Effects of Simulated Sulfuric Acid Rain on Crop Plants

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ABSTRACT

Since relatively little is known about the effects of acid precipitation on growth and productivity of crop plants, a crop survey was initiated to study effects of H_2SO_4 rain simulants on growth, yield, and quality of selected crops which were chosen to represent diverse taxonomic groups and crop products. Yield responses of 28 crop cultivars were examined. Plants were grown in pots in field-exposure chambers and subjected to three H_2SO_4 rain simulants (pH levels 4.0, 3.5, and 3.0) and to a control simulant (pH 5.6). Yield of approximately two-thirds of the crops surveyed was not affected by the H_2SO_4 rain treatments. Equal numbers of the remaining crops exhibited stimulatory and inhibitory yield responses at some H_2SO_4 rain simulant pH levels. These results did not suggest that acid rain treatment either generally inhibited or stimulated crop productivity. Crop response depended on crop species and crop product. For example, while forage yield of alfalfa and timothy was stimulated at some acid rain pH levels, yield of the remaining forage legume and grass species was not generally affected by acid rain treatment. However, root and fruit crop species exhibited generalized responses (yield inhibition and stimulation, respectively) which appeared to be more closely associated with crop product than occurred for other crop product groupings. Effects on crop quality were also important. For instance, although yield of some horticultural leaf and fruit crops was either unaffected or stimulated by H_2SO_4 rain treatment, marketability was adversely affected at low pH because of the presence of discoloration and/or lesions produced by H_2SO_4 rain treatment. This preliminary study demonstrates considerable variability in crop response to acid rain. Furthermore, little or no information is currently available concerning the effects of numerous plant, soil, environmental, and stress factors on crop response to acid rain. Consequently, general statements regarding acid rain effects on crop quality and yield are premature.

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CONTENTS

TABLES

EFFECTS OF SIMULATED SULFURIC ACID RAIN ON CROP PLANTS

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INTRODUCTION

Acid precipitation has been identified as a major environmental concern in Scandinavian countries, other northern European countries, Canada, Japan, and, more recently, the United States (Galloway et al., 1978). Formed following the oxidation and hydration of sulfur and nitrogen oxides in the atmosphere, acid precipitation is defined as rain or snow having pH values less than approximately 5.6, the equilibrium pH value for dissolution of CO_2 in water, a reaction which produces carbonic acid (Likens and Bormann, 1974). Analysis of precipitation samples from the northeastern United States has indicated widespread occurrence of pH values less than 4.4, as well as increased geographic area impacted by acid precipitation and increased intensity of acid deposition in this region during recent decades (Cogbill and Likens, 1974). More recently, the occurrence of acid precipitation has been documented at several sites in the western United States (Liljestrand and Morgan, 1978; Lewis and Grant, 1980; McColl, 1980). Although H_2SO_4 is the predominant acid species of acid precipitation in the northeastern United States (Cogbill and Likens, 1974), HNO_3 has been shown to predominate in two California studies (Liljestrand and Morgan, 1978; McColl, 1980).

Numerous studies have discussed the effects of acid precipitation on aquatic ecosystems (e.g., Almer et al., 1974; Grahn et al., 1974; Hall and Likens, 1980; Schindler, 1980). Relatively little, however, is known about effects on terrestrial ecosystems, particularly agroecosystems, although numerous hypotheses regarding potential effects on plant growth have been proposed (Cowling, 1978).

A limited number of controlled environment and field studies of crop species exposed to simulated rain treatments have been conducted. Radish and barley seedlings were not affected by rain simulants acidified with H_2SO_4 at pH 3.5, although radish leaf and root growth were reduced at the unrealistically low pH of 2.5 (Harcourt and Farrar, 1980). Seed yield of pinto bean exposed to H_2SO_4 rain simulant at pH 3.1 and below decreased because of reductions in both pod number per plant and seed number per pod, but soybean seed yield increased at pH 3.1, because of greater average seed weight, and decreased at pH 2.5 (Evans and Lewin, 1980). Yield of field-grown soybean plants exposed to acid rain simulant (containing both H_2SO_4 and HNO_3 at a pH of approximately 3.5) from bloom stage until plant senescence was not significantly different from plants exposed to control simulant. Average seed dry weight was approximately 4% greater, however, and photosynthetic rate of acid-treated plants also tended to be greater (Irving, 1979). Ferenbaugh (1976) found that apparent photosynthetic rates of young _Phaseolus vulgaris_ plants exposed to H_2SO_4 mist at pH 2.5 were more than 80% greater than in the control, although carbohydrate production and vegetative growth were significantly reduced. He suggested that H^+ input uncoupled photophosphorylation and, thereby, resulted in the reduction of carbohydrate-producing capacity and plant productivity. Vegetative and reproductive development of bush bean as well as leaf concentrations of chlorophyll, N, P, Mg, and Ca were reduced as the pH of H_2SO_4 mist was decreased from 5.5 to 2.0. Foliar K concentrations were not affected, and leaf and soil S was increased (Hindawi et al., 1980). Several foliar leaching studies have suggested that acid rain may increase loss of several cation species from leaves, particularly Ca and Mg (Wood and Bormann, 1975; Fairfax and Lepp, 1975).

Shriner (1977) found in host-parasite interaction studies that H_2SO_4 rain simulant at pH 3.2 reduced kidney bean and soybean growth in some cases and inhibited nodulation by Rhizobia bacteria. In addition, disease development involving two rust organisms (fusiform rust on host willow oak and bean rust on kidney bean) and one root-knot nematode (on kidney bean) was inhibited, while halo blight of kidney bean was either stimulated or inhibited depending on the stage of the disease cycle when acidic simulant was applied.

