation alone. No indication of any acid rain effects on either Mn or Cu was found at H2.)

At H2, only one effect occurred which was both statistically and biologically significant. Percent S was significantly greater than the control in all H_2SO_4 rain treatments (0.31 to 0.34 percent versus 0.25 percent). All other significant effects were either easily explained or of little importance. At pH 3.0 in H_2SO_4-HNO_4 rain, the significant increases in total N and total S were either entirely (N) or primarily (S) caused by a concurrent increase in top dry weight. The significant decreases seen in P, K, Ca, B, and Zn with H_2SO_4 rain treatment are of questionable importance for several reasons. First, seven treatment means for all five of these elements (pH 3.0, 3.5, 4.0 for H_2SO_4 rain and pH 3.0, 3.5, 4.0, 5.6 for H_2SO_4-HNO_3 rain) were close together, but the H_2SO_4 rain control mean was much greater than the others in each case. Second, there was no suggestion of a trend, either up or down, among the three H_2SO_4 rain treatment means for any of these variables. Finally, none of the five showed significant effects at H1. In contrast, data for ADF and NDF fall into another category: no statistically significant differences were found, but H2 data suggested noteworthy patterns. For ADF, all H_2SO_4-HNO_3 rain treatment means exceeded the control (by 2.0 to 3.3 percent). In H_2SO_4 rain, mean ADF at pH 3.0 was up 3.3 percent. For NDF, acid rain treatment means were about 4 to 6 percent greater than the control in both rain types.

Simulated acid rain appeared to have consistent effects on only two of the measures of forage quality studies. H_2SO_4 acid rain treatment increased H2 S concentration in forage tissue. Both types of acid rain also appeared to increase ADF in top dry matter by about 2 to 3.5 percent. Increases in both S and ADF occurred most frequently at pH 3.0. Although H_2SO_4-HNO_3 rain treatment (particularly at pH 3.0) increased total N and S, this resulted primarily from increases in top dry weight, not percent N or S.

Table 16. 'Potomac' orchardgrass grown in chambers: effects of simulated sulfuric and sulfuric-nitric acid rain on tiller and dry matter production and shoot-to-root ratio (S:R)

Treatment	Top dry wt.	Root dry wt.	Total dry wt.	S:R	Tiller number 7/11	Tiller number 7/24	Tiller number 8/8	Tiller number 9/16	Avg. tiller rate (no./wk.)	Dry wt./ tiller
	g	g	g							mg
Sulfuric acid rain										
5.6	37.63	24.61	62.25	1.69	14.8	37.0	47.4	98.8	8.8	397
4.0	38.34	21.25	59.58	1.96	14.3	38.6	48.5	92.9	8.2	421
3.5	39.41	32.29	71.70	1.56	14.4	38.7	49.9	118.0*	10.8*	338*
3.0	36.20	30.81	67.01	1.36	14.6	38.6	49.8	107.7	9.7	356
S.E.[a]	1.12	3.81	4.14	0.15	0.6	1.2	1.3	5.8	0.6	20
F[b]	N.S.	N.S.	N.S.	*	N.S.	N.S.	N.S.	*	*	*
Sulfuric-nitric acid rain										
5.6	39.50	23.12	62.62	1.73	16.6	42.4	54.2	127.6	11.6	319
4.0	40.14	22.02	62.16	1.94	15.2	40.9	54.8	107.4	9.6*	379*
3.5	41.52	22.90	64.42	1.91	15.6	40.6	52.4	102.1**	9.0**	415**
3.0	45.35	29.56*	74.91**	1.65	16.3	44.1	56.4	109.1*	9.7*	427**
S.E.	1.78	2.06	3.32	0.11	0.7	1.8	2.3	6.1	0.6	20
F	N.S.	*	*	N.S.	N.S.	N.S.	N.S.	*	*	**

[a]Standard error of the mean.

[b]Significance level of the F-test from one-way ANOVA with * and ** denoting $P \leq 0.05$ and 0.01, respectively.

*,**Symbols after the table values denote significant differences from control means with $P \leq 0.05$ and 0.01, respectively, for two-sided t-test.

Table 17. 'Alta' tall fescue grown in chambers: effects of simulated sulfuric and sulfuric-nitric acid rain on tiller and dry matter production and shoot-to-root ratio (S:R) [a]

Treatment	Tiller number				Yield/tiller			Top dry weight				Stubble	Root	Total	
	7/11	7/31	8/30	9/30	H1	H2	H3	H1	H2	H3	H1-H3	dry wt.	dry wt.	dry wt.	S:R
Sulfuric acid rain					mg			g							
5.6	22.7	49.6	72.8	143.3	58.8	99.2	86.8	2.86	7.23	12.14	22.23	13.50	20.49	56.22	1.80
4.0	24.1	55.1*	75.1	145.6	57.9	106.3	83.5	3.15	7.84	11.71	22.69	15.31*	17.04*	55.04	2.31**
3.5	25.1	56.6*	77.8	151.7	59.4	102.9	86.6	3.32	7.82	13.02	24.17	12.99	16.76**	53.92	2.24**
3.0	25.6	57.6**	74.7	154.4	58.7	97.2	78.5	3.34	7.00	11.85	22.19	14.05	20.67	56.91	1.83
S.E.[b]	1.1	2.0	3.0	6.1	3.2	7.0	4.9	0.14	0.42	0.49	0.67	0.56	1.03	1.57	0.10
F[c]	N.S.	*	N.S.	N.S.	N.S.	N.S.	N.S.	N.S.	N.S.	N.S.	N.S.	*	**	N.S.	**
Sulfuric-nitric acid rain															
5.6	22.8	54.2	83.7	192.8	46.6	81.3	71.2	2.50	6.65	13.51	22.66	20.52	24.14	67.31	1.94
4.0	26.3*	56.9	89.3	181.9	56.0	82.9	74.5	3.11**	7.02	13.46	23.59	21.06	24.72	69.36	2.17
3.5	24.6	56.9	88.4	177.6	50.4	80.4	65.1	2.82	6.95	11.39	21.16	18.36	21.76	61.28	1.94
3.0	27.8**	64.3**	99.7**	197.8	45.8	82.5	52.4*	3.31**	8.99**	11.74	24.04	19.60	18.50	62.14	2.40
S.E.	1.2	1.9	3.9	7.3	4.2	8.9	5.7	0.15	0.51	0.84	1.03	0.77	2.38	3.10	0.16
F	*	**	*	N.S.	N.S.	N.S.	*	**	**	N.S.	N.S.	N.S.	N.S.	N.S.	N.S.

[a]Harvest dates were July 31 (H1), August 29 (H2), and September 30 (H3).

[b]Standard error of the mean.

[c]Significance level of the F-test from one-way ANOVA with * and ** denoting $P \leq 0.05$ and 0.01, respectively.

*,**Symbols after table values denote significant differences from control means with $P \leq 0.05$ and 0.01, respectively, for two-sided t-test.

Table 18. 'Alta' tall fescue grown in chambers: effects of simulated sulfuric and sulfuric-nitric acid rain on total N and S uptake and concentrations of N, S, crude protein (CP), acid detergent fiber (ADF), neutral detergent fiber (NDF), and 10 mineral elements at two harvests [a]

Treatment	Total N	Total S	N	S	CP	ADF	NDF	P	K	Ca	Mg	Mn	Fe	Cu	B	Zn	Al
	mg		%									ppm					
Harvest 1																	
Sulfuric acid rain																	
5.6	80.3	12.6	2.81	0.44	17.55	19.85	35.65	0.40	3.77	0.65	0.52	108	242	10	6	18	124
4.0	84.7	11.4	2.71	0.36	16.93	20.96	38.41	0.37	3.54	0.59	0.49	98	197	9	7	15	121
3.5	82.6	13.8	2.49	0.41	15.57	23.21*	39.02	0.47	3.65	0.60	0.42	106	222	9	10	19	156
3.0	87.0	10.0	2.60	0.30	16.28	22.40*	40.54	0.45	3.84	0.71	0.43	105	223	10	14	24	158
$\bar{x}$	83.6	11.9	2.65	0.38	16.58	21.61	38.41	0.42	3.70	0.64	0.46	105	221	10	9	19	140
Sulfuric-nitric acid rain																	
5.6	61.1	11.3	2.44	0.45	15.22	20.86	34.09	0.42	3.52	0.71	0.46	103	161	9	10	18	78
4.0	78.9**	14.2	2.53	0.45	15.82	20.99	35.33	0.31	3.07	0.57	0.48	77**	148	7*	2	12	68
3.5	75.4*	13.0	2.67	0.46	16.69	20.44	35.01	0.36	3.45	0.66	0.49	97	192	11*	7	16	109
3.0	83.4**	16.0	2.51	0.48	15.68	22.34	38.26	0.34	3.20	0.62	0.43	87*	263	9	7	21	83
$\bar{x}$	74.7	13.6	2.54	0.46	15.85	21.16	35.67	0.36	3.31	0.64	0.46	91	191	9	7	17	85
S.E.[b]	3.5	1.8	0.10	0.04	0.65	0.74	1.38	0.02	0.14	0.04	0.04	5	37	0.6	2	4	22
pH-F for sulfuric[c]	NS	NS	NS	NS	NS	*	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
pH-F for sul.-nitric	**	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	*	NS	**	NS	NS	NS
Harvest 2																	
Sulfuric acid rain																	
5.6	231.5	18.7	3.21	0.25	20.04	27.35	39.73	0.33	2.37	0.38	0.27	83	162	4	10	15	105
4.0	246.3	24.3	3.16	0.31*	19.73	29.16	44.61	0.27**	2.17	0.32**	0.29	69	170	3	3**	10*	114
3.5	248.5	25.7	3.18	0.33**	19.88	25.51	43.70	0.26**	1.99**	0.29**	0.25	70	158	4	6*	11*	119
3.0	230.5	24.1	3.31	0.34**	20.67	30.62	45.49	0.24**	2.07**	0.31**	0.30	64	137	3	2**	9**	96
$\bar{x}$	239.2	23.2	3.21	0.31	20.08	28.16	43.39	0.28	2.15	0.33	0.28	72	157	4	5	11	109
Sulfuric-nitric acid rain																	
5.6	198.4	16.6	2.97	0.25	18.57	25.11	39.83	0.27	1.97	0.36	0.28	69	131	3	6	11	82
4.0	200.2	15.5	2.86	0.22	17.86	27.85	44.62	0.25	1.90	0.32	0.26	62	117	4	5	11	52
3.5	216.4	17.2	3.13	0.25	19.58	27.11	43.39	0.23	1.94	0.34	0.31	62	126	4	5	10	77
3.0	279.3*	27.7**	3.06	0.30	19.14	28.41	45.99	0.23	2.12	0.31	0.32	59	124	3	3	9	72
$\bar{x}$	223.6	19.2	3.01	0.25	18.79	27.12	43.46	0.25	1.98	0.33	0.30	63	125	4	5	11	71
S.E.	17.3	2.2	0.16	0.02	1.00	1.45	1.93	0.01	0.07	0.01	0.02	5	14	0.3	1	1	13
pH-F for sulfuric	NS	NS	NS	*	NS	NS	NS	**	*	**	NS	NS	NS	NS	**	*	NS
pH-F for sul.-nitric	*	*	NS	*	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS

[a]Concentrations are expressed on a dry weight basis. Harvest dates were July 31 (H1) and August 29 (H2).

[b]Standard error of the mean of one pH for one rain type (sample size = 2).

[c]Significance levels of the F-tests from one-way analyses of variance, one for sulfuric and one for sulfuric-nitric acid rain, with * and ** denoting $P \leq 0.05$ and 0.01, respectively. At each harvest, a pooled estimate of error with 8 d.f. was used in the F-tests.

*,**Symbols after table values denote significant differences from control means with $P \leq 0.05$ and 0.01, respectively, for two-sided t-test.

Root crops: beet, carrot, and radish

Evidence of both stimulation and inhibition of root growth by acid rain treatment was found for the three root crops studied. Decreases in root growth for 'Danvers Half Long' carrot (H_2SO_4-HNO_3 rain), increases for 'Detroit Dark Red' beet (H_2SO_4-HNO_3 rain), and both increases and decreases, depending on treatment pH and rain type, for 'Cherry Belle' radish were observed.

In carrot, mean root fresh and dry weights at pH levels 3.5 and 3.0 were reduced by approximately 21 and 14 percent ($P \leq 0.01$ and $P \leq 0.10$), respectively (Table 19). Carrot shoulder diameter was also reduced. Greater percentages of roots were less than 3.2 centimeters in diameter at pH levels 3.5 ($P \leq 0.10$) and 3.0 ($P \leq 0.05$). Root growth was abnormal, however, in all treatments: roots were abnormally twisted and small, perhaps as a result of transplanting. Mean top dry weight was significantly reduced at pH levels 3.5 and 3.0 by 24 and 20 percent, respectively, and total dry weights were reduced to a similar extent in these treatments.

In beet, progressive increases in root fresh and dry weights occurred as treatment pH dropped. Significant increases of 15 and 27 percent in root fresh weight and 16 and 20 percent in root dry weight occurred at pH levels 3.5 and 3.0, respectively, were significant (Table 20). A similar effect on top dry weight was not observed, however, and acid rain treatment means were within 3 percent of the control. Total plant dry weight increased because of the stimulation in root growth and was significantly greater than the control at pH 3.0 by 13 percent. Neither the percent water in roots nor the percent marketable-sized beets (> 3.8 centimeter diameter) was affected by acid rain treatment.

In radish, root fresh and dry weights were significantly lower than the respective controls in pH levels 3.0 and 3.5 in H_2SO_4-HNO_3 rain and at pH 3.0 in H_2SO_4 rain (Table 21). The reductions in root fresh weight ranged from 20 to 40 percent in H_2SO_4-HNO_3 rain, and root fresh weight at pH 3.0 was 34 percent lower than the control in H_2SO_4 rain. Reductions in mean top dry weight at these pH levels also were evident with the 18 percent reduction at pH 3.5 in H_2SO_4-HNO_3 rain statistically significant.

Significantly greater root and top growth at pH 4.0, however, occurred in the H_2SO_4 rain treatment (Table 21). Root fresh and dry weights at pH 4.0

were 23 percent greater than the control, and top dry weight was 16 percent greater. In H_2SO_4-HNO_3 rain, mean root fresh and dry weights and top dry weight at pH 4.0 also exceeded the control (by 11, 8, and 6 percent respectively), but these increases were not statistically significant.