This introduction summarizes most, if not all, published reports of the effects of acid rain simulants on crop productivity, physiological processes, and host-parasite/symbiont interactions. Since only a limited number of crop species have been examined in this studies, it is not known whether crop response to acid rain is a general phenomenon. For this reason, a crop growth survey was initiated in spring 1979 at the Schmidt Farm Research Station of Oregon State University. Experimental objectives were to determine whether simulated H_2SO_4 rain treatments affected (1) the productivity of 28 crop cultivars, selected to represent diverse taxonomic groups and crop products, and (2) the quality characteristics of several of these cultivars.

MATERIALS AND METHODS

Yield responses of 28 crop cultivars exposed to simulated H_2SO_4 rain were studied. Plants were grown in pots in stationary, closed-top field-exposure chambers and exposed to three H_2SO_4 rain simulants (pH levels 4.0, 3.5, and 3.0) and to a control simulant at approximately pH 5.6. Rain simulants were prepared using a stock solution of deionized water to which 11 μeq/l Ca^{++}, 12 μeq/l Na^{+}, 2 μeq/l K^{+}, 5 μeq/l Mg^{++}, 11 μeq/l SO_4^{--}, 12 μeq/l NO_3^{-}, and 12 μeq/l Cl^{-} 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 reagent grade 3.6 N H_2SO_4.

Rain simulants were delivered through stainless steel nozzles at the average rate of 6.7 mm/hr, 1.5 hours per day, three days per week, for a total of 30 mm/week. The pH of rain simulants 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.

Three types of field-exposure chambers were used. Large round (LR) chambers covered with Krene measured 4.6 meters in diameter and 2.4 meters in height; one chamber per treatment was used and contained 14 pots per crop for all crops except potato which had 10 pots. Small round (SR) chambers covered with Krene were 3.0 meters in diameter and 2.4 meters in height; two chambers per treatment, each containing seven pots per crop, were used. Square (SQ) chambers covered with teflon measured 2.4 meters width by 2.1 meters height; five chambers per treatment, each containing five pots per crop, were used.

Pots were assigned at random to treatments giving 14, 14, and 25 pots per treatment per crop for LR, SR, and SQ chambers, respectively. The chamber type in which a given crop was grown is shown in Table 1. Pots of each crop within LR and SR chambers were placed in a wedge-shaped arrangement so any unevenness in nozzle spray patterns was averaged across all pots. In addition, nozzles were rotated among nozzle positions (4, 3, and 2 positions for LR, SR, and SQ 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.

Blowers were attached to SR and SQ chambers to control chamber heat load and provided complete chamber air exchange with ambient air at the rate of approximately 1.5 air changes per minute. Convective cooling in LR chambers, due to chamber design, sufficiently controlled chamber temperature buildup. No other 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 and crop products (e.g., leaf, tuber, root, forage, and grain crops). Plants were grown in six liter plastic pots (except potato, which was grown in 15 liter pots) which contained sandy loam soil obtained from the flood plain of the Willamette River near Corvallis, Oregon. The pH of this soil averaged 6.3, and no lime was added. Soil was pasteurized by exposure to aerated steam at 75°C for 40 minutes and mixed with peat moss (7.7 kg per m^3-soil) and fertilizer before planting. At planting, leguminous species were fertilized with 67-224-224 kg/ha of N-P_2O_5-K_2O and all others with 112-224-224 kg/ha using commerical 6-20-20 and 10-20-20 fertilizer sources, respectively. Legumes were inoculated with appropriate Rhizobia species immediately before seeding. Several species received additional fertilizer during the study according to individual crop needs from urea, 0-10-10, 0-20-20, and 10-20-20 fertilizer sources. Irrigation with well water was supplied according to individual pot needs. Pesticides for insect (diazinon) and disease (maneb) control were applied as needed. Crop species and cultivar names, total seasonal fertilizer application rates, and dates of seeding, first treatment exposure, and final harvest are listed in Table 1.

More than half the crops were first exposed to rain simulants within a day of seeding. The remainder received first exposure several weeks after seeding, because they were germinated in a greenhouse to provide uniform seedlings and later transplanted to study pots. In all cases, exposure to simulated rain continued until final harvest. Crops first exposed to rain simulants immediately after seeding were subsequently thinned to uniform seedling size. The number of plants per pot after thinning or transplanting is shown in Table 1.

The types of data collected and harvest regimes varied with crop species. For example, grain dry weight for barley, top dry weight at multiple harvests for alfalfa, and fruit fresh weight, number, and size classes at multiple harvests for tomato were determined. In addition to data for marketable crop portions, data for the remainder of plant dry matter production were collected. Dry weight determinations were made after plant material was oven dried at 60°C for at least 48 hours. Components of forage quality were evaluated for several of the forage species. The Plant Analysis Laboratory, Oregon State University, determined total S using a Leco Sulfur Analyzer as described by Jones and Isaac (1972) and all other mineral elements, except N, using direct reading emission spectrometry as described by Chaplin and Dixon (1974). The Forage Analytical Service, Oregon State University, determined carotene, nitrogen (N), crude fiber (CF), acid detergent fiber (ADF), and neutral detergent fiber (NDF). The methods of Goering and Van Soest (1970) were used to determine ADF and NDF. Standard methods were used to determine N and CF (AOAC, 1975) and a modified AOAC method was used for carotene (AOAC, 1950). Crude protein (CP) content was calculated by multiplying N by 6.25.

Data were first subjected to a one-way analysis of variance. If the resulting F value was significant at the 5% level, two-sided t-tests were conducted to determine which acid rain treatment means differed significantly from the control ($P \leq 0.05$). Data in the following tables are expressed as pot means, unless otherwise indicated.

Table 1. Crop cultivars, total fertilizer application rates, dates of seeding, first exposure, and final harvest, number of plants per pot after thinning or transplanting, and chamber type used for the study.

Crop	Cultivar	Chamber Type	Plants per pot (No.)	Total fertilizer application rate (kg/ha)[a]	Dates of		
					Seeding	First exposure	Final harvest
Grain Crops							
Barley *(Hordeum vulgare)*	Steptoe (spring)	LR	3	112-224-224	4/19	4/20	7/31
Corn *(Zea mays)*	Golden Midget	LR	1	168-336-336	7/23	7/23	9/05
Oat *(Avena sativa)*	Cayuse (spring)	LR	3	112-224-224	4/19	4/20	8/06
Wheat *(Triticum aestivum)*	Fieldwin (spring)	LR	3	112-224-224	4/19	4/20	8/03
Forage Legume Crops							
Alfalfa *(Medicago sativa)*	Vernal	SR	2	67-252-252	5/25	5/26	10/03
Red clover *(Trifolium pratense)*	Kenland	SR	2	67-336-336	5/25	5/26	10/02
Forage and Turfgrass Crops							
Bluegrass *(Poa pratensis)*	Newport	SR	3	224-448-448	5/25	5/26	11/07
Orchardgrass *(Dactylis glomerata)*	Potomac	SR	3	112-224-224	6/14	7/07	9/25
Ryegrass *(Lolium perenne)*	Linn	SR	3	112-224-224	6/14	7/07	11/16
Tall fescue *(Festuca arundinacea)*	Alta	SR	3	168-336-336	6/14	7/07	11/20
Timothy *(Phleum pratense)*	Climax	SR	3	112-224-224	6/14	7/07	9/19
Root Crops							
Beet *(Beta vulgaris)*	Detroit Dark Red	SQ	2	112-224-224	7/26	7/26	9/25
Carrot *(Daucus carota)*	Danvers Half Long	SQ	2	224-224-224	7/26	7/26	11/01
Radish *(Raphanus sativus)*	Cherry Belle Exp. 1	LR	3	168-224-224	4/19	4/20	5/21
	Cherry Belle Exp. 2	SR	2	112-224-224	5/25	5/26	6/21
	Cherry Belle Exp. 3	LR	3	112-224-224	9/26	9/26	10/31
	Cherry Belle Exp. 3	SR,SQ	3	112-224-224	9/26	9/27	10/31
Fruit Crops							
Green pepper *(Capsicum annuum)*	California Wonder	SR	1	224-448-448	5/16	6/28	9/24
Strawberry *(Fragaria x ananassa)*	Quinalt	LR	1	224-336-336	b	4/20	10/16
Tomato *(Lycopersicon esculentum)*	Patio	LR	1	224-448-448	5/16	6/29	10/25
Cole Crops							
Broccoli *(Brassica oleracea)*	Italian Green Sprouting	LR	1	168-224-224	2/21	4/20	6/10
Cabbage *(Brassica oleracea)*	Golden Acre	LR	1	224-224-224	2/21	4/20	7/17
Cauliflower *(Brassica oleracea)*	Early Snowball	LR	1	224-224-224	2/21	4/20	6/11
Leaf Crops							
Swiss chard *(Beta vulgaris)*	Lucullus	SR	1	168-224-224	5/25	5/26	8/07
Lettuce *(Lactuca sativa)*	Limestone Bibb	LR	1	112-224-224	8/31	9/19	11/13
Lettuce *(Lactuca sativa)*	Great Lakes Head	LR	1	112-224-224	8/31	9/19	11/15
Mustard greens *(Brassica japonica)*	Southern Giant Curled	SR	2	112-224-224	5/25	5/26	6/26
Spinach *(Spinacia oleracea)*	Improved Thick Leaf	SR	2	112-224-224	5/25	5/26	6/29
Other Crops							
Onion *(Allium cepa)*	Sweet Spanish Type	LR	2	336-336-336	4/19	4/20	9/17
Pea *(Pisum sativum)*	Little Marvel	LR	2	67-224-224	4/19	4/20	6/22
Potato *(Solanum tuberosum)*	White Rose	LR	c	247-224-224	4/19	4/20	8/15

[a] Fertilization rates are for kg/ha of N-P_2O_5-K_2O.

[b] Strawberry starts were obtained from a commercial nursery and were transplanted into pots before first exposure.

[c] Two 25-g seed pieces, each having 2 "eyes", were planted per pot; all other visible eyes were removed.

RESULTS AND DISCUSSION

Yield of 18 of 28 crop cultivars surveyed was not significantly affected by treatment with H_2SO_4 rain simulant. For the remaining crops, yield was greater in four, but lower in four others, at some acid rain pH levels compared with controls. A mixed response, which depended on pH level, occurred in one crop. (Assessment of effects on yield of the final crop, corn, was not possible.)

Effects on yield and other aspects of productivity and quality are discussed in greater detail in the following sections. Crop groupings in these sections were chosen to delineate similarities in crop products and/or taxonomic relationships.

Grain Crops

Grain production in the barley, oat, and wheat varieties studied was not significantly different from the control (Table 2). However, barley yield component compensation at pH 3.0 was suggested by the lower mean head number ($P \leq 0.10$) and 15% greater average head dry weight which occurred (Table 3). Consequently, in future studies, additional data on numbers of tillers and fertile tillers and on the yield components, kernel number per head and average kernel weight, should be examined.

No significant treatment differences in stubble dry weight and total dry matter production (which included root and non-grain influorescence dry weights) of these three grain crops were found (Table 2). Greater root dry weight at pH 3.5 in oat, but lower root weights in all three acid rain treatments in wheat, occurred. Harvest index (HI), which describes the efficiency of dry matter partitioning into economic yield, was computed as the ratio between grain and total dry matter production. The higher mean HI at pH 3.5 in wheat ($P \leq 0.10$) appeared to be due to the severe reduction in root dry weight (-47%) which occurred in this treatment. In oat, the lower mean HI at pH 3.0 ($P \leq 0.10$) was not associated with an increase in total dry matter production and, therefore, was caused by the 8% (though statistically nonsignificant) mean reduction in grain dry weight that occurred.