Table 19. 'Danvers Half-Long' carrot grown in LR chambers: effects of simulated sulfuric-nitric acid rain on root growth and dry matter production

Treatment	Root weight: Fresh	Root weight: Dry	Top dry wt.	Total dry wt.	Root percent water	Root size classes: Shoulder dia. <3.2 cm	Root size classes: Length <12.7 cm
	g				%		
5.6	59.71	6.05	7.56	13.60	89.8	78.6	79.8
4.0	59.29	6.07	7.05	13.11	89.8	75.0	71.4
3.5	47.21**	4.72**	5.76**	10.48**	90.0	92.9	89.3
3.0	51.57	5.13	6.04**	11.17**	90.0	100.0*	89.3
S.E.[a]	3.10	0.33	0.38	0.58	0.2	6.0	7.2
F[b]	**	**	**	**	N.S.	*	N.S.

[a]Standard error of the mean.

[b]Significance level of the F-test from one-way ANOVA with * and ** denoting $P \le 0.05$ and 0.01, respectively.

*,**Symbols after the table values denote significant differences from control means with $P \le 0.05$ and 0.01, respectively, for two-sided t-test.

Table 20. 'Detroit Dark Red' beet grown in LR chambers: effects of simulated sulfuric-nitric acid rain on root and top growth

Treatment	Root weight Fresh	Root weight Dry	Top dry weight	Total dry weight	Root percent water	Percent beets >3.8 cm dia.
	g				%	
5.6	95.00	20.05	13.13	33.19	78.8	92.9
4.0	101.07	20.61	12.92	33.53	79.6	89.3
3.5	109.36*	23.20*	12.94	36.14	78.7	100.0
3.0	121.14**	24.07**	13.54	37.62**	80.0	96.4
S.E.[a]	4.88	1.04	0.46	1.17	0.5	4.1
F[b]	**	*	N.S.	*	N.S.	N.S.

[a]Standard error of the mean.

[b]Significance level of the F-test from one-way ANOVA with * and ** denoting $P \leq 0.05$ and 0.01, respectively.

*,**Symbols after the table values denote significant differences from control means with $P \leq 0.05$ and 0.01, respectively, for two-sided t-test.

Table 21. 'Cherry Belle' radish grown in chambers: effects of simulated sulfuric and sulfuric-nitric acid rain on root and top growth

Treatment	Root weight Fresh	Root weight Dry	Root percent water	Top dry wt.	Total dry wt.
	g	g	%	g	g
Sulfuric acid rain					
5.6	26.41	1.38	94.7	1.27	2.65
4.0	32.50*	1.70*	94.7	1.48*	3.19**
3.5	27.44	1.43	94.7	1.25	2.68
3.0	17.38**	0.98**	94.2 **	1.14	2.12**
S.E.[a]	2.02	0.09	0.1	0.06	0.12
F[b]	**	**	**	**	**
Sulfuric-nitric acid rain					
5.6	30.24	1.64	94.5	1.30	2.94
4.0	33.58	1.77	94.7	1.38	3.15
3.5	24.12*	1.36*	94.2 *	1.06**	2.41**
3.0	18.15**	1.06**	94.1 **	1.21	2.27**
S.E.	1.76	0.08	0.1	0.06	0.12
F	**	**	**	**	**

[a]Standard error of the mean.

[b]Significance level of the F-test from one-way ANOVA with ** denoting $P \leq 0.01$.

*,**Symbols after the table values denote significant differences from control means with $P \leq 0.05$ and 0.01, respectively, for two-sided t-test.

Fruit crop: tomato

Ripe fruits of 'Patio' tomato were harvested twice weekly from September 30 until October 30. The remaining, unripe fruits were also picked at the final harvest. Ripe fruit fresh weight comprised only 15 and 13 percent of total fruit production, on average in the H_2SO_4 and H_2SO_4-HNO_3 rain studies, respectively, because of the late planting date and vigorous vegetative growth.

Tomato fruit production was not significantly affected by either H_2SO_4 or H_2SO_4-HNO_3 rain treatment (Table 22). In addition, neither top nor root dry weight was affected by either rain type. Means for top dry weight were particularly uniform, i.e., within 5 and 8 percent of the controls in the H_2SO_4 and H_2SO_4-HNO_3 rain treatments, respectively.

Two interesting observations regarding chamber-type and pH differences were made for the occurrence of floral abortion near the start of flowering. First, while floral abortion occurred in all treatments in both rain-type studies, two or three times as many aborted flowers were observed in all treatments, including the control, in the LRC, H_2SO_4-HNO_3 rain study as in the SRC, H_2SO_4 rain study. Second, while treatment differences for the amount of floral abortion were not observed in the H_2SO_4 rain study, they were apparent in the H_2SO_4-HNO_3 rain study. About twice as many aborted flowers were observed at pH 3.0 as in the other treatments. (These observations were based on counts of aborted flowers per pot made on two occasions. Counts were not analyzed statistically, because all aborted flowers could not be counted; some fell outside pots to the chamber floor or fell to the ground below the chamber floor boards.)

Table 22. 'Patio' tomato grown in chambers: effects of simulated sulfuric and sulfuric-nitric acid rain on fruit and dry matter production

Treatment	Total fruit		Ripe fruit			Unripe fruit		Top dry weight	Root dry weight
	No.	Fresh weight	No.	Fresh weight	Avg fresh weight	No.	Fresh weight		
		— g —		g			g		
Sulfuric acid rain									
5.6	31.7	2178.57	3.3	376.44	116.19	28.4	1802.13	108.15	7.65
4.0	30.5	2252.09	2.9	322.27	109.82	27.6	1929.82	109.21	7.31
3.5	35.7	2409.60	2.7	320.15	114.43	33.0	2089.45	108.23	7.24
3.0	31.5	2060.65	2.8	339.97	133.00	28.7	1720.68	102.97	7.59
S.E.[a]	2.5	135.46	0.6	66.24	9.06	2.4	127.02	7.41	0.41
F[b]	NS	NS	NS	NS	NS	NS	NS	NS	NS
Sulfuric-nitric acid rain									
5.6	25.0	1882.93	2.1	225.66	116.02	22.9	1657.26	132.43	8.57
4.0	27.5	1957.16	2.5	299.81	119.67	24.8	1624.04	122.18	8.17
3.5	21.1	1561.75	2.5	321.55	130.52	18.6	1240.20	132.83	9.23
3.0	20.7	1589.31	0.8	70.63	88.75	19.9	1518.68	136.91	10.11
S.E.	3.2	215.74	0.7	92.37	15.43	2.7	165.12	10.44	0.67
F	NS	NS	NS	NS	NS	NS	NS	NS	NS

[a]Standard error of the mean.

[b]Significance level of the F-test from one-way ANOVA.

Leaf crops: lettuce and mustard greens

Acid rain treatment reduced yield of 'Southern Giant Curled' mustard greens in both rain types at pH 3.0. Effects on 'Summer Bibb' lettuce varied with rain type.

Decreases of 35 and 22 percent in mean top fresh weight of mustard greens at pH 3.0 occurred in the H_2SO_4 and H_2SO_4-HNO_3 studies, respectively (Table 23). Effects on root growth were similar to those on top growth. Root dry weight was 38 and 39 percent lower at pH 3.0 in the two studies.

Although H_2SO_4-HNO_3 rain treatment did not affect top growth of 'Summer Bibb' lettuce, H_2SO_4 rain treatment at pH levels 3.5 and 3.0 produced significant reductions (Table 24). Top dry weight was 17 and 12 percent lower than the control in the 3.5 and 3.0 treatments, respectively. Root dry weight, however, was not affected by acid rain treatment in either rain type. The reductions in top dry weight in H_2SO_4 rain resulted in lower total plant dry weights at pH levels 3.5 and 3.0.

'Improved Thick Leaf' spinach was also exposed to both rain types in chamber studies, but data could not be used to assess acid rain treatment effects because an obvious, severe nutritional problem developed in these studies. Well-defined, interveinal chlorosis was observed. This condition was more pronounced on older leaves and developed progressively on young leaves until they were fully expanded. Tissue analysis of apparently healthy leaves and of those exhibiting interveinal chlorosis did not suggest any micronutrient deficiencies (as might have been expected because of the high soil pH), but Mg levels were low (Appendix Table 6).

Interestingly, this condition developed on plants exposed to pH 5.6 (control) rain simulant, and to a lesser extent in pH 4.0 treatments, but did not occur in pH 3.5 or 3.0 treatments. In the H_2SO_4 and H_2SO_4-HNO_3 rain studies, respectively, symptoms developed in 86 and 57 percent of the pots at pH 5.6; at pH 4.0, symptoms developed in 50 percent of the pots in both rain types. Thus, acid rain treatment appeared to ameliorate symptom development. This apparent effect explains the increases in leaf fresh weight and dry matter production which occurred at pH levels 3.0 and 3.5 in H_2SO_4-HNO_3 rain and in all three acid rain treatments in H_2SO_4 rain (Appendix Table 5). Acid rain treatment did not, however, have any effect on end-of-the-study soil pH (Table 13).

Table 23. 'Southern Giant Curled' mustard greens grown in chambers: effects of simulated sulfuric and sulfuric-nitric acid rain on top and root growth

Treatment	Top weight Fresh	Top weight Dry	Root dry wt.	Total dry wt.	Top percent water
	g	g	g	g	%
Sulfuric acid rain					
5.6	63.20	5.49	1.48	6.97	91.1
4.0	58.25	5.19	1.36	6.55	91.0
3.5	59.05	5.09	1.27	6.36	91.4
3.0	41.09**	3.58**	0.91**	4.49**	91.2
S.E.[a]	3.58	0.29	0.12	0.35	0.2
F[b]	**	**	**	**	N.S.
Sulfuric-nitric acid rain					
5.6	86.48	8.71	2.62	11.34	89.9
4.0	81.22	7.91	2.30	10.21	90.2
3.5	84.83	8.02	2.38	10.40	90.6
3.0	67.35**	6.26**	1.59**	7.85**	90.7
S.E.	3.07	0.38	0.28	0.57	0.2
F	**	**	*	**	N.S.

[a]Standard error of the mean.

[b]Significance level of the F-test from one-way ANOVA with * and ** denoting $P \leq 0.01$.

**Symbols after the table values denote significant differences from control means with $P \leq 0.01$ for two-sided t-test.

Table 24. 'Summer Bibb' lettuce grown in chambers: effects of simulated sulfuric and sulfuric-nitric acid rain on top and root growth

Treatment	Top weight Fresh	Top weight Dry	Root dry wt.	Total dry wt.	Top percent water
	g				%
Sulfuric acid rain					
5.6	141.64	7.37	1.96	9.33	94.8
4.0	137.93	7.28	1.97	9.25	94.7
3.5	110.93**	6.08**	1.88	7.96**	94.4
3.0	120.57*	6.49*	1.91	8.39*	94.5
S.E.[a]	6.02	0.27	0.11	0.34	0.1
F[b]	**	**	N.S.	**	N.S.
Sulfuric-nitric acid rain					
5.6	129.71	7.32	2.30	9.63	94.2
4.0	112.50	7.06	2.57	9.63	93.4*
3.5	128.36	7.04	2.14	9.18	94.4
3.0	134.93	7.55	1.93	9.47	94.3
S.E.	8.83	0.39	0.23	0.52	0.2
F	N.S.	N.S.	N.S.	N.S.	*

[a]Standard error of the mean.

[b]Significance level of the F-test from one-way ANOVA with * and ** denoting $P \leq 0.05$ and 0.01, respectively.

*,**Symbols after the table values denote significant differences from control means with $P \leq 0.05$ and 0.01, respectively, for two-sided t-test.

Other crops: onion, pea, and potato

Onion

Fresh and dry bulb weights of 'White Sweet Spanish' onion were not significantly affected by H_2SO_4-HNO_3 rain treatment, nor was the size class distribution of bulbs (Table 25). Shoot production appeared to be stimulated by acid rain treatment, however. Mean top dry weights were 32, 54, and 23 percent greater than the control at pH levels 4.0, 3.5, and 3.0, respectively, with the increase at pH 3.5 statistically significant. Acid rain treatment means for root dry weight were higher than the control by similar magnitudes, but differences were not significant.

Pea

No significant effects of H_2SO_4-HNO_3 rain treatment on pod, pea, shoot, root, or nodule production of 'Marvel' pea were found (Table 26). Acid rain treatment means frequently exceeded control means, however. For example, acid rain treatment means were 23 to 33 percent greater than the control for top dry weight, 8 to 27 percent greater for root dry weight, 12 to 22 percent greater for total dry weight, and 4 to 17 percent greater to mature pod plus pea fresh weight.

Potato

Effects of acid rain treatment on seed-piece sprouting and on tuber production of single-stem transplants of 'Russet Burbank' potato were studied separately.

Tuber yield was not affected by acid rain treatment in either rain type (Table 27). Class "A" tubers (tubers $\geq$ 4.8 centimeters in diameter) accounted for more than 85 percent of total yield in both rain types. Acid rain treatment means for "A" tuber fresh weight were within 3 and 8 percent of the control in the H_2SO_4 and H_2SO_4-HNO_3 rain studies, respectively. In addition, fresh and dry weights of the smaller "B" tubers and top, root, and total plant dry weights were not significantly affected by acid rain treatment.

Seed-piece sprouting was not affected by H_2SO_4-HNO_3 rain treatment, but was stimulated by H_2SO_4 rain treatment (Table 28). In H_2SO_4 rain, mean sprout dry weight increased at pH 4.0 (+66 percent), peaked at pH 3.5 (+76 percent), and then dropped at pH 3.0 to a level 32 percent greater than the control ($P \leq 0.10$). Mean differences for sprout number and root and total dry weights followed the same pattern but were not statistically significant. These results do not support the hypothesis that a decrease in seed-piece sprouting can result in decreased tuber production. Instead, they suggest that H_2SO_4 rain treatment can promote seed-piece sprouting of 'Russet Burbank' potato. Whether such promotion could result in increased tuber production should be examined in future studies.