'Golden Midget' sweet corn was not grown to maturity, but was harvested when about 1 meter tall as plants were blocking spray nozzles. As a result, yield data were not collected. Though differences were not statistically significant, mean top and root dry weights at pH 3.0 were 13 and 12% greater than the control ($P \leq 0.10$ for top dry weight), respectively, and resulted in an unchanged shoot-to-root ratio (Table 4).

Forage Legumes

Response to acid rain simulants differed for the two forage legume species examined. Data suggested a stimulatory effect on 'Vernal' alfalfa dry matter producion at intermediate pH levels. 'Kenland' clover dry matter

Table 2. Effects of simulated sulfuric acid rain on grain and dry matter production and harvest index of 'Steptoe' barley, 'Cayuse' oat, and 'Fieldwin' wheat.

Treatment	'Steptoe' barley					'Cayuse' oat					'Fieldwin' wheat				
	Grain	Stubble	Root	Total dry matter	Harvest index	Grain	Stubble	Root	Total dry matter	Harvest index	Grain	Stubble	Root	Total dry matter	Harvest index
	g					g					g				
5.6	34.71	21.85	6.35	70.16	0.50	31.41	26.69	3.78	67.07	0.47	29.29	29.34	11.44	81.56	0.36
4.0	34.76	22.34	7.18	73.07	0.49	31.47	27.01	3.67	66.72	0.47	28.78	29.01	8.11**	76.53	0.38
3.5	38.06	24.56	5.64	75.84	0.50	31.50	27.61	6.03**	70.57	0.45	28.58	26.81	6.08**	71.53	0.40
3.0	36.53	22.55	5.58	73.45	0.51	28.88	26.31	4.37	65.33	0.44	28.28	29.81	7.33**	75.86	0.37
S.E.[a]	1.70	1.08	0.43	2.97	0.01	1.45	1.43	0.58	2.94	0.01	1.62	1.54	0.74	3.80	0.01
F[b]	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] Standard error of the mean.

[b] Significance level of the F-test for treatment effects with * and ** denoting $P \leq 0.05$ and 0.01, respectively.

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

Table 3. Effects of simulated sulfuric acid rain on head and grain production of 'Steptoe' barley.

Treatment	Head dry weight (g)	Grain dry weight (g)	Head Number	Average head dry weight (g)
5.6	41.96	34.71	22.9	1.96
4.0	42.09	34.76	22.1	1.87
3.5	45.15	38.06	21.8	2.02
3.0	43.65	36.53	19.4	2.25**
S.E.[a]	1.94	1.70	1.0	0.06
F[b]	N.S.	N.S.	N.S.	**

[a] Standard error of the mean.

[b] Significance level of the F-test for treatment effects with ** denoting $P \leq 0.01$.

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

Table 4. Effects of simulated sulfuric acid rain on dry matter production and shoot:root ratio of 'Golden Midget' corn.

Treatment	Top dry weight (g)	Root dry weight (g)	Shoot:Root
5.6	35.56	6.36	5.72
4.0	35.09	6.56	5.57
3.5	35.76	6.54	5.57
3.0	40.13	7.14	5.72
S.E.[a]	1.54	0.40	0.26
F[b]	N.S.	N.S.	N.S.

[a] Standard error of the mean.

[b] Significance level of the F-test for treatment effects.

production was not significantly different from the control at any harvest (Table 5).

The pattern of response for alfalfa top dry matter consisted of an increase at pH 4.0 that peaked at pH 3.5 and then dropped back to a level near the control at pH 3.0 (Table 5). Increases were significant at pH 3.5 for dry weights of total top, leaf, and stem portions at each of three harvests, total top across harvests (+31%), and stubble and root portions at the end of the experiment and at pH 4.0 for dry weights of harvest 3 (H3) total top, leaf, and stem portions and total top across harvests (+17%). Total top, leaf, and stem dry weights were significantly reduced at pH 3.0 at the second harvest, but were not different from the control at other harvests or summed across harvests. The trend shown of increased dry matter production at intermediate pH levels (3.5 and 4.0) with a return to or decrease below the control at a lower pH (3.0) suggests that both stimulatory and inhibitory effects of acid rain may occur in alfalfa. Since alfalfa has a relatively high sulfur (S) requirement, the observed growth stimulation might be caused by the greater supply of SO_4-S provided in sulfuric acid rain treatments, a so-called "fertilizer effect". Though this effect has been suggested by other workers (e.g., Irving, 1979), no critical studies have been performed to determine if acid rain exposure can help meet crop nutrient requirements.

Several other parameters were assessed to explore possible treatment effects on legume forage quality. Top dry matter at each harvest was divided into stem and leaf fractions, and percent leafiness was calculated. Leafiness of clover forage was not affected by acid rain treatment at any harvest (Table 5). Alfalfa percent leafiness was only affected in the final harvest when significant reductions occurred in all three acid rain treatments (Table 5). Since dry weights of both the leaf and stem fractions exceeded the control at pH levels 3.5 and 4.0 in this harvest, reduced leafiness of these treatments indicates that stem growth was stimulated relatively more than leaf growth. Stimulated leaf production did not occur at pH 3.0 to offset reduced leafiness as it did in the 3.5 and 4.0 treatments. Since approximately three-fourths of the nutritional value of alfalfa is contained in leaves (Hanson, 1972), consistent reductions in leafiness without compensating growth stimulation could result in reduced forage feed value.

Leaf and stem crude protein and crude fiber and leaf carotene concentrations of alfalfa and clover are shown in Table 6. (Two samples per treatment, each a composite of tissue from seven pots, were analyzed at the first and final harvests.) No statistically significant treatment differences in forage quality components were found for either clover or alfalfa. However, alfalfa H1 leaf mean crude protein concentration at pH 3.5 was more than 2% greater than the control mean. If this were a real treatment effect, it could be quite important to protein yield, which is a product of protein concentration and dry matter yield, since dry matter production was also greater in this treatment. However, final harvest mean crude protein concentrations of leaves and stems of both alfalfa and clover at pH 3.0 were lower than control means. More extensive tissue sampling and analysis are needed in future studies to investigate these possible effects on legume forage quality.

Table 5. Effects of simulated sulfuric acid rain on dry matter production and percent leafiness of 'Kenland' clover at four harvest and 'Vernal' alfalfa at three harvests.[a]

Treatment	Harvest 1				Harvest 2				Harvest 3				Harvest 4						
	Total top	Leaf	Stem	% Leaf	Total top	Leaf	Stem	% Leaf	Total top	Leaf	Stem	% Leaf	Total top	Leaf	Stem	% Leaf	All Harv. Total top	Stubble	Root
	g				g				g				g				g		
'Kenland' clover																			
5.6	7.53	5.79	1.68	79.38	7.09	5.17	1.59	76.54	7.72	5.09	2.44	68.52	8.71	6.84	1.87	78.55	31.05	5.99	7.37
4.0	8.33	6.25	1.71	78.99	6.51	4.94	1.37	77.89	8.04	5.50	2.77	67.08	8.81	7.42	1.39	84.44	31.68	6.76	8.19
3.5	7.42	5.98	1.63	78.70	7.31	5.39	1.62	77.39	7.76	5.16	2.42	69.09	9.55	7.68	1.87	81.65	32.04	6.36	7.56
3.0	6.29	4.87	1.07	82.05	7.34	5.26	1.78	75.04	8.09	5.16	2.35	69.09	9.10	7.30	1.80	80.80	30.83	6.18	7.74
S.E.[b]	0.49	0.36	0.18	1.84	0.33	0.26	0.14	1.54	0.56	0.30	0.23	1.47	0.45	0.32	0.23	1.68	1.33	0.33	0.35
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.	N.S.	N.S.	N.S.
'Vernal' alfalfa																			
5.6	9.59	4.94	4.18	54.34	8.51	5.36	3.36	61.91	10.61	7.37	3.24	70.21					28.72	5.11	19.72
4.0	10.74	5.51	4.68	54.43	9.04	5.45	3.62	60.27	13.92**	8.91**	5.01**	64.73**					33.70*	5.66	20.04
3.5	11.98**	6.37**	5.64**	52.87	11.13**	6.79**	4.47**	60.77	14.48**	9.24**	5.24**	64.68**					37.59**	6.49**	23.01**
3.0	9.23	4.64	4.10	53.19	6.93*	4.53*	2.58*	63.68	10.80	6.97	3.83	64.72**					26.96	4.97	19.75
S.E.	0.56	0.31	0.29	1.31	0.51	0.24	0.25	1.58	0.77	0.42	0.39	1.29					1.45	0.22	0.77
F	**	**	**	N.S.	**	**	**	N.S.	**	**	**	**					**	**	**

[a] Forage was clipped to 8 cm stubble height at 10% bloom stage on 26 July, 27 August, and 3 October for alfalfa and 26 July, 17 August, 6 September, and 2 October for clover.

[b] Standard error of the mean.

[c] Significance level of the F-test for treatment effects with * and ** denoting $P \leq 0.05$ and 0.01, respectively.

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

TABLE 6 . Effects of simulated sulfuric acid rain on leaf and stem crude protein (CP) and crude fiber (CF) and on leaf carotene concentrations of 'Vernal' alfalfa and 'Kenland' clover at two harvests.[a]

Treatment	Alfalfa					Clover				
	Leaves			Stems		Leaves			Stems	
	CP	CF	Carotene	CP	CF	CP	CF	Carotene	CP	CF
	%		ppm	%		%		ppm	%	
	Harvest 1					Harvest 1				
5.6	15.97	11.14	26	7.03	41.47	16.32	14.95	29	7.50	29.89
4.0	17.03	12.05	28	7.00	43.05	16.47	15.02	32	7.63	28.88
3.5	18.29	11.48	40	6.95	42.92	16.02	13.96	26	7.37	29.30
3.0	15.69	12.10	22	6.70	40.83	15.92	13.93	33	7.83	25.60
S.E.[b]	0.82	0.83	5	0.31	0.70	0.33	0.80	2	0.29	0.87
F[c]	N.S.	N.S.	N.S.	N.S.	N.S.	N.S.	N.S.	N.S.	N.S.	N.S.
	Harvest 3					Harvest 4				
5.6	28.97	14.04	269	13.56	37.85	28.35	14.97	109	13.83	27.87
4.0	28.71	14.26	316	13.60	37.65	28.01	13.99	109	14.16	26.48
3.5	28.74	13.96	310	13.99	37.30	27.59	14.36	117	13.45	27.28
3.0	26.30	14.12	277	12.32	37.41	26.43	14.40	116	13.05	27.78
S.E.	0.63	0.55	35	0.68	1.25	0.53	0.37	8	0.60	0.67
F	N.S.	N.S.	N.S.	N.S.	N.S.	N.S.	N.S.	N.S.	N.S.	N.S.

[a]Crude protein, crude fiber, and carotene concentrations are expressed on a dry weight basis.

[b]Standard error of the mean.

[c]Significance level of the F-test for treatment effects.

Forage and Turf Grass Species

The growth of four forage and one turf grass species was studied. While production of top dry matter generally was not affected by acid rain treatment in multiple harvests of 'Newport' bluegrass and 'Linn' perennial ryegrass or in the single harvest of 'Potomac' orchardgrass, response varied with pH and harvest in 'Alta' tall fescue. Top dry weight at pH 3.0 at the single harvest of 'Climax' timothy was significantly greater than the control.

Orchardgrass and timothy were harvested once in the fall. In timothy, top dry weight at pH 3.0 exceeded the control by 23%; no significant differences in root dry weight or shoot-to-root ratio (S:R) were found (Table 7). Though mean orchardgrass top dry weight at pH 3.0 was also 23% greater than the control, this difference was not statistically significant ($P \leq 0.10$) (Table 7). Orchardgrass root dry weight was 32% lower than the control at pH 4.0 and increased linearly, returning to the control level at pH 3.5 and exceeding the control by 35% at pH 3.0.