Table 25. 'White Sweet Spanish' onion grown in LR chambers: effects of simulated sulfuric-nitric acid rain on bulb and dry matter production

Treatment	Bulb weight		Bulb size classes			Bulb percent water	Top dry wt.	Root dry wt.	Total dry wt.
	Fresh	Dry	<5 cm.	5-8 cm.	>8 cm.				
	g		%				g		
5.6	186.20	19.25	42.9	53.6	3.6	89.6	7.93	1.41	28.60
4.0	192.37	20.58	39.3	50.0	10.7	89.3	10.45	1.91	32.94
3.5	238.81	24.60	28.6	64.3	7.1	89.7	12.21**	2.23	39.04
3.0	189.63	20.57	21.4	75.0	3.6	89.1	9.77	1.77	32.11
S.E.[a]	19.81	2.21	8.1	9.3	4.5	0.3	1.06	0.27	2.89
F[b]	N.S.	N.S.	N.S.	N.S.	N.S.	N.S.	*	N.S.	N.S.

[a]Standard error of the mean.

[b]Significance level of the F-test from one-way ANOVA with * denoting $P \leq 0.05$.

**Symbol after the table value denotes significant difference from control mean with $P \leq 0.01$ for two-sided t-test.

Table 26. 'Marvel' pea grown in LR chambers: effects of simulated sulfuric-nitric acid rain on dry matter production, yield components, and numbers of root nodules, flowers, and aborted flowers plus pods present at harvest

Treatment	Top dry wt.	Root dry wt.	Total dry wt.	Number of: Mature pods	Number of: Peas per mature pod	Mature pod + pea: Fresh wt.	Mature pod + pea: Dry wt.	Mature pea: Fresh wt.	Mature pea: Dry wt.	Avg. mature pod + pea: Fresh wt.	Avg. mature pod + pea: Dry wt.
	g	g	g			g	g	g	g	g	g
5.6	9.99	2.30	21.22	5.6	4.6	40.76	7.73	14.85	3.97	7.23	1.34
4.0	12.30	2.49	24.29	6.8	4.2	46.49	8.24	16.03	3.73	6.77	1.18
3.5	13.31	2.92	25.81	6.4	5.1	47.90	8.33	15.47	3.70	7.56	1.31
3.0	12.79	2.56	23.70	6.2	4.5	42.33	7.52	13.33	3.35	6.69	1.25
S.E.[a]	1.57	0.24	1.82	0.7	0.3	5.60	1.03	2.34	0.62	0.39	0.09
F[b]	N.S.	N.S.	N.S.	N.S.	N.S.	N.S.	N.S.	N.S.	N.S.	N.S.	N.S.

Treatment	Number of: Nodules	Number of: Flowers	Number of: Aborted flowers + pods	Number of: Immature pods	Immature pod + pea: Fresh wt.	Immature pod + pea: Dry wt.
					g	g
5.6	227	0.9	2.2	4.3	9.39	1.19
4.0	147	2.1	3.6	4.1	8.96	1.26
3.5	182	2.1	4.0	4.6	10.03	1.25
3.0	182	2.2	3.7	3.8	6.33	0.82
S.E.	22	0.4	0.7	0.9	2.19	0.27
F	N.S.	N.S.	N.S.	N.S.	N.S.	N.S.

[a]Standard error of the mean.

[b]Significance level of the F-test from one-way ANOVA.

Table 27. 'Russet Burbank' potato grown in chambers: effects of simulated sulfuric and sulfuric-nitric acid rain on tuber yield and dry matter production

Treatment	Total tuber wt. Fresh	Total tuber wt. Dry	"A" tuber weight[a] Fresh(F)	"A" tuber weight[a] Dry	"A" tuber weight[a] Avg.F.	"B" tuber weight Fresh(F)	"B" tuber weight Dry	"B" tuber weight Avg.F.	Tuber no. "A"	Tuber no. "B"	Tuber no. Total	Top dry wt.	Root dry wt.	Total dry wt.
	g											g		
Sulfuric acid rain														
5.6	1249.1	284.02	1027.5	232.79	256.2	221.6	51.23	42.1	4.1	5.4	9.5	30.80	1.70	316.52
4.0	1161.5	266.26	994.5	230.22	238.8	167.0	36.04	40.2	4.6	4.9	9.5	27.63	2.06	295.95
3.5	1132.7	256.02	1045.5	236.28	276.3	87.2	19.75	26.9	3.9	3.6	7.5	27.60	1.90	285.53
3.0	1245.8	288.98	1011.5	234.37	256.8	234.3	54.61	38.5	4.3	5.2	10.3	25.08	1.28	317.45
S.E.[b]	51.8	13.03	59.2	15.09	25.8	42.4	9.54	5.9	0.4	1.3	1.4	2.19	0.26	14.49
F[c]	N.S.	N.S.	N.S.	N.S.	N.S.	N.S.	N.S.	N.S.	N.S.	N.S.	N.S.	N.S.	N.S.	N.S.
Sulfuric-nitric acid rain														
5.6	1190.2	269.96	1065.2	241.89	310.4	125.1	28.07	36.0	3.9	4.1	8.0	30.75	1.92	302.63
4.0	1153.9	261.01	983.0	222.99	255.5	170.9	38.02	45.0	4.0	4.1	8.1	27.35	1.88	290.24
3.5	1226.4	280.32	1086.7	250.23	266.5	139.8	30.10	32.5	4.5	4.6	9.1	28.75	1.49	310.56
3.0	1232.9	267.17	1111.5	241.64	258.4	121.4	25.54	35.0	4.5	3.2	7.7	28.49	1.23	296.90
S.E.	75.3	16.38	80.5	18.06	30.0	37.2	8.24	7.4	0.5	1.0	1.0	2.00	0.26	16.44
F	N.S.	N.S.	N.S.	N.S.	N.S.	N.S.	N.S.	N.S.	N.S.	N.S.	N.S.	N.S.	N.S.	N.S.

[a]Class "A" and "B" tubers are ≥ 4.8 and < 4.8 cm diameter, respectively.

[b]Standard error of the mean.

[c]Significance level of the F-test from one-way ANOVA.

Table 28. 'Russet Burbank' potato grown in flats in chambers: effects of simulated sulfuric and sulfuric-nitric acid rain on sprout number and sprout and root dry weights

Treatment	Sprout number	Sprout dry wt.	Root dry wt.	Total dry wt.
		g		
Sulfuric acid rain				
5.6	137.0	26.53	47.18	73.72
4.0	183.0	43.98**	54.13	98.11
3.5	192.0	46.79**	57.96	104.75
3.0	146.0	35.04	49.88	84.92
S.E.[a]	16.4	2.78	4.76	6.38
F[b]	N.S.	*	N.S.	N.S.
Sulfuric-nitric acid rain				
5.6	193.0	48.61	49.62	98.23
4.0	198.0	49.63	53.39	103.02
3.5	171.5	42.23	53.08	95.31
3.0	180.5	48.68	62.89	111.57
S.E.	11.5	2.95	2.57	5.17
F	N.S.	N.S.	N.S.	N.S.

[a]Standard error of the mean.

[b]Significance level of the F-test from one-way ANOVA with * denoting $P \leq 0.05$.

**Symbols after the table values denote significant differences from control mean with $P \leq 0.01$ for two-sided t-test.

Alfalfa Studies

Materials and Methods

'Vernal' alfalfa was grown in pots in both chamber types as part of the general yield survey and in the ancillary fertility level experiments. The fertility level experiments were conducted to determine whether varying S and/or N fertilizer levels affected the response to acid rain. An unamended silty clay loam soil obtained from Berry Creek Ranch, Camp Adair, Oregon, was used. (This soil was different than that used in all other chamber experiments, and no peat moss was added to it.) Based on an historical response to S, this soil was considered to be S-deficient (T. Jackson, personal communication), and no S fertilizer had been added to this soil within the last three years. Pre-study characteristics of this soil are listed in Table 29.

Two factorial experiments were conducted, one for each rain type. For H_2SO_4 rain, only S was varied. S levels of 0 (low S, LS) and 78 (high S, HS) kg/ha were compared. For H_2SO_4-HNO_3 rain, both N and S were varied; either 0 or 78 kg/ha S and either 0 (low N, LN) or 34 (high N, HN) kg/ha N were added. Thus, HN x HS, HN x LS, LN x HS, and LN x LS treatments consisted of 34-78, 34-0, 0-78, and 0-0 kg/ha N-S fertilization rate regimes, respectively. All treatments were inoculated with Rhizobium meliloti at seeding using standard methods. The high N regime was used to ensure that adequate N was present during the initial period of Rhizobium establishment (i.e., before adequate nodulation had occurred). All treatments received P_2O_5-K_2O-B fertilization at the rate of 224-224-3 kg/ha and hydrated lime at 6.7 metric T/ha (24.7 grams/-pot). Average soil pH at the end of the study was 7.0 (Tables 30a and 30b). Urea, TSP, potassium chloride, calcium sulfate ($CaSO_4$), and boric acid fertilizer sources were used. Only the rates of urea and $CaSO_4$ were varied to provide the stated fertilization rate regimes. Irrigation with deionized water was provided according to individual pot needs. All other experimental conditions were the same as in the other chamber studies. Dates of seeding and first rain exposure were May 16 and July 1, respectively.

Top dry matter to a 7.6 centimeter stubble height was harvested at approximately 10 percent bloom stage on July 25, August 20, and September 24. Forage was separated into leaf plus petiole and stem fractions, and percent leafiness was calculated. Tissue was analyzed for quality components and elemental composition at the first two alfalfa harvests. After leaf and stem portions were recombined for this analysis, samples were combined on a chamber basis (i.e., top dry matter of all seven pots per chamber was combined into one composite sample, giving two samples per treatment pH per rain type) and ground to pass through a 0.5 millimeter screen. The HN x HS tissue samples were analyzed for concentrations of N, ADF, NDF, total S, and 10 other elements: K, P, Ca, Mg, Mn, Fe, Cu, B, Zn, and Al. The HN x LS, LN x HS, and LN x LS tissue samples were analyzed for N and S concentrations only. Thus, acid rain treatments could be compared for total N and S uptake at different fertility levels and for other forage quality components at HN x HS. Crude protein was calculated by multiplying N by 6.25. The Forage Analytical Service, Oregon State University, determined N, ADF, and NDF, and the Plant Analysis Laboratory, Oregon State University, determined total S and the 10 other elements using methods described previously.

Table 29. Pre-study characteristics of alfalfa experiment soil [a]

pH	Lime req.[b]	ppm P	ppm K	ppm B	ppm SO_4-S	ppm NO_3-N	ppm NH_4-N	% Total N	% OM	meq/100 g Ca	meq/100 g Mg	meq/100 g Na	meq/100 g CEC
5.5	6.3	17	215	0.20	3.49	1.8	4.85	0.19	2.81	4.4	1.7	0.07	14.0

[a] Mean values for Camp Adair S-deficient soil before fertilizer or lime additions are listed.
[b] SMP buffer test.

Table 30a. Study-end alfalfa experiment soil analysis results [a,b]

Treatment	Soil pH	Lime req.[c]	ppm			meq/100 g				%		ppm		% Free $CaCo_3$
			SO_4-S	P	K	Ca	Mg	Na	CEC	OM	Total N	NO_3-N	NH_4-N	
Sulfuric acid rain														
3.0	7.1	7.1	33.0	20	254	13.7	0.98	0.04	15.7	2.94	0.19	2.38	10.9	0.69
3.5	7.3	7.3	24.2	21	250	13.7	0.93	0.03	15.6	3.58	0.19	0.60	7.92	1.0
4.0	7.4	7.2	16.9	20	203	13.7	0.94	0.10	16.3	3.91	0.18	0.53	6.72	0.94
5.6	7.3	7.1	19.7	20	250	13.6	0.94	0.04	15.6	3.51	0.19	5.23	7.20	0.59
Sulfuric-nitric acid rain														
3.0	7.0	7.0	70.6	16	218	12.7	1.0	0.04	15.6	3.70	0.20	2.35	9.47	0.94
3.5	7.0	7.0	65.5	16	234	13.1	1.1	0.06	14.8	3.38	0.19	3.25	9.47	0.98
4.0	7.0	7.0	54.8	18	222	13.1	1.1	0.05	15.1	3.96	0.19	3.16	10.4	1.1
5.6	7.0	7.0	60.9	16	226	13.3	1.1	0.07	16.0	3.64	0.19	3.28	8.88	0.84

[a] Samples were composited on a treatment basis.

[b] Values shown are for high N-high S fertilization treatment.

[c] SMP buffer test.

Table 30b. Study-end alfalfa experiment soil analysis results[a]

Treatment		Soil pH	ppm SO_4-S	ppm NO_3-N	ppm NH_4-N
Sulfuric acid rain					
HNHS[b]	3.0	7.1	41.8	0.70	9.71
	3.0		37.6	0.70	9.59
	3.5	7.3	16.0	0.43	6.60
	3.5		20.4	0.60	8.16
	4.0	7.4	16.7	0.60	7.32
	4.0		17.2	0.45	7.68
	5.6	7.3	24.2	0.70	8.40
	5.6		18.1	0.53	7.92
HNLS	3.0	6.8	26.0	6.94	8.99
	3.0		15.8	3.11	9.83
	3.5	7.2	13.3	0.92	9.23
	3.5		12.4	0.89	9.11
	4.0	7.0	11.6	4.40	10.8
	4.0		11.7	7.47	8.28
	5.6	7.0	8.05	11.4	6.96
	5.6		8.18	5.49	11.1
Sulfuric-nitric acid rain					
HNHS	3.0	7.0	69.2	1.16	8.28
	3.0		58.8	0.53	7.80
	3.5	7.0	55.4	0.75	9.47
	3.5		44.1	0.53	8.52
	4.0	7.0	35.7	1.09	8.52
	4.0		40.3	2.48	12.7
	5.6	7.0	38.2	0.94	10.9
	5.6		57.1	0.67	10.9
HNLS	3.0	7.0	22.3	1.34	10.9
	3.0		27.1	3.78	10.5
	3.5	6.9		(missing sample)	
	3.5		12.3	1.22	8.59
	4.0	7.1	10.1	1.88	7.66
	4.0		9.77	1.02	10.5
	5.6	7.0	8.21	3.54	8.59
	5.6		10.1	1.48	8.81
LNHS	3.0	6.8	44.2	2.85	8.81
	3.0		43.5	2.43	7.85
	3.5	6.9	36.4	1.64	8.81
	3.5		39.4	1.71	14.1
	4.0	6.8	31.2	2.88	10.3
	4.0		27.4	3.57	10.3
	5.6	6.9	28.2	1.42	11.7
	5.6		39.6	1.26	8.33
LNLS	3.0	6.5	17.5	4.57	7.37
	3.0			(missing sample)	
	3.5	6.9	10.7	4.31	6.41
	3.5		10.5	3.85	8.81
	4.0	6.7	9.97	1.95	9.78
	4.0		7.83	1.32	14.2
	5.6	6.9	7.34	1.99	7.85
	5.6		7.65	1.52	8.33

[a] The pH values shown were obtained from soil samples which were composited on a treatment basis; all other values were obtained for soil composited on a chamber basis.