For the first four harvests of 'Newport' turftype bluegrass, the grass was allowed to grow to approximately 15 cm. before it was clipped, leaving a 5 cm. stubble; these four harvests occurred at approximately two-week intervals. Thereafter, a weekly clipping schedule was imposed to more closely simulate a turfgrass management regime. The study was terminated when regrowth was limited by cool fall temperatures, and data on stubble and root dry weights and tiller number, as an estimate of turf density, were collected. Significant treatment effects were only found for top dry weight in the first harvest (H1) when top dry weights at pH levels 3.5 and 3.0 were 28 and 30% lower than the control, respectively (Table 8). Mean top dry weights at pH 4.0 in H1 and in all three acid rain treatments in H2 were also lower than the control, but these differences were not statistically significant. Acid rain treatment means at subsequent harvests tended to be comparable to or slightly greater than control means and, summed across all harvests, were within 6% of the control. The data suggest that the early inhibitory acid rain effect was transitory and was not important to final yield.

For 'Alta' tall fescue, an 8 cm. stubble was left after the first harvest (August 23). Clipping height was changed to 5 cm. for the second (September 25) and subsequent harvests, which were conducted at two-week intervals to approximate a pasture management situation. 'Linn' perennial ryegrass was also clipped at two-week intervals to a 5 cm. stubble height starting September 21. The area of harvested green leaf material at H3 through H6 for tall fescue and H2 through H4 for ryegrass was measured using a Licor 3000 leaf area meter.

Treatment differences in ryegrass top dry weight generally were not significant. Summed across all harvests, acid rain treatment means for top dry weight were quite uniform and within 4% of the control (Table 9). While H2 green leaf area at pH 4.0 was 38% greater than the control ($P \leq 0.01$), top dry weight was only 14% greater (N.S.). This might indicate reductions at pH 4.0 in leaf senescence and/or specific leaf weight. Though differences were not statistically significant, acid rain treatment mean stubble dry weights were 3 to 19% greater and mean root dry weights were 14 to 16% lower than the control ($P \leq 0.10$ for root dry weight). The latter effect resulted in higher mean S:R ratios, significantly so at pH 3.5.

Tall fescue forage growth in harvests 4 through 6 was much reduced because of cool fall temperatures (Table 10). Although significant treatment differences in top dry weight occurred at various pH levels and harvests, no consistent treatment response was observed. Relative to the control, mean top dry weight tended to decrease at pH 4.0, increase at pH 3.5 (significant for H3), and then decrease to around the control level at pH 3.0 (significantly lower for H3, H6, and H3-H6). Summed across all harvests, however, mean top dry weights of acid rain treatments were all within 8% of the control. Root dry weights were significantly lower thanthe control at pH levels 4.0 and 3.0. Green leaf area at H6 was significantly lower than the control in all three acid rain treatments. Leaf area and dry matter production were at a very low level at this final harvest in all treatments. Means were particularly low in most acid rain treatments. This suggests that active shoot growth may have ceased somewhat earlier in these treatments.

Chamber-composite samples of harvested top material of tall fescue and perennial ryegrass were analyzed for crude protein (CP), crude fiber (CF), acid detergent fiber (ADF), neutral detergent fiber (NDF), and nutrient contents. No significant treatment effects on CP, CF, ADF, or NDF of either species were found (Table 11). The general comparability of control and acid rain treatment means suggests that acid rain treatment did not affect these tall fescue and ryegrass forage quality components. Several trends for effects on leaf nutrient content were apparent, however. Relative to controls, higher mean total S concentrations were found in all acid rain treatments in both species at both harvests, though these differences were not statistically significant (Table 12). In H1, a continuous increase in S content occurred in both species as treatment pH decreased. This effect is not surprising, since treatment sulfate level also increased as pH decreased. Further study is needed to determine the fate of accumulated S, e.g., to determine if it was incorporated into organic compounds, such as the amino acids cysteine and methionine, or stored as sulfate ion in vacuoles (Bonner and Varner, 1976).

Mean perennial ryegrass Ca and Mg concentrations were lower than respective controls at low acid rain pH levels, particularly at pH 3.0 (Table 12). Differences for Mg were significant at pH levels 3.5 and 3.0 in H1. Acid rain treatment did not appear to affect K levels. Several foliar leaching studies have suggested that acid rain may increase cation loss from leaves. For instance, increased foliar losses of K^+, Mg^{++}, and Ca^{++} from leaves of pinto bean and sugar maple seedlings occurred as pH of an artificial mist was reduced (Wood and Bormann, 1975). Loss of Ca^{++} from tobacco leaves also increased as pH of the leaching solution decreased (Fairfax and Lepp, 1975). Leachate was removed from the growth environment in these two studies, and the possibility that root reabsorption of leached cations might balance previous losses, as was demonstrated with apple (Blanpied, 1979), was not assessed. Further study of acid rain effects on foliar cation leaching and root reabsorption is needed.

Forage nutrient content is important in animal nutrition, as well as plant growth. Grass tetany, hypomagnesaemia, is a metabolic disorder of ruminants associated with low intake or poor utilization of forage Mg. Kemp (1960) suggested a critical level of 0.20% Mg in forage after finding that no cases of grass tetany occurred at herbage Mg concentrations above 0.19%. Since

Kemp and t'Hart (1957) concluded that forage equivalent ratios for K/Mg + Ca greater than 2.2 were associated with significantly increased occurrence of grass tetany, many workers have used this ratio to identify grass tetany potential and to study factors affecting its occurrence (e.g., Karlen et al., 1980a, 1980b; Stratton and Sleper, 1979; Sleper et al., 1980; Brown and Sleper, 1980). In our study, H1 ryegrass Mg levels at pH levels 3.0 and 3.5 fell below the "safe" level of 0.20%, but K/Mg + Ca ratios were well below the critical 2.2 value (1.43 and 1.44 for pH 3.0 and 3.5 treatments, respectively). Consequently, a potential grass tetany problem was not indicated. However, since acid rain treatments (3.0 and 3.5) appeared to affect ryegrass Ca and Mg concentrations, acid rain might affect grass tetany potential of ryegrass under different environmental conditions.