[b] Fertilizer group. HN = high nitrogen, HS = high sulfur, LN = low nitrogen, LS = low sulfur.

Results and Discussion

In the H_2SO_4 rain studies, there was no significant response of major growth parameters to acid rain treatment, regardless of S fertilization level (Tables 31 and 32). For instance, no response to acid rain occurred for total top dry weight or percent leafiness at any harvest or summed across harvests, for stubble, root, total dry weights, or shoot-to-root ratios. Mean total top dry weight summed across harvests and mean root dry weight were within 10 percent of the control for all H_2SO_4 rain treatments at both S fertilization levels.

In contrast to this lack of response to H_2SO_4 rain, S fertilization by itself had a clear effect on top growth (Table 32). More top growth occurred in the absence of S fertilization. Total top dry weight summed across harvests was 15 percent greater in the zero S treatment. Root and stubble growth, however, were not affected by S level. The decrease in top growth in response to S fertilization was unexpected and is unexplained.

In the four H_2SO_4-HNO_3 rain studies, acid rain treatment had no significant effect on important growth parameters, regardless of N or S fertilization levels (Tables 33 and 34). For example, total top dry weight summed across harvests was within 5 to 15 percent of the control in the acid rain treatments in all four studies. Mean total plant dry weight was within 10 percent of the control in acid rain treatments except for the low N-high S study.

Despite the lack of any statistically significant H_2SO_4-HNO_3 rain effects, several patterns were observed. Acid rain generally reduced root dry weight by 10 to 25 percent at the high S fertilization rate, independent of N level. In addition, while acid rain reduced total top dry weight summed across harvests in the low N-high S fertilization regime, it increased top growth in the high H-high S, high N-low S, and low N-low S fertilization regimes. Thus, while no significant pH x fertilization level interactions were found, results suggest that varying the ratio of S to N fertilization may affect plant response to acid rain.

As in the H_2SO_4 rain studies, the level of fertilization in the H_2SO_4-HNO_3 rain studies had a significant effect on growth, though treatment pH did not, and the response to one fertilizer depended on the level of the other. Increases S fertilization generally stimulated top growth at the high, but not the low, level of N. Similarly, high N fertilization increased top growth at high S but not at low S. For example, the addition of S produced a 14 percent increase in mean total top dry weight summed across harvests in the presence of N fertilizer but a 3 percent decrease in the absence of N. The addition of N resulted in a 12 percent increase in the high S study but a 4 percent decrease in the low S study. A similar pattern of response was seen for root dry weight, but greater increases (25-28 percent) and decreases (13-14 percent) occurred. These greater changes in root than top dry weight resulted in an 11 percent decrease in shoot-to-root ratio with the addition of either N or S in the presence of the other fertilizer. These N-S fertility level interactions were consistent with expected patterns of plant response to varying fertilization levels.

Effects of acid rain on indicators of alfalfa forage quality varied with rain type, harvest, and fertilization level. While H_2SO_4 rain treatment did not affect H1 S or N concentration, adding S fertilizer significantly reduced both (from 0.32 to 0.29 percent S and from 4.35 to 3.84 percent N) (Table 35). Total N and total S were also reduced by S fertilization. This would be expected, since S addition reduced top dry weight, as well as percent S.

At H2, percent S was significantly increased by H_2SO_4 rain at pH 3.0 under both fertilization regimes (Table 35). Relative to the control, the increase was greatest (0.08 percent) for the low S regime (from 0.26 to 0.34 percent S). Total S was also greater than the control at pH 3.0 (by 60 percent) in the low S study, primarily because of increased top dry weight. Despite the lack of a statistically significant pH-by-S fertilization interaction, this increase occurred only in the absence of S fertilization. Harvest Two percent N was not affected by either acid rain or S level. Total N at H2 was not affected by acid rain but decreased with S fertilization (-19 percent), reflecting the decrease in forage dry weight which occurred. The response seen in total S and total N of forage summed across harvests reflected H2 response, since forage dry weight was more than three times greater in H2 than in H1. The key finding was the significant increase in total S at pH 3.0 in the absence of S fertilization.

Treatment with H_2SO_4-HNO_3 rain did not significantly effect concentrations of S or N or total S and N uptake at either harvest, regardless of S or N fertilization level (Table 36). Though not statistically significant, a possible exception occurred in the high N-high S study. Acid rain treatment percent S exceeded the control by 0.03 to 0.07 percent in H1 and by 0.05 to 0.07 percent in H2, and total S was 17 to 48 percent greater than the control in H1 and 32 to 41 percent greater in H2.

Varying the rates of S and N fertilization did not affect percent S or N in H1 in the H_2SO_4-HNO_3 rain studies. However, S fertilization increased H1 total forage S and N content for the high N, but not the low N, fertilization regime. At H2, S fertilization increased percent S at high N (from 0.25 to 0.30 percent S) but reduced it at low N (from 0.32 to 0.29 present S). In addition, N fertilization reduced mean percent S in H2 (from 0.32 to 0.25 percent S) in the low S regime but had no effect in the presence of S. In contrast, the effects of S and N fertilization on percent N were independent of one another. Nitrogen fertilization increased percent N (by 0.18 percent on average), but S reduced percent N (by about 0.15 percent). Changes in H2 total S and N reflected fertilization effects on concentrations of S and N and top dry weight. For total S, the addition of either S or N produced significant increases if the other fertilizer was present but significant decreases if it was not. The addition of N fertilizer, however, increased total N with or without S (the increase was much greater with S). The effects on total S and N summed over both harvests were essentially the same as for H2 alone.

Few significant effects on the other indicators of forage quality were found (Table 37). At H1 tissue, P concentration increased at pH levels 4.0 and 3.5 in H_2SO_4-HNO_3 rain. While percent B decreased at pH 3.5 and 3.0 in H_2SO_4 rain, it increased at pH 4.0 in H_2SO_4-HNO_3 rain. At H2, no significant effects for ADF, NDF, or any of the 10 elements were found. In particular, there was no suggestion of any effect on either P or B. Since H1 was quite small (only about 2.5 g/pot top dry weight vs. 9-10 g/pot in Harvests Two and Three), more importance should be attached to H2 results which indicated the complete absence of acid rain effects on these indicators of forage quality.

Table 31. 'Vernal' alfalfa grown in SR chambers: effects of simulated sulfuric acid rain on dry matter production and percent leafiness at three harvests at two sulfur fertilization levels [a]

Treatment	Harvest 1				Harvest 2				Harvest 3			
	Total top	Leaf	Stem	% Leaf	Total top	Leaf	Stem	% Leaf	Total top	Leaf	Stem	% Leaf
	g				g				g			
High N - High S												
5.6	1.84	1.27	0.57	69.9	7.35	4.26	3.09	58.5	9.11	6.12	2.99	68.0
4.0	1.54	1.15	0.39	75.5	7.73	4.52	3.20	59.2	9.41	6.44	2.98	69.0
3.5	1.86	1.34	0.52	73.1	8.20	4.87	3.33	59.5	9.50	6.66	2.83	70.6
3.0	1.67	1.18	0.48	72.1	7.20	4.38	2.82	60.9	9.85	6.93	2.92	70.6
$\bar{X}$	1.73	1.24	0.49	72.7	7.62	4.51	3.11	59.5	9.47	6.54	2.93	69.5
High N - Low S												
5.6	2.07	1.40	0.67	68.2	9.10	5.11	3.98	56.8	10.01	6.81	3.20	68.4
4.0	2.15	1.47	0.68	69.6	9.51	5.50	4.02	58.0	8.99	6.10	2.89	68.5
3.5	1.99	1.39	0.60	70.3	9.99	5.69	4.30	57.0	9.37	6.45	2.92	69.7
3.0	2.36	1.62	0.74	69.6	11.13	6.51	4.62	58.7	9.88	6.75	3.14	68.7
$\bar{X}$	2.14	1.47	0.67	69.4	9.93	5.70	4.23	57.6	9.56	6.53	3.04	68.8
S.E.[b]	0.18	0.12	0.07	1.4	0.54	0.30	0.28	1.4	0.66	0.41	0.28	1.2
pH-F[c]	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
S-F	**	**	**	**	**	**	**	NS	NS	NS	NS	NS
pHxS-F	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS

[a] Fertilizer rates used for high N - high S and high N - low S treatments were 34-78 and 34-0 kg/ha N-S, respectively. Harvest dates were July 25 (H1), August 20 (H2), and September 24 (H3).

[b] Standard error of the mean for pH treatment at one fertilization level. Divide by two to get standard error of the mean for fertilization level averaged across pH treatments.

[c] Significance level of the F-tests for pH, S, and pH-S interaction effects from two-way ANOVA with ** denoting $P \leq 0.01$.

Table 32. 'Vernal' alfalfa grown in SR chambers: effects of simulated sulfuric acid rain on dry matter production, percent leafiness, shoot-to-root ratio (S:R), stem number and yield per stem at final harvest, and nodule number at two sulfur fertilization levels [a]

Treatment	All harvests: Total top	All harvests: Leaf	All harvests: Stem	All harvests: % Leaf	Stubble	Root	Total dry wt.	S:R	Yield/ stem (H3)	Number: Stem (H3)	Number: Nodule
	g	g	g		g	g	g		mg		
High N - High S											
5.6	18.30	11.65	6.65	64.3	4.61	13.81	36.72	1.72	160.8	58.1	103.9
4.0	18.68	12.11	6.57	65.3	4.27	14.97	37.93	1.59	149.2	65.8	113.6
3.5	19.57	12.88	6.69	65.9	4.64	14.25	38.46	1.78	168.1	57.4	65.7
3.0	18.90	12.61	6.22	66.6	4.39	13.91	37.41	1.69	147.5	68.1	89.8
$\overline{X}$	18.86	12.31	6.53	65.5	4.48	14.23	37.64	1.69	156.4	62.3	93.2
High N - Low S											
5.6	21.18	13.32	7.86	63.2	4.85	13.73	39.75	2.06	151.9	66.4	
4.0	20.65	13.07	7.59	63.5	4.49	14.14	39.28	1.93	144.8	61.7	
3.5	21.36	13.54	7.82	63.5	4.48	13.55	39.39	2.02	176.1	54.3	
3.0	23.37	14.88	8.49	63.8	4.63	13.11	41.11	2.22	174.7	58.2	
$\overline{X}$	21.64	13.70	7.49	63.5	4.61	13.63	39.88	2.06	161.9	60.1	
S.E.[b]	1.17	0.71	0.52	1.1	0.24	1.16	2.34	0.11	11.9	2.8	15.1
pH-F[c]	NS	NS	NS	NS	NS	NS	NS	NS	NS	*	NS
S-F	**	**	**	**	NS	NS	NS	**	NS	NS	
pHxS-F	NS	NS	NS	NS	NS	NS	NS	NS	NS	**	

[a]Fertilizer rates used for high N-high S and high N-low S treatments were 34-78 and 34-0 kg/ha N-S, respectively.

[b]Standard error of the mean for pH treatment at one fertilization level. Divide by two to get standard error of the mean for fertilization level averaged across pH treatments.

[c]Significance level of the F-tests for pH, S, and pH-S interaction effects from two-way ANOVA with * and ** denoting P $\leq$ 0.05 and 0.01, respectively.

Table 33. 'Vernal' alfalfa grown in LR chambers: effects of simulated sulfuric-nitric acid rain on dry matter production and percent leafiness at three harvests at different nitrogen (N) and sulfur (S) fertilization levels [a]

Treatment	Harvest 1 Total top	Harvest 1 Leaf	Harvest 1 Stem	Harvest 1 % Leaf	Harvest 2 Total top	Harvest 2 Leaf	Harvest 2 Stem	Harvest 2 % Leaf	Harvest 3 Total top	Harvest 3 Leaf	Harvest 3 Stem	Harvest 3 % Leaf
	g	g	g		g	g	g		g	g	g	
High N - High S												
5.6	2.32	1.57	0.76	69.0	9.69	5.83	3.86	60.1	11.04	7.21	3.83	65.6
4.0	2.80	1.84	0.96	67.3	10.87	6.32	4.55	58.7	11.73	7.69	4.03	66.4
3.5	2.27	1.51	0.76	69.0	10.79	6.13	4.66	57.2	10.13	6.54	3.59	65.1
3.0	2.52	1.68	0.84	68.1	10.88	6.43	4.45	59.3	10.88	7.16	3.71	66.0
$\bar{X}$	2.48	1.65	0.83	68.3	10.56	6.18	4.38	58.8	10.94	7.15	3.79	65.8
High N - Low S												
5.6	1.67	1.18	0.49	72.3	8.51	5.26	3.26	61.9	9.30	6.18	3.13	66.4
4.0	2.25	1.55	0.69	70.2	9.90	5.70	4.20	57.8	10.49	6.68	3.82	64.7
3.5	2.04	1.43	0.63	71.4	9.32	5.53	3.80	59.4	10.07	6.26	3.80	62.5
3.0	1.79	1.28	0.51	72.9	9.45	5.71	3.75	60.7	10.07	6.72	3.35	67.1
$\bar{X}$	1.94	1.36	0.58	71.7	9.29	5.55	3.74	60.0	9.98	6.46	3.53	65.2
Low N - High S												
5.6	2.74	1.86	0.89	69.0	8.94	5.18	3.76	57.9	11.40	7.39	4.01	65.0
4.0	2.50	1.68	0.81	68.4	7.94	4.71	3.23	59.0	9.80	6.40	3.39	65.1
3.5	2.59	1.73	0.86	67.8	8.25	4.97	3.29	60.1	11.25	7.26	3.99	65.2
3.0	2.09	1.46	0.63	70.8	8.25	4.93	3.32	60.4	9.84	6.41	3.43	65.6
$\bar{X}$	2.48	1.68	0.80	69.0	8.35	4.95	3.40	59.4	10.57	6.86	3.71	65.2
Low N - Low S												
5.6	2.80	1.80	1.00	66.7	8.52	4.77	3.75	56.1	9.52	6.32	3.19	66.7
4.0	2.87	1.89	0.98	67.1	9.10	5.36	3.74	58.9	10.94	7.14	3.80	66.0
3.5	2.89	1.93	0.96	67.6	8.98	5.29	3.69	59.2	10.04	6.65	3.38	67.7
3.0	2.88	1.89	0.96	66.5	9.34	5.45	3.89	58.5	9.74	6.62	3.12	68.6
$\bar{X}$	2.86	1.88	0.97	67.0	8.98	5.22	3.77	58.2	10.06	6.68	3.37	67.3
S.E.[b]	0.25	0.14	0.11	1.5	0.47	0.27	0.25	1.2	0.72	0.43	0.34	1.4
pH-F[c]	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
N-F	**	**	**	**	**	**	**	NS	NS	NS	NS	NS
S-F	NS	NS	NS	NS	NS	NS	NS	NS	*	*	NS	NS
NxS-F	**	**	**	**	**	**	**	*	NS	NS	NS	NS
pH xFert-F	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS

[a] Fertilizer rates used for high N-high S, high N-low S, low N-high S, and low N-low S treatments were 34-78, 34-0, 0-78, and 0-0 kg/ha N-S, respectively. Harvest dates were July 25 (H1), August 20 (H2), and September 24 (H3).

[b] Standard error of the mean for pH treatment at one fertilization level. Divide by two to get standard error of the mean for fertilization level averaged across pH treatments.

[c] Significance level of the F-tests for pH, N, S, NxS interaction, and pH x fertilizer level interaction effects from three-way ANOVA with * and ** denoting $P \leq 0.05$ and 0.01, respectively. The pH x fertilizer F value tests if response to pH was the same for all four

Table 34. 'Vernal' alfalfa grown in LR chambers: effects of simulated sulfuric-nitric acid rain on dry matter production, percent leafiness, shoot-to-root ratio (S:R), stem number and yield per stem at final harvest, and nodule number at different nitrogen (N) and sulfur (S) fertilization levels

Treatment	All harvests: Total top	leaf	Stem	% Leaf	Stubble	Root	Total dry wt.	S:R	Yield/ stem (H3)	Number: Stem (H3)	Nodule
	g				g				mg		
High N - High S[a]											
5.6	22.74	14.45	8.45	63.7	4.89	18.48	45.53	1.57	199.3	57.9	85.4
4.0	25.39	15.86	9.54	62.9	4.91	16.55	46.86	1.89	211.3	57.7	105.4
3.5	23.20	14.18	9.02	61.6	4.82	15.05	43.07	2.00	197.8	52.2	66.8
3.0	24.26	15.26	9.00	63.0	4.87	15.23	44.36	1.97	189.2	59.6	82.9
$\bar{X}$	23.94	14.95	9.00	62.8	4.87	16.33	44.93	1.87	199.4	56.9	85.1
High N - Low S											
5.6	19.48	12.61	6.87	64.6	4.52	12.64	36.65	2.08	184.8	52.4	
4.0	22.25	13.72	8.53	62.1	4.45	12.77	38.87	2.23	182.6	58.4	
3.5	21.10	13.09	8.23	62.0	4.52	12.65	38.41	2.04	195.1	52.0	
3.0	21.32	13.71	7.61	64.4	4.66	12.94	38.92	2.09	133.8	77.8	
$\bar{X}$	21.02	13.28	7.80	63.3	4.54	12.75	38.20	2.11	174.1	60.1	
Low N - High S											
5.6	23.08	14.42	8.66	62.4	5.14	14.46	42.68	2.04	196.9	60.0	
4.0	19.85	12.58	7.27	63.1	3.94	10.76	34.13	2.45	185.2	53.1	
3.5	22.09	13.96	8.14	63.3	4.43	14.57	41.10	1.91	204.7	55.8	
3.0	20.18	12.80	7.38	63.5	4.29	12.51	36.98	2.09	161.9	60.6	
$\bar{X}$	21.33	13.45	7.87	63.1	4.45	13.08	38.81	2.11	187.2	57.4	
Low N - Low S											
5.6	20.84	12.89	7.95	61.8	4.71	14.31	39.86	1.89	156.3	61.2	
4.0	22.91	14.39	8.52	63.1	4.73	15.87	43.51	1.87	188.8	59.1	
3.5	21.90	13.87	8.03	63.9	5.28	14.22	41.41	2.03	171.7	58.6	
3.0	22.31	14.20	7.97	63.6	5.11	15.09	42.87	1.95	151.0	64.9	
$\bar{X}$	21.98	13.83	8.12	63.1	4.96	14.87	41.89	1.93	167.0	60.9	
S.E.[b]	1.12	0.69	0.53	1.0	0.32	1.13	2.26	0.13	14.6	3.0	11.6
pH-F[c]	NS	NS	NS	NS	NS	NS	NS	NS	**	**	NS
N-F	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	
S-F	*	NS	NS	NS	NS	NS	NS	NS	**	*	
NxS-F	**	**	**	NS	**	**	**	**	NS	NS	
pHxFert-F	NS	NS	NS	NS	NS	NS	NS	*	NS	NS	

[a]Fertilizer rates used for high N-high S, high N-low S, low N-high S, and low N-low S treatments were 34-78, 34-0, 0-78, and 0-0 kg/ha N-S, respectively.

[b]Standard error of the mean for pH treatment at one fertilization level. Divide by two to get standard error of the mean for fertilizer levels averaged across pH treatments.

[c]Significance level of the F-tests for pH, N, S, NxS interaction, and pH x fertilizer level interaction effects from three-way ANOVA with * and ** denoting $P \leq 0.05$ and 0.01, respectively. The pH x fertilizer F-value tests if response to pH was the same for all four fertilization regimes. Numerator degrees of freedom for F-tests are 3, 1, 1, 1, and 9, respectively.

Table 35. 'Vernal' alfalfa grown in SR chambers at two sulfur fertilization levels: effects of simulated sulfuric acid rain on total nitrogen (N) and sulfur (S) uptake and concentrations of N, S, and crude protein (CP) at two harvests [a]

Treatment	Harvest 1					Harvest 2					H1 + H2	
	Total N	Total S	N	S	CP	Total N	Total S	N	S	CP	Total N	Total S
	mg		%			mg		%			mg	
High N - high S[b]												
5.6	69.4	5.5	3.74	0.30	23.37	232.0	22.5	3.17	0.30	19.79	301.4	28.0
4.0	59.3	4.5	3.86	0.29	24.10	231.3	22.3	3.02	0.29	18.85	290.6	26.8
3.5	68.8	5.2	3.70	0.28	23.11	234.6	25.5	2.86	0.31	17.86	303.5	30.7
3.0	68.5	5.2	4.07	0.31	25.41	215.8	25.2	3.00	0.35*	18.73	284.3	30.4
$\overline{x}$	66.5	5.1	3.84	0.29	24.00	228.4	23.9	3.01	0.31	18.81	295.0	29.0
High N - low S												
5.6	89.7	6.9	4.34	0.33	27.14	268.5	23.6	2.96	0.26	18.50	358.2	30.5
4.0	93.1	7.5	4.35	0.35	27.18	295.1	26.2	3.10	0.27	19.38	388.2	33.7
3.5	84.9	5.6	4.26	0.28	26.61	272.8	29.5	2.73	0.29	17.04	357.7	35.1
3.0	105.4	7.3	4.47	0.31	27.94	296.6	37.8*	2.66	0.34*	16.65	401.9	45.0*
$\overline{x}$	93.2	6.8	4.35	0.32	27.22	283.3	29.3	2.86	0.29	17.89	376.5	36.1
S.E.[c]	12.0	0.8	0.11	0.01	0.67	14.0	2.2	0.16	0.02	0.98	22.4	2.1
pH-F[d]	N.S.	N.S.	N.S.	N.S.	N.S.	N.S.	*	N.S.	*	N.S.	N.S.	*
S-F	**	**	**	*	**	**	**	N.S.	N.S.	N.S.	**	**
pHxS-F	N.S.	N.S.	N.S.	N.S.	N.S.	N.S.	N.S.	N.S.	N.S.	N.S.	N.S.	N.S.

[a]Concentrations of N, S, and CP are expressed on a dry-weight basis. Harvest dates were July 25 (H1) and August 20 (H2).

[b]Fertilizer rates used for high N - high S and high N - low S treatments were 34-78 and 34-0 kg/ha N-S, respectively.

[c]Standard error of the mean for pH treatment at one fertilization level. Divide by two to get standard error of the mean for fertilization level averaged across pH treatments.

[d]Significance level of the F-tests for pH, S, and pH-S interaction effects from two-way ANOVA with * and ** denoting P $\leq$ 0.05 and 0.01, respectively.

Table 36. 'Vernal' alfalfa grown in LR chambers at different nitrogen (N) and sulfur (S) fertilization levels: effects of simulated sulfuric-nitric acid rain on total N and S uptake and concentrations of N, S, and crude protein (CP) at two harvests [a]

Treatment	Harvest 1 Total N	Total S	N	S	CP	Harvest 2 Total N	Total S	N	S	CP	H1 + H2 Total N	Total S
	mg	mg	%	%	%	mg	mg	%	%	%	mg	mg
High N - high S												
5.6	101.6	6.0	4.32	0.25	26.98	290.5	25.6	3.00	0.26	18.76	392.1	31.6
4.0	123.9	8.9	4.45	0.32	27.79	294.6	33.7	2.71	0.31	16.94	418.6	42.6
3.5	94.3	7.4	4.17	0.32	26.06	319.1	36.2	2.95	0.33	18.45	413.4	43.7
3.0	111.1	7.0	4.38	0.28	27.39	309.3	34.0	2.85	0.31	17.79	420.4	41.0
$\bar{x}$	107.7	7.3	4.33	0.29	27.06	303.4	32.4	2.88	0.30	17.99	411.1	39.7
High N - low S												
5.6	70.0	5.1	4.22	0.31	26.37	267.2	19.0	3.15	0.22	19.71	337.2	24.1
4.0	100.2	6.7	4.45	0.30	27.83	292.4	25.8	2.95	0.26	18.44	392.7	32.6
3.5	82.2	5.9	4.10	0.29	25.65	279.7	23.2	3.00	0.25	18.74	361.8	29.2
3.0	77.7	5.8	4.32	0.32	27.02	306.2	24.2	3.25	0.25	20.31	382.9	30.0
$\bar{x}$	82.5	5.9	4.27	0.31	26.72	286.4	23.1	3.09	0.25	19.30	368.9	29.0
Low N - high S												
5.6	115.6	8.5	4.24	0.31	26.48	246.0	25.9	2.75	0.29	17.19	361.5	34.4
4.0	105.5	7.1	4.23	0.28	26.42	222.1	22.2	2.79	0.28	17.43	327.5	29.3
3.5	107.0	8.0	4.13	0.31	25.83	225.0	24.7	2.75	0.30	17.18	332.0	32.7
3.0	92.0	6.3	4.41	0.30	27.58	229.6	23.5	2.78	0.28	17.40	321.6	29.8
$\bar{x}$	105.0	7.5	4.25	0.30	26.58	230.7	24.1	2.77	0.29	17.30	335.7	31.6
Low N - low S												
5.6	119.9	8.2	4.00	0.30	25.02	255.2	26.0	2.99	0.30	18.72	365.7	34.2
4.0	123.4	8.9	4.37	0.31	27.28	263.0	27.8	2.89	0.30	18.04	388.3	36.7
3.5	120.5	8.8	4.22	0.30	26.36	240.0	25.5	2.67	0.28	16.67	360.5	34.3
3.0	125.3	9.0	4.29	0.31	26.81	270.9	35.8	2.90	0.38	18.13	394.3	44.9
$\bar{x}$	110.5	8.7	4.22	0.31	26.37	257.3	28.8	2.86	0.32	17.89	377.2	37.5
S.E.[c]	10.7	0.8	0.17	0.02	1.07	12.2	2.9	0.14	0.03	0.84	22.4	2.9
pH-F[d]	N.S.	N.S.	N.S.	N.S.	N.S.	N.S.	N.S.	N.S.	N.S.	N.S.	N.S.	N.S.
N-F	**	**	N.S.	N.S.	N.S.	**	N.S.	*	N.S.	*	**	N.S.
S-F	N.S.	N.S.	N.S.	N.S.	N.S.	N.S.	N.S.	*	N.S.	*	N.S.	N.S.
NxS-F	**	**	N.S.	N.S.	N.S.	**	**	N.S.	**	N.S.	**	**
pHxFert-F	N.S.	N.S.	N.S.	N.S.	N.S.	N.S.	N.S.	N.S.	N.S.	N.S.	N.S.	N.S.

[a]Concentrations of N, S, and CP are expressed on a dry weight basis. Harvest dates were July 25 (H1) and August 20 (H2).

[b]Fertilizer rates used for high N-high S, high N-low S, low N-high S, and low N-low S treatments were 34-78, 34-0, 0-78, and 0-0 Kg/ha N-S, respectively.

[c]Standard error of the mean for pH treatment at one fertilization level. Divide by two to get standard error of a mean for fertilization level averaged across pH treatments.

[d]Significance level of the F-tests for pH, N, S, N-S interaction, and pHxfertilizer interaction effects from three-way ANOVA with * and ** denoting $P \leq 0.05$ and 0.01, respectively. The pHxfertilizer F-value tests if response to pH was the same for all four fertilization regimes. Numerator degrees of freedom for F-tests are 3, 1, 1, 1, and 9, respectively.