Data for tall fescue did not suggest a similar effect of acid rain on Ca or Mg concentrations. (Note, however, that mean K/Mg + Ca ratios greater than 2.2 occurred in H2 at pH levels 3.5, 4.0, and 5.6.)

Table 7. Effects of simulated sulfuric acid rain on dry matter production and shoot-to-root ratios (S:R) of 'Potomac' orchardgrass and 'Climax' timothy.

Treatment	'Potomac' orchardgrass			'Climax' timothy		
	Top dry weight	Root dry weight	S:R	Top dry weight	Root dry weight	S:R
	g	g		g	g	
5.6	22.47	14.74	1.67	21.07	13.27	1.72
4.0	22.42	10.05**	1.97	18.07	11.73	1.66
3.5	24.74	14.80	1.75	22.94	12.64	1.81
3.0	27.63	19.98**	1.45	26.03*	15.35	1.80
S.E.[a]	1.65	1.26	0.13	1.44	1.10	0.13
F[b]	N.S.	**	N.S.	**	N.S.	N.S.

[a]Standard error of the mean.

[b]Significance level of the F-test for treatment effects with ** denoting $P \leq 0.01$.

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

Table 8. Effects of simulated sulfuric acid rain on dry matter production, tiller number, and shoot-to-root ratio (S:R) of 'Newport' bluegrass.[a]

Treatment	Top Dry Weight at Each Harvest (H)										
	H1	H2	H3	H4 (g)	H5	H6	H7	H8	H9	H10	H11
5.6	2.04	2.17	3.27	2.61	1.06	0.62	0.50	0.15	0.18	0.13	0.05
4.0	1.69	1.96	3.27	2.94	1.12	0.63	0.44	0.15	0.17	0.14	0.07
3.5	1.47**	1.93	3.06	2.75	1.10	0.69	0.47	0.13	0.19	0.13	0.06
3.0	1.42**	1.80	3.13	3.11	1.28	0.78	0.50	0.15	0.21	0.11	0.05
S.E.[b]	0.15	0.15	0.22	0.16	0.08	0.06	0.06	0.02	0.03	0.01	0.01
F[c]	*	N.S.	N.S.	N.S.	N.S.	N.S.	N.S.	N.S.	N.S.	N.S.	N.S.

Treatment	Sum of Top Dry Weights			g			
	H1-H4	H5-H11	H1-H11	Stubble	Root	S:R[d]	Tiller Number
5.6	10.10	2.68	12.81	3.56	6.48	2.84	142.3
4.0	10.00	2.76	12.76	3.01	4.87	3.65	126.1
3.5	9.21	2.77	11.98	3.01	5.49	3.34	136.9
3.0	9.39	3.12	12.61	3.25	5.99	2.92	146.5
S.E.	0.55	0.15	0.59	0.19	0.64	0.33	7.3
F	N.S.	N.S.	N.S.	N.S.	N.S.	N.S.	N.S.

[a]See text for explanation of cutting height and frequency.

[b]Standard error of the mean.

[c]Significance level of the F-test for treatment effects with * denoting $p \leq 0.05$.

[d]S:R was calculated as total top dry weight across all harvests plus stubble, divided by root dry weight.

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

Table 9. Effects of simulated sulfuric acid rain on dry matter production, shoot-to-root ratio (S:R), and green leaf area of 'Linn' ryegrass.[a]

Treatment	Top Dry Weight H1	H2	H3	H4	H5	Total H1-H5	Stubble	Root	S:R[b]
	g								
5.6	16.42	1.89	1.43	0.35	0.15	20.24	6.44	37.38	0.72
4.0	15.35	2.16	1.19	0.55**	0.21	19.46	6.65	32.18	0.83
3.5	15.99	1.84	1.42	0.32	0.17	19.75	7.66	31.32	0.95**
3.0	15.93	2.12	1.45	0.36	0.18	20.03	6.80	32.12	0.87
S.E.[c]	0.55	0.18	0.27	0.05	0.02	0.57	0.34	1.87	0.06
F[d]	N.S.	N.S.	N.S.	**	N.S.	N.S.	N.S.	N.S.	*

Treatment	Green leaf area (cm^2) H2	H3	H4
5.6	193.66	127.00	41.75
4.0	266.51**	131.20	66.14
3.5	201.51	155.46	40.40
3.0	198.55	139.85	42.68
S.E.	15.31	26.63	9.23
F	**	N.S.	N.S.

[a] See text for explanation of cutting height and frequency.

[b] S:R was calculated as total top dry weight across all harvests plus stubble, divided by root dry weight.

[c] Standard error of the mean.

[d] Significance level of the F-test for treatment effects with * and ** denoting $P \leq 0.05$ and 0.01, respectively.