Table 37. 'Vernal' alfalfa grown in chambers at high N-high S: effects of simulated sulfuric and sulfuric-nitric acid rain on total N and S uptake and concentrations of N, S, crude protein (CP), acid detergent fiber (ADF), neutral detergent fiber (NDF), and 10 mineral elements at two harvests [a]

Treatment	Total N	Total S	N	S	CP	ADF	NDF	P	K	Ca	Mg	Mn	Fe	Cu	B	Zn	Al
	mg		%									ppm					
Harvest 1																	
Sulfuric acid rain																	
5.6	69.4	5.5	3.74	0.30	23.37	18.64	22.97	0.23	2.58	- [d]	0.28	117	138	6	97	24	104
4.0	59.3	4.5	3.86	0.29	24.10	17.15	21.60	0.20	2.48	-	0.29	108	136	5	92	20	107
3.5	68.8	5.2	3.70	0.28	23.11	17.40	21.71	0.21	2.32	2.43	0.27	109	137	6	70**	19	99
3.0	68.5	5.2	4.07	0.31	25.41	15.65	18.48	0.22	2.40	2.41	0.27	129	156	7	80**	19	106
x̄	66.5	5.1	3.84	0.29	24.00	17.21	21.19	0.22	2.45	-	0.28	116	142	6	85	21	104
Sulfuric-nitric acid rain																	
5.6	101.6	6.0	4.32	0.25	26.98	19.09	23.67	0.25	2.29	2.37	0.27	81	168	5	51	17	99
4.0	123.9	8.9	4.45	0.32**	27.79	18.82	22.27	0.35**	2.81	2.53	0.24	100	171	7	73*	25	78
3.5	94.3	7.4	4.17	0.32**	26.06	17.95	22.45	0.32*	2.51	2.59	0.22	89	202	5	60	24	133
3.0	111.1	7.0	4.38	0.28	27.39	17.25	22.38	0.27	2.35	2.34	0.28	86	161	4	57	19	95
x̄	107.7	7.3	4.33	0.29	27.06	18.28	22.69	0.30	2.49	2.46	0.25	89	175	5	60	22	101
S.E. [b]	11.9	0.8	0.16	0.01	0.98	1.25	1.03	0.02	0.15	0.10	0.02	7	35	1	3	3	29
pH-F for sulfuric [c]	NS	NS	NS	NS	NS	NS	NS	NS	NS	-	NS	NS	NS	NS	**	NS	NS
pH-F for sul.-nitric	NS	NS	NS	*	NS	NS	NS	**	NS	NS	NS	NS	NS	NS	**	NS	NS
Harvest 2																	
Sulfuric acid rain																	
5.6	232.0	22.5	3.17	0.30	19.79	23.15	28.93	0.30	2.62	2.16	0.21	77	120	5	53	10	82
4.0	231.3	22.3	3.02	0.29	18.85	22.32	28.33	0.27	2.50	2.13	0.20	75	134	5	60	8	90
3.5	234.6	25.5	2.86	0.31	17.86	22.74	28.54	0.24	2.13	1.79	0.20	62	191	4	48	6	206
3.0	215.8	25.2	3.00	0.35	18.73	22.29	27.76	0.28	2.51	2.21	0.21	77	131	6	64	11	89
x̄	228.4	23.9	3.01	0.31	18.81	22.63	28.39	0.27	2.44	2.07	0.21	73	144	5	56	9	117
Sulfuric-nitric acid rain																	
5.6	290.5	25.6	3.00	0.26	18.76	21.07	27.88	0.25	2.18	2.23	0.18	69	124	4	48	18	108
4.0	294.6	33.7	2.71	0.31	16.94	21.90	29.25	0.25	2.18	2.37	0.19	51	99	2	49	17	96
3.5	319.1	36.2	2.95	0.33	18.45	22.61	30.03	0.27	2.20	2.18	0.16	58	226	4	44	19	255
3.0	309.3	34.0	2.85	0.31	17.79	20.77	28.72	0.29	2.41	2.60	0.16	61	146	4	55	23	138
x̄	303.4	32.4	2.88	0.30	17.99	21.59	28.97	0.27	2.24	2.35	0.17	60	149	4	49	19	150
S.E.	13.0	3.6	0.11	0.03	0.67	1.06	1.15	0.03	0.16	0.21	0.02	5	50	1	8	2	74
pH-F for sulfuric	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
pH-F for sul.-nitric	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS

[a] Concentrations are expressed on a dry-weight basis. The high N-high S fertilizer rate was 34-78 kg/ha N-S. Harvest dates were July 25 (H1) and August 20 (H2).

[b] Standard error of the mean of one pH for one rain type (sample size = 2).

[c] Significance levels of the F-tests from one-way analyses of variance, one for sulfuric and one for sulfuric-nitric acid rain, with * and ** denoting $P \leq 0.05$ nad 0.01, respectively. At each harvest, a pooled estimate of error with 8 d.f. was used in the F-tests.

[d] Means and F-test could not be computed since all data were missing.

*,**Symbols after table values denote significant differences from control means with $P \leq 0.05$ and 0.01, respectively, for two-sided t-test.

RADISH RHIZOCYLINDER pH EXPERIMENTS

The radish rhizocylinder pH experiments were conducted to determine whether acidic rain simulants affected the pH of either bulk soil or rhizocylinder samples. Evidence of significantly reduced pH would support the hypothesis that previously observed dramatic reductions in root growth at low rain treatment pH arose through direct effects on root growth, rather than indirect effects relating to carbohydrate supply from the radish plant top.

Bulk soil and rhizocylinder pH were measured for radish grown at pH levels 3.0 and 5.6 (control) in both rain types and in both the chamber and field studies. Samples were collected during harvests of the studies, and the pH of 1:2 ratios of sample: 0.01 M $CaCl_2$ suspensions was measured. Suspensions were stirred intermittently for at least one hour before measurement and during measurement (Smiley and Cook, 1972).

Rhizocylinder samples were obtained by cutting tap roots off harvested main roots at the point of greatest curvature and gently shaking these tap roots to remove all but strongly-adhering soil ($\leq$ two millimeters from the root surface); fibrous roots plus strongly-adhering soil were then cut from the tap roots and comprised the rhizocylinder sample. Bulk soil samples consisted of soil five centimeters distance from the harvested root portions. The pH of four rhizocylinder and bulk soil samples per pH level and rain type was compared by sampling two randomly selected pots in each of the two chambers per treatment pH in the chamber studies (samples were composites of the two plants per pot) and composite sampling two randomly selected plants in each of the four blocks per treatment pH in the field studies.

Rhizocylinder pH of radish was not affected by acid rain treatment in either the chamber or field studies (the one significant difference found was a statistical artifact caused by a much smaller than average standard error) (Table 38). Consequently, an hypothesized direct effect of acid rain on root growth (through reduced rhizosphere pH, concomitant increased Al and/or Mn availability, and resultant toxicity) is not supported by this study. Instead, one might suggest that the significant reductions in root growth which were found (Table 21) occurred as a secondary effect of acid rain on top growth. Reduced root growth may have resulted from a restriction of carbohydrate supply from the plant top as might occur if acid rain treatment were to adversely affect production of carbohydrate in leaves and/or its translocation to the root.

Table 38. 'Cherry Belle' radish grown in chambers and in the field: effects of sulfuric and sulfuric-nitric acid rain on rhizocylinder and bulk soil pH [a]

Treatment	Rhizocylinder pH	Bulk soil pH
Chamber sulfuric acid rain		
5.6	7.74	7.73
3.0	7.60**	7.73
S.E.	0.02	0.02
Chamber sulfuric-nitric acid rain		
5.6	7.72	7.78
3.0	7.76	7.75
S.E.	0.07	0.05
Field sulfuric acid rain		
5.6	5.91	5.64
3.0	5.79	5.65
S.E.	0.13	0.13
Field sulfuric-nitric acid rain		
5.6	5.69	5.65
3.0	5.80	5.72
S.E.	0.13	0.14

[a]Measurements of pH were made of 1:2 sample:0.01 M $CaCl_2$ suspensions.

**Significantly different from the control (pH 5.6) at $P \leq 0.01$ according to the two-sided t-test.

FOLIAR INJURY

Leaves, and other plant parts, were examined regularly for injury throughout the growing season. When injury from acid rain exposure was suspected, care was taken to make sure that the observed injury was not present on plants grown in control treatments and was not a result of insect or disease damage. The extent of foliar injury was evaluated several times during each crop's growth by estimating the percent leaf area covered by acid rain lesions. Lesions were also described with respect to predominant coloration, shape, size, tissue dryness and/or pitting, and localization of injury, e.g., along veins, between veins, or near leaf margins. Also noted were whether markings extended all the way through leaves, extent of injury varied with leaf age, markings occurred on other plant parts, and any plant parts were distorted in shape. (Foliar injury descriptions for each crop are presented in Appendix II.)

Of the 18 crops studied, only two showed no foliar injury caused by acid rain treatment at any time during their growth (lettuce and onion). All other crops exhibited at least some injury at some time during growth in at least one study. However, the extent of injury generally was very slight, i.e., 1 percent or less leaf area affected, and injury for most crops occurred only in the lower pH treatments, i.e., 3.0 and 3.5 (Table 39). In general, the nature of foliar injury did not differ with rain type (H_2SO_4 versus H_2SO_4-HNO_3). When present on both field- and chamber-grown plants, injury showed similar characteristics. Of the five crops which were grown both in the field and in chambers, two exhibited foliar injury in both growth environments (alfalfa and spinach). Interestingly, however, the severity of injury was much less pronounced for field-grown plants. This suggests that chamber growth may exaggerate acid rain foliar injury. The acid rain pH level(s) at which injury was observed varied with crop species, rain type, and chamber versus field growth (Table 39). For most crops, foliar injury consisted of generally round, white lesions less than 2 millimeters in diameter. Lesions appeared dry and pitted and extended all the way through leaves to the opposite leaf surface but were not localized anywhere on leaves.

Table 39. Percent foliar injury caused by simulated sulfuric acid (H_2SO_4) and sulfuric-nitric acid (H_2SO_4-HNO_3) rain treatment of 1980 survey crops grown in chambers (C) or in the field (F)[a]

Crop - Study			No. of ratings	pH	Range in mean foliar injury	Mean foliar injury at harvest
(C) Alfalfa	- H_2SO_4	HNHS	5	3.0	0-1.0	0.4 (H1), 1.0 (H2), 0.9 (H3)
		HNLS	5	3.0	0-1.0	0.4 (H1), 1.0 (H2), 0.9 (H3)
	- H_2SO_4-HNO_3	HNHS	5	3.0	0-1.0	0.4 (H1), 1.0 (H2), 0.9 (H3)
		HNLS	5	3.0	0-0.9	0.4 (H1), 0.9 (H2), 0.9 (H3)
		LNHS	5	3.0	0-1.0	0.5 (H1), 0.9 (H2), 1.0 (H3)
		LNLS	5	3.0	0-0.9	0.4 (H1), 0.8 (H2), 0.9 (H3)
(F) Alfalfa	- H_2SO_4		3	3.0	0-0.8	0.8 (H1), 0 (H2)
				4.0	0-0.3	0.3 (H1), 0 (H2)
	- H_2SO_4-HNO_3		3	-	0	0
Barley	- H_2SO_4		6	3.0	0-1.0	1.0
	- H_2SO_4-HNO_3		6	3.0	0-1.0	1.0
Beet	- H_2SO_4-HNO_3		4	3.0	1.0-3.6	1.2
				3.5	0-0.9	0
				4.0	0-0.2	0
Cabbage	- H_2SO_4-HNO_3		6	3.0	0-1.0	1.0
Carrot	- H_2SO_4-HNO_3		3	3.0	0.4-0.6	0.6
Clover	- H_2SO_4-HNO_3		7	3.0	0-1.0	0.4 (H1), 0.9 (H2), 1.0 (H3)
				3.5	0-0.2	0
(F) Corn	- H_2SO_4-HNO_3		6	3.0	0-1.0	0
(C) Tall fescue	- H_2SO_4		6	3.0	0-1.0	1.0 (H1), 1.0 (H2), 1.0 (H3)
				3.5	0-0.2	0.2 (H2)
	- H_2SO_4-HNO_3		6	3.0	0-1.0	1.0 (H1), 1.0 (H2), 1.0 (H3)
				3.5	0-0.4	0.4 (H2)
(F) Tall fescue	- H_2SO_4		3	-	0	0
	- H_2SO_4-HNO_3		3	-	0	0
Lettuce	- H_2SO_4		4	-	0	0
	- H_2SO_4-HNO_3		4	-	0	0
(C) Mustard greens	- H_2SO_4		3	3.0	1.0-18.5[b]	1.0
				3.5	0.4- 2.4[b]	0.4
	- H_2SO_4-HNO_3		3	3.0	1.0-24.6[b]	1.0
				3.5	0.7- 3.6[b]	0.7
				4.0	0- 4.1[b]	0
(F) Mustard greens	- H_2SO_4		4	-	0	0
	- H_2SO_4-HNO_3		4	-	0	0
Onion	- H_2SO_4-HNO_3		7	-	0	0
Orchardgrass	- H_2SO_4		3	3.0	0-1.0	1.0
				3.5	0-0.1	0.1
	- H_2SO_4-HNO_3		3	3.0	0-1.0	0
Pea	- H_2SO_4-HNO_3		4	3.0	1.0	1.0
				3.5	0-0.9	0.9
Potato	- H_2SO_4		5	3.0	0-1.0	1.0
	- H_2SO_4-HNO_3		5	3.0	0-1.0	1.0
(C) Radish	- H_2SO_4		4	3.0	1.4- 8.1[b]	1.9
				3.5	0.3- 0.8	0.8
	- H_2SO_4-HNO_3		4	3.0	1.0-17.0[b]	2.7
				3.5	0.6- 1.0	0.9
(F) Radish	- H_2SO_4		3	-	0	0
	- H_2SO_4-HNO_3		3	-	0	0

Table 39. (continued)

Crop - Study		No. of ratings	pH	Range in mean foliar injury	Mean foliar injury at harvest
(C) Spinach	- H_2SO_4	3	3.0	2.2-5.7[b]	2.8
			3.5	0.1-0.9	0.9
	- H_2SO_4-HNO_3	3	3.0	1.7-3.5	3.5
			3.5	0-1.0	0.9
			4.0	0-0.4	0.3
(F) Spinach	- H_2SO_4	3	3.0	0.8-1.0	1.0
	- H_2SO_4-HNO_3	3	3.0	0-0.8	0
Tomato	- H_2SO_4	7	3.0	1.0-1.8	1.0
			3.5	0-0.3	0
	- H_2SO_4-HNO_3	7	3.0	1.0-3.5	1.0
			3.5	0-1.0	0.6
Wheat	- H_2SO_4-HNO_3	6	3.0	0-1.0	1.0

[a] Estimates of leaf area injured by acid rain were made by assigning each pot or plot to one of 13 injury intervals (i.e., interval 0 = 0% leaf area injured, 1 = >0-2, 2 = 2-5, 3 = 5-10, 4 = 10-20, 5 = 20-35, 6 = 35-65, 7 = 65-80, 8 = 80-90, 9 = 90-95, 10 = 95-98, 11 = 98-<100, 12 = 100). Interval midpoints were used to compute mean foliar injury at each rating/observation date. The range in percent mean foliar injury across all rating dates and the mean percent foliar injury at harvest (or at the last rating date before harvest for barley, cabbage, corn, orchardgrass, potato, and wheat, since rating at harvest was not possible) is given for the pH levels at which injury was observed.

[b] The maximum values reported are for cotyledonary, not true leaf, injury.

SUMMARY AND CONCLUSIONS

Yields of approximately half the 15 surveyed crops were not affected by either H_2SO_4 or H_2SO_4-HNO_3 rain treatment in either field or chamber studies (Tables 40 and 41). Both stimulatory and inhibitory yield responses occurred in the remaining crops.

In the field H_2SO_4 rain studies, no significant effects on yields of radish, mustard greens, or spinach occurred, but yields of alfalfa and tall fescue were stimulated. In the field H_2SO_4-HNO_3 rain studies, yields of alfalfa, tall fescue, radish, and spinach were not significantly affected, but yield decreases in corn and mustard greens occurred.

In the chamber H_2SO_4 rain studies, yields of five crops were not significantly affected (alfalfa, orchardgrass, tall fescue, tomato, and potato), yield reductions occurred in two crops (mustard greens and lettuce), and a mixed response was found in one (radish). In radish, significantly greater yield at pH 4.0, but lower yield at pH 3.0, was found. In the chamber H_2SO_4-HNO_3 rain studies, yields of nine crops were not significantly affected (alfalfa, clover, orchardgrass, tall fescue, tomato, lettuce, onion, peas, and potato), yield reductions occurred in three crops (carrot, radish, and mustard greens), and a yield increase was found in one crop (beet).

Root sensitivity of crops was similar to yield sensitivity, except for forage grasses (Tables 40 and 41). Foliar injury generally was minimal with mean injury rarely exceeding 1 to 2 percent of total leaf area. Most indicators of forage quality were not consistently affected by either H_2SO_4 or H_2SO_4-HNO_3 rain treatment.

These results support the 1979 H_2SO_4 rain survey conclusion that acid rain treatment does not appear to either generally inhibit or stimulate crop productivity (Cohen et al., 1981). Furthermore, crops which did not exhibit yield inhibition under the conditions of this study would not be expected to show an inhibitory response to ambient acid rain under field conditions, since the acid rain simulant treatments used in these experiments represent fairly extreme conditions. Treatments consisted of regular applications of rains of low (e.g., 3.0) and constant pH during most or all of the crops' growth and development. This contrasts with information obtained from hourly precipitation sampling at Brookhaven National Laboratory, New York, which showed that pH frequently increased during individual rain events and varied considerably from rain event to rain event (Raynor, 1979).

The yield response of several crops appeared to vary with rain type. For example, in the field, yield of mustard greens was significantly reduced in H_2SO_4-HNO_3 rain, but not in H_2SO_4 rain. Yield of tall fescue and alfalfa was significantly increased in H_2SO_4 rain, but was not affected by H_2SO_4-HNO_3 rain. In chamber studies, lettuce growth was reduced in H_2SO_4 rain but was not affected in H_2SO_4-HNO_3 rain, and the response pattern of radish varied with rain type. For radish, yield inhibition at low pH occurred in both rain types, but a stimulatory effect at intermediate pH in H_2SO_4 rain occurred as well. Rain composition, therefore, may be an important factor influencing crop response. Since ambient acid rain composition currently varies with geographical location (c.f., Cogbill and Likens, 1974; Liljestrand and Morgan, 1978; McColl, 1980) and may change in the future with the imposition of different pollution control strategies, further research on the influence of rain composition will be needed to predict crop response to acid rain.

Since environmental variability (e.g., in soil and air temperature, radiant energy supply, and the pattern of rainfall) is known to affect yield development in agricultural research and may have an important effect on crop response to acid rain, it will be necessary to conduct multiple-year studies before the response of a given crop can be characterized. Crop response may also vary for potted-plant, chamber growth versus field growth. To broaden the relevance and predictive usefulness of study findings, crop response should continue to be evaluated in the field in future studies.

Table 40. Summary of effects of simulated sulfuric (H_2SO_4) and sulfuric-nitric (H_2SO_4-HNO_3) acid rain on yield[a] and root dry weight of crops grown in field studies.

	pH's resulting in significant[b] change from control (↑ = stimulation; ↓ = reduction; NS = no significant effect)			
	Yield		Root dry weight	
Crop species	H_2SO_4	H_2SO_4-HNO_3	H_2SO_4	H_2SO_4-HNO_3
Grain crop				
Corn	-[c]	4.0↓	-	-
Forage crops				
Alfalfa[d]	4.0↑	NS	-	-
Tall fescue[d]	3.5↑, 4.0↑	NS	-	-
Cool-season crops				
Mustard greens	NS	3.0↓, 4.0↓	NS	NS
Radish	NS	NS	NS	NS
Spinach	NS	NS	NS	NS

[a]Dry weight of marketable portion of corn, alfalfa, and tall fescue, and fresh weight of marketable portion of cool-season crops.

[b]Significant at 5% level.

[c]"-" indicates crop not grown or roots not harvested in an experiment. Otherwise, crop was exposed to simulated acid rain at pH levels 3.0, 3.5, and 4.0 and to control rain, pH 5.6

[d]Effects on total yield summed across all harvests are shown.

Table 41. Summary of effects of simulated sulfuric (H_2SO_4) and sulfuric-nitric (H_2SO_4-HNO_3) acid rain on yield[a] and root dry weight of crops grown in chamber studies.

Crop species	pH's resulting in significant[b] change from control (↑ = stimulation; ↓ = reduction; NS = no significant effect)			
	Yield		Root dry weight	
	H_2SO_4	H_2SO_4-HNO_3	H_2SO_4	H_2SO_4-HNO_3
Forage legume crops				
Alfalfa[c,d]	NS	NS	NS	NS
Red clover[d]	-[e]	NS	-	NS
Forage grass crops				
Orchardgrass[d]	NS	NS	NS	3.0↑
Tall fescue[d]	NS	NS	3.5↓, 4.0↓	NS
Root crops				
Beet	-	3.0↑, 3.5↑	-	3.0↑, 3.5↑
Carrot	-	3.5↓	-	3.5↓
Radish	3.0↓, 4.0↑	3.0↓, 3.5↓	3.0↓, 4.0↑	3.0↓, 3.5↓
Fruit crop				
Tomato[d]	NS	NS	NS	NS
Leaf crops				
Lettuce	3.0↓, 3.5↓	NS	NS	NS
Mustard greens	3.0↓	3.0↓	3.0↓	3.0↓
Other crops				
Onion	-	NS	-	NS
Pea	-	NS	-	NS
Potato	NS	NS	NS	NS

[a]Fresh weight of marketable portion of crop except for alfalfa, red clover, orchardgrass, and tall fescue. For these crops, yield based on dry weight of marketable portion.

[b]Significant at 5% level.

[c]Results for high nitrogen and sulfur fertilization levels are shown.

[d]Effects on total yield summed across all harvests are shown.

[e]"-" indicates crop not grown in an experiment. Otherwise, crop was exposed to simulated acid rain at pH levels 3.0, 3.5, and 4.0 and to control rain, pH 5.6.

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APPENDIX I: ADDITIONAL DATA COLLECTED

Several additional crop studies were conducted. Data for these studies are not discussed in the main body of this report, because results were considered invalid because of technical or cultural problems during the growth of these crops. Data in Appendix Tables 2-6 are presented to document the fact that these studies were performed under USEPA Contract No. 68-03-2702.

Additional data for corn (Appendix Table 1) were also collected. Yield component data were not presented previously because the 12-ear subsamples were collected without regard to whether plants sampled produced more than one ear and multiple ear production had an important effect on grain yield.

Appendix Table 1. 'Pioneer 3992' corn grown in the field: effects of simulated sulfuric-nitric acid rain on total top water content, non-grain top dry wt., percent of top dry wt. in grain, and yield components

Treatment	Percent water in total top	Non-grain top dry wt	Percent top dry wt in grain	12 ear subsample Dry wt	Avg dry wt	Kernel No.	Avg. kernel dry wt
		— Kg —		— g —			— mg —
5.6	54.1	6.2	37.4	1223.2	101.9	5897	207
4.0	55.0	6.1	35.7	1253.2	104.4	5747	218
3.5	53.5	6.1	37.0	1333.8	111.1	6175	216
3.0	54.4	6.0	37.9	1307.1	108.9	5988	219
S.E.[a]	0.6	0.1	0.5	38.8	3.2	493	45
F[b]	NS	NS	NS	NS	NS	NS	NS

[a]Standard error of the mean.

[b]Significance level of the F-test from one-way ANOVA.

Effects of acid rain on barley (Appendix Table 2) and wheat (Appendix Table 3) could not be assessed. Because of late planting and high temperatures, these crops exhibited abnormal growth--weak tillers, very low grain production, and renewed tillering following head emergence. These abnormalities were particularly evident for barley.

Appendix Table 2. 'Steptoe' barley grown in chambers: grain, tiller, and dry matter production

Treatment	Head no.	Head dry wt	Grain dry wt	Stubble dry wt	Green tiller dry wt (GT)	GT as % of total top	Root dry wt	Total dry wt	S:R	Tiller No. 7/10	Tiller No. 9/10(H)
		g					g				
Sulfuric acid rain											
5.6	14.4	7.28	1.25	17.64	21.78	46.0	6.55	53.25	8.36	21.7	20.8
4.0	12.9	6.71	1.13	14.69	20.73	49.2	6.34	48.47	7.40	22.1	17.9
3.5	12.4	6.82	1.02	16.32	20.35	45.7	5.09	48.81	8.97	22.4	19.6
3.0	13.1	7.21	1.18	17.71	17.09	39.0	4.40	46.40	10.77	21.9	20.0
S.E.[a]	0.6	0.50	0.27	0.69	1.66	2.6	0.57	2.11	0.78	0.6	1.2
Sulfuric-nitric acid rain											
5.6	13.9	7.76	1.78	17.59	17.52	39.2	5.24	48.12	8.97	21.6	21.6
4.0	13.9	8.15	2.01	15.19	18.25	42.3	4.93	46.52	9.28	21.9	18.5
3.5	13.1	7.88	1.84	15.77	19.70	45.2	6.89	50.24	6.76	20.0	18.9
3.0	14.6	7.94	1.60	18.25	19.98	42.4	6.38	52.55	8.65	22.6	21.7
S.E.	0.6	0.51	0.31	0.82	1.83	3.0	0.57	2.07	0.79	0.8	1.4

[a] Standard error of the mean.

Appendix Table 3. 'Fieldwin' wheat grown in LR chambers: grain, tiller, and dry matter production, yield components, and harvest index (HI)

Treatment	Grain dry wt.	Head			Adjusted Kernel[a]			HI
		No.	Dry wt	Avg dry wt	No.	No/head	Avg dry wt	
	— g —		— g —				— mg —	
5.6	10.60	17.7	21.34	1.21	271	15.5	39.5	0.17
4.0	14.32	17.4	24.39	1.40	369	21.3	39.5	0.25
3.5	15.26	16.6	24.37	1.50	368	22.9	41.6	0.26
3.0	14.80	16.6	25.22	1.53	380	23.0	39.3	0.24
S.E.[b]	1.23	0.6	1.31	0.08	33	2.1	1.1	0.02

Treatment	Stubble dry wt	Green tiller(GT) dry wt	GT dry wt as % of total top	Root dry wt	Total dry wt	Tiller No. 7/10	Tiller No. 9/10(H)	Percent fertile tillers
	— g —	— g —		— g —	— g —			
5.6	24.33	3.23	6.3	13.98	62.88	29.4	24.4	73.7
4.0	23.43	0.69	1.5	8.77	57.28	30.0	25.9	68.0
3.5	22.74	1.25	2.6	10.63	58.99	30.3	25.0	66.7
3.0	24.02	0.65	1.3	10.34	60.23	32.5	27.2	61.9
S.E.	0.80	0.80	1.6	1.42	2.27	0.9	0.8	3.0

[a]Because of kernel cracking during the machine count, kernel number was adjusted by dividing the number of uncracked kernels (the only ones counted) by the dry weight ratio of uncracked-to-uncracked plus cracked kernels. The adjusted kernel number was used to calculate kernel number per head and average dry weight.

[b]Standard error of the mean.

Appendix Table 4. 'Stonehead' cabbage grown in LR chambers: head and dry matter production

Treatment	Head weight Fresh	Head weight Dry	Nonmarketable stem dry wt.[a]	Root dry wt.	Total dry wt.	Percent water in head
	g					%
5.6	214.06	18.86	51.51	20.60	90.97	90.8
4.0	240.63	21.44	49.20	16.70	87.34	91.0
3.5	218.67	19.82	54.19	18.90	92.92	90.5
3.0	230.28	20.41	50.94	22.70	94.05	90.8
S.E.[b]	22.15	1.50	1.65	2.09	2.90	0.3

[a]Dry weight of nonmarketable loose leaves and stem portion.

[b]Standard error of the mean.

Note: Symptoms associated with N deficiency[1] occurred and persisted during the growth of 'Stonehead' cabbage, even though supplemental N was applied in a readily available form [$Ca(NO_3)_2$]. These symptoms consisted of yellowing of older leaves followed by development of pink/purple coloration and premature leaf senescence. Examination of plant root systems revealed a root-bound condition which may have caused the suspected N deficiency. These conditions precluded assessment of acid rain response.

[1]Nieuwhop, M. 1969. Cole crops. Leonard Hill. London.