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

Table 10. Effects of simulated sulfuric acid rain on dry matter production, shoot-to-root ratio (S:R), and green leaf area of 'Alta' tall fescue.[a]

Treatment	Top Dry Weight								
	H1	H2	H1+H2	H3	H4	H5	H6	H3-H6	H1-H6
	g								
5.6	10.14	11.52	21.66	2.52	0.63	0.32	0.12	3.59	25.25
4.0	8.79	10.95	19.73	2.45	0.69	0.37	0.08	3.60	23.33
3.5	10.37	12.59	22.96	3.21*	0.65	0.21	0.11	4.18	27.13
3.0	9.07	12.51	21.59	1.77**	0.58	0.25	0.05**	2.64**	24.23
S.E.[b]	0.53	0.46	0.79	0.20	0.06	0.05	0.02	0.23	0.85
F[c]	N.S.	*	*	**	N.S.	N.S.	**	**	*

Treatment	Stubble	Root	S:R[d]	Green leaf area (cm^2)				
				H3	H4	H5	H6	H3-H6
5.6	5.33	21.48	1.47	308.91	129.12	51.38	23.54	545.14
4.0	5.23	18.27*	1.64	267.76	129.64	54.95	10.13**	469.65
3.5	4.90	21.77	1.49	319.27	127.58	40.49	14.17*	514.23
3.0	4.76	17.60**	1.69	219.84	115.68	44.09	7.33**	381.94
S.E.	0.34	0.98	0.08	33.20	15.06	9.15	3.16	56.82
F	N.S.	**	N.S.	N.S.	N.S.	N.S.	**	N.S.

[a]See text for explanation of cutting height and frequency.

[b]Standard error of the mean.

[c]Significance level of the F-test for treatment effects with * and ** denoting $P \leq 0.05$ and 0.01, respectively.

[d]S:R was calculated as total top dry weight across all harvests plus stubble, divided by root dry weight.

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

TABLE 11. Effects of simulated sulfuric acid rain on crude protein (CP), crude fiber (CF), acid detergent fiber (ADF), and neutral detergent fiber (NDF) concentrations of 'Alta' tall fescue and 'Linn' ryegrass at two harvests.[a]

Treatment	Tall fescue				Ryegrass			
	CP	CF	ADF	NDF	CP	CF	ADF	NDF
	%							
Harvest 1					Harvest 1			
5.6	14.33	24.53	31.95	56.94	6.98	22.95	32.26	49.87
4.0	15.02	23.18	32.71	57.83	7.18	22.75	33.59	53.94
3.5	13.70	24.12	32.38	56.00	7.41	23.88	34.21	54.09
3.0	15.75	23.66	32.99	56.97	7.40	22.29	33.00	51.81
S.E.[b]	0.52	1.16	1.12	2.16	0.51	1.10	1.06	2.17
F[c]	N.S.	N.S.	N.S.	N.S.	N.S.	N.S.	N.S.	N.S.
Harvest 2					Harvest 3[d]			
5.6	10.53	24.70	33.75	56.39	8.56	26.58		
4.0	10.60	22.88	31.51	54.38	8.96	26.70		
3.5	10.57	23.86	33.12	55.16	8.14	26.80		
3.0	9.87	25.01	34.21	57.04	8.47	26.82		
S.E.	0.61	0.34	0.73	0.94	0.73	0.54		
F	N.S.	*	N.S.	N.S.	N.S.	N.S.		

[a]Crude protein, crude fiber, acid and neutral detergent fiber concentrations are expressed on a dry weight basis.

[b]Standard error of the mean.

[c]Significance level of the F-test for treatment effects with * denoting $P \leq 0.05$.

[d]Insufficient sample amounts did not permit H3 ryegrass ADF and NDF analyses.

Table 12. Effects of simulated sulfuric acid rain on leaf nutrient concentrations and K/Mg+Ca ratios of 'Alta' tall fescue and 'Linn' ryegrass at two harvests.[a]

Treatment	N	S	K	P	Ca	Mg	Mn	Fe	Cu	B	Zn	Al	K/Mg+Ca
	%						ppm						
Tall fescue - Harvest 1													
5.6	2.29	0.29	2.25	0.45	0.32	0.23	175	65	6	8	33	6	1.89
4.0	2.40	0.36	2.63	0.47	0.34	0.28	216	170	6	7	36	11	1.67
3.5	2.19	0.41	2.69	0.45	0.38	0.25	183	75	5	9	32	6	1.78
3.0	2.52	0.48	2.57	0.37	0.31	0.25	203	467	5	6	48	40	1.83
S.E.[b]	0.08	0.04	0.14	0.04	0.07	0.02	19	182	1	2	10	13	0.20
F[c]	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
Tall fescue - Harvest 2													
5.6	1.68	0.18	2.63	0.56	0.21	0.24	292	129	4	6	19	86	2.24
4.0	1.69	0.27	2.69	0.61	0.21	0.23	328	86	4	6	19	61	2.30
3.5	1.69	0.23	2.65	0.49	0.16	0.21	274	79	4	4	16	46	2.68
3.0	1.58	0.23	2.33	0.41	0.23	0.25	279	83	4	6	17	56	1.98
S.E.	0.09	0.03	0.18	0.04	0.03	0.02	25	15	1	1	2	15	0.46
F	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
Ryegrass - Harvest 1													
5.6	1.12	0.24	1.98	0.33	0.44	0.26	281	84	5	9	27	63	1.17
4.0	1.14	0.30	1.84	0.30	0.46	0.25	273	114	6	10	29	103	1.09
3.5	1.18	0.36	2.02	0.33	0.43	0.17**	297	70	4	11	32	43	1.44
3.0	1.18	0.44	1.99	0.31	0.39	0.19*	237	77	5	8	28	55	1.43
S.E.	0.08	0.03	0.12	0.02	0.04	0.01	36	18	1	2	3	21	0.10
F	NS	*	NS	NS	NS	*	NS	NS	NS	NS	NS	NS	NS
Ryegrass - Harvest 3													
5.6	1.37	0.29	1.67	0.50	0.32	0.24	668	151	6	6	30	130	1.21
4.0	1.43	0.35	1.91	0.57	0.34	0.25	823	550	6	8	40	120	1.30
3.5	1.30	0.34	1.73	0.52	0.28	0.21	617	132	5	8	28	106	1.43
3.0	1.35	0.36	1.66	0.46	0.22	0.20	720	151	5	6	25	150	1.55
S.E.	0.12	0.04	0.14	0.04	0.02	0.02	72	207	1	1	4	21	0.14
F	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS

[a]Concentration data are expressed on a dry