Appendix Table 5. 'Improved Thick Leaf' spinach grown in chambers: leaf fresh weight and dry matter production

Treatment	Leaf weight Fresh	Leaf weight Dry	Nonmarketable stem dry wt.	Root dry wt.	Total dry wt.	Leaf percent water
	g					%
Sulfuric acid rain						
5.6	9.41	0.66	0.19	0.33	1.18	92.7
4.0	17.82	1.65	0.32	0.40	2.36	90.8
3.5	17.53	1.81	0.32	0.72	2.85	89.5
3.0	15.53	1.60	0.33	0.50	2.42	90.0
S.E.[a]	1.43	0.14	0.04	0.07	0.21	0.3
Sulfuric-nitric acid rain						
5.6	14.81	1.42	0.30	0.72	2.45	90.5
4.0	18.04	1.82	0.24	1.00	3.06	89.9
3.5	21.05	1.98	0.47	0.72	3.17	90.5
3.0	20.07	2.11	0.38	1.00	3.50	89.6
S.E.	1.59	0.16	0.04	0.11	0.27	0.2

[a]Standard error of the mean.

Appendix Table 6. Leaf nutrient concentrations of healthy and chlorotic spinach grown in chambers and common nutrient ranges reported for young, mature spinach leaves [a]

	N	K	P	Ca	Mg	Mn	Fe	Cu	B	Zn	Al
	%					ppm					
Healthy	5.14	7.12	0.75	2.50	1.30	53	169	1	26	57	37
Chlorotic	4.67	6.58	1.12	2.65	1.11	83	303	15	60	86	90
Common range	4.0-6.0	3.0-5.3	0.25-0.58	0.60-1.39	1.6-1.8	30-85	220-245	5-20	40-63	50-75	

[a]The common nutrient ranges listed were compiled from information contained in: [1]/L.M. Walsh and J.D. Beaton. 1973. Soil testing and plant analysis. Soil Science Society of America, Inc. Madison, Wisconsin.

[2]/H.D. Chapman. 1966. Diagnostic criteria for plants and soils. University of California, Riverside.

Appendix Table 7. Study-end soil analysis results for crops excluded from chamber survey [a].

Crop	Treatment		Soil pH
Barley	1:0[b]	3.0	8.1
		3.5	8.2
		4.0	8.2
		5.6	8.2
	2:1[b]	3.0	7.8
		3.5	8.2
		4.0	8.2
		5.6	8.1
Cabbage	2:1	3.0	7.9
		3.5	8.0
		4.0	7.9
		5.6	7.9
Spinach	1:0	3.0	7.9
		3.5	7.9
		4.0	7.9
		5.6	8.0
	2:1	3.0	7.9
		3.5	7.9
		4.0	7.9
		5.6	7.9
Wheat	2:1	3.0	8.1
		3.5	8.2
		4.0	8.2
		5.6	8.0

[a] All values were obtained for soil composited on a treatment basis.

[b] 1:0 refers to H_2SO_4 rain type, and 2:1 refers to H_2SO_4-HNO_3 rain type.

APPENDIX II: FOLIAR INJURY DESCRIPTIONS

Alfalfa (Field and chamber: H_2SO_4 and H_2SO_4-HNO_3 rain)

Chamber studies: the nature of foliar injury did not differ for acid rain type or fertility level. Generally round, white markings less than 2 millimeters in diameter occurred throughout the season at pH 3.0. Marked tissue appeared dry and pitted. Lesions extended all the way through leaves and were not localized anywhere on leaves. As the season progressed, older leaves showed more injury than younger leaves. This difference for leaf age was from accumulation of injury on older leaves that were below clipping height.

Field studies: No injury was observed on alfalfa leaves in the H_2SO_4-HNO_3 rain type field study. In the H_2SO_4 rain type field study, injury was present only at H2 at pH 3.0 (3 of 4 blocks) and pH 4.0 (1 block only). Lesions were the same in appearance as described for chamber-grown alfalfa. However, neither younger nor older leaves showed more injury at this harvest, as was also true at this observation date in the chamber studies.

Barley (Chamber: H_2SO_4 and H_2SO_4-HNO_3 rain)

Injury was not evaluated at harvest because of leaf senescence. Generally round, white markings less than 2 millimeters in diameter were seen on leaves and awns at pH 3.0 in both rain types before harvest. Marked tissue generally appeared dry and pitted. Lesions extended through the leaf, but were not localized. Before the final observation date (August 19). younger leaves showed more injury than older leaves. Secondary marking colorations that were tan (H_2SO_4-HNO_3 rain) or brown (both rain types) were also observed.

Beet (Chamber: H_2SO_4-HNO_3 rain)

Lesions initially appeared as reddish markings. As damage progressed, tissue at the center of lesions turned white. Lesions on cotyledons were rated on the first observation date (May 30) and were predominantly white at pH levels 3.0 and 3.5, but were reddish at pH 4.0 (less severe damage). Injury to true leaves was not observed at pH 4.0 and was extremely minor at pH 3.5. At pH 3.0, the percent leaf area injured for true leaves increased over time until one week before harvest and then decreased, since less injury occurred on new leaves that appeared just before harvest. Lesions on true leaves were predominantly reddish in color. Lesions were generally round, less that 2 millimeters in diameter, pitted, and dry in appearance. They extended through the leaf but were not localized. Injury occurred to a greater extent on older leaves at all observation dates as damage accumulated.

Cabbage (Chamber: H_2SO_4-HNO_3 rain)

Foliar injury of cabbage occurred at pH 3.0 primarily as black, pitted, round lesions less than 2 millimeters in diameter. Lesions appeared to be dry and were not localized. A color transition from injured to healthy tissue was noted. Before harvest, it occurred as a yellow halo surrounding the central black lesion. At harvest, this transition coloration was brown, rather than yellow. Early in the season, lesions were observed on petioles and extended through the leaf; once head formation began, however, observations of petioles and both leaf surfaces were not possible. More extensive damage occurred on older leaves early in the season, but a difference for leaf age was not apparent later.

Carrot (Chamber: H_2SO_4-HNO_3 rain)

Tan, round lesions less than 2 millimeters in diameter, which were dry, pitted, and extended through the leaf, appeared on carrot leaves at pH 3.0. These lesions were not localized. Older leaves always showed more injury than younger leaves as injury accumulated. At harvest, some lesions were also yellow in color.

Clover (Chamber: H_2SO_4-HNO_3 rain)

Foliar injury of clover occurred at pH 3.0 as reddish, pitted, round lesions less than 2 millimeters in diameter. Lesions appeared dry and extended through the leaf. At the final harvest, some lesions were tan colored, and a reddish color transition from injured to healthy tissue was seen. Lesions were not localized and occurred to a similar extent on younger and older leaves throughout the season.

Corn (Field: H_2SO_4-HNO_3 rain)

Foliar injury of field-grown corn was only identified on one observation date (July 10) at pH 3.0. Acid rain injury may have been present after this date, but was not distinguishable from numerous other markings present on corn leaves. When observed, foliar injury consisted of yellow streaks 2 to 5 millimeters long and less that 2 millimeters wide which were dry, pitted, and extended through leaves. Older leaves showed more injury than younger leaves. Lesions were localized on the distal third of leaves.

Tall Fescue (Field and Chamber: H_2SO_4 and H_2SO_4-HNO_3 rain)

Chamber studies: Tall fescue foliar injury occurred in both rain types as white, generally round lesions less than 2 millimeters in diameter. Lesions appeared dry and pitted and extended through the leaf. While this injury was observed through the season at pH 3.0, it was seen at pH 3.5 only at H2. Injury at pH 3.0 was not localized anywhere on the leaf, and neither younger nor older leaves exhibited more injury. Injury at pH 3.5, however, was localized on the stem and flag leaf below seed heads and was not seen at pH 3.5 on any plants not having seed heads. A secondary tan coloration of injury was seen in August at pH 3.0.

Field studies: Foliar injury was not observed on field-grown tall fescue in either rain type at any time during the season.

Mustard Greens (Field and chamber: H_2SO_4 and H_2SO_4-HNO_3 rain)

Chamber studies: Foliar injury of mustard occurred in both rain types. In H_2SO_4-HNO_3 rain, injury occurred in all three acid rain treatments, but in H_2SO_4 rain, injury occurred only at pH levels 3.5 and 3.0. Injury of cotyledons was much more severe than of true leaves. The percent area of cotyledons showing injury was greater, and cotyledons were misshapen or twisted at pH levels 3.0 (both rain types) and 3.5 (H_2SO_4 rain). Injury occurred as white or grey, irregularly-shaped patches which were pitted and dry. At one of the three observation dates, injury appeared to be localized near leaf margins. As the season progressed, more injury occurred on older than younger leaves as damage accumulated. At harvest, injury was also seen on petioles at pH 3.0 in both rain types.

Field studies: Injury ratings taking on May 28 on field-grown mustard reflect the heavy flea beetle infestation that occurred. No clearly discernible leaf injury from acid rain was seen in either rain type.

Orchardgrass (Chamber: H_2SO_4 and H_2SO_4-HNO_3 rain)

Foliar injury of orchardgrass consisted of white, generally round lesions less than 2 millimeters in diameter which were dry, pitted, and extended through leaves. Lesions were not localized. Injury occurred at pH 3.0 in both rain types. (It was seen at pH 3.5 in H_2SO_4 rain in only one pot on the final observation date, August 19). Older leaves showed greater injury than younger leaves on one observation date (July 21) in H_2SO_4-HNO_3 rain. In both rain types, a secondary tan coloration of lesions was seen later in the season.

Pea (Chamber: H_2SO_4-HNO_3 rain)

Acid rain injury to pea occurred throughout the growing season at pH 3.0 and was present on leaves, petioles, stems, and flowers but not on pods. Foliar injury at pH 3.5 was seen at harvest. Injury generally occurred as brown, round lesions less than 2 millimeters in diameter that were dry, pitted, and extended through leaves. Injury was not localized anywhere on the leaf at pH 3.0 and occurred to a greater extent on older than younger leaves throughout the season. At pH 3.5, lesions tended to be localized near the leaf-petiole junction and were irregular in shape. Grey and tan secondary lesion colorations were seen at pH 3.0.

Potato (Chamber: H_2SO_4 and H_2SO_4-HNO_3 rain)

Foliar injury of potato occurred at pH 3.0 in both rain types. Lesions initially were reddish but became brown as damage progressed. Lesions were round, less than 2 millimeters in diameter, dry, pitted, and extended through leaves but were not localized. Older leaves showed more injury than younger leaves as damage accumulated. In H_2SO_4-HNO_3 rain, injury was also observed on petioles and flowers. Necrotic areas on petals and sepals were associated with twisted floral shape.

Radish (Field and chamber: H_2SO_4 and H_2SO_4-HNO_3 rain)

Chamber studies: Foliar acid rain injury was observed at pH levels 3.0 and 3.5 in both rain types. At pH 3.0, injury occurred as irregularly shaped, white patches which generally extended through the leaf, were pitted and dry, and were not localized. Secondary tan (H_2SO_4 rain) and black (both rain types) lesion colorations were seen at pH 3.0. Distortions in shapes of cotyledons and true leaves occurred at pH 3.0 in both rain types but not at pH 3.5. Injury to cotyledons was much more severe than to true leaves. At pH 3.5, the predominant lesion coloration changed from white to grey after approximately one (H_2SO_4-HNO_3 rain) to two (H_2SO_4 rain) weeks of exposure. A secondary tan lesion coloration was seen at pH 3.5 in H_2SO_4-HNO_3 rain. In both rain types, older leaves consistently showed more injury than younger leaves as damage accumulated.

Field studies: No foliar injury attributable to acid rain exposure was seen in either rain type in the field.

<u>Spinach</u> (Field and chamber: H_2SO_4 and H_2SO_4-HNO_3 rain)

Chamber studies: Foliar injury was seen at pH 3.0 in both rain types and at pH 3.5 in H_2SO_4 rain within a week of initial exposure. It occurred subsequently at pH levels 3.5 and 4.0 in H_2SO_4-HNO_3 rain. In both rain types, lesions at pH 3.0 were white, generally round, less than 2 millimeters in diameter, dry, pitted, and extended through leaves. Injury was not localized, but did accumulate on older leaves. At higher acid rain pH levels, the predominant lesion coloration was grey (pH 4.0, H_2SO_4-HNO_3 rain) or changed from white to grey after the first observation (pH 3.5, both rain types). In both rain types, injury at pH 3.0 occurred on petioles, as well as on true leaves and cotyledons, and cotyledons were distorted in shape. Cotyledonary lesions also occurred at pH 3.5 (both rain types), but not at pH 4.0.

Field studies: Foliar injury was observed during the season at pH 3.0 in both rain types. Injury was present at harvest in H_2SO_4 rain but not in H_2SO_4-HNO_3 rain. Lesions were the same in appearance as those at pH 3.0 in the chamber studies; i.e., they were white, round, less than 2 millimeters in diameter, dry, pitted, unlocalized, extended through leaves, and occurred to a greater extent on older leaves. Cotyledons (both rain types) and petioles (H_2SO_4 rain), as well as true leaves, showed injury.

<u>Tomato</u> (Chamber: H_2SO_4 and H_2SO_4-HNO_3 rain)

Foliar injury of tomato occurred at pH levels 3.0 and 3.5 in both rain types. Injury at pH 3.0 was observed within one week of initial exposure in both rain types. Injury at pH 3.5, however, was not observed until three to four weeks later. Although it was present for the remainder of the season in H_2SO_4-HNO_3 rain, it was not observed after August 6 in H_2SO_4 rain. In general, injury appeared to be more severe in H_2SO_4-HNO_3 rain than in H_2SO_4 rain, particularly earlier in the season. Lesions in both rain types were tan or brown, round, less than 2 millimeters in diameter, dry, pitted, and unlocalized. Lesions extended through leaves when observed the month before harvest, but did not at harvest. Younger leaves had a greater percentage of leaf area injured earlier in the season, but older leaves showed more injury at later observation dates (after August 6) as injury accumulated. Lesions also occurred on petioles, stems, flowers, and fruits at pH 3.0 in both rain types and on flowers at pH 3.5 in H_2SO_4-HNO_3 rain.

<u>Wheat</u> (Chamber: H_2SO_4-HNO_3 rain)

Foliar injury of wheat was not identified until approximately seven weeks after initial exposure and was not observed after July 28 (injury was not evaluated at harvest because of leaf senescence). Present only at pH 3.0, it occurred as white, round lesions less than 2 millimeters in diameter that were dry, pitted, and extended through leaves, but were not localized. Younger leaves had more injury than older leaves. Awns, as well as leaves, showed this type of injury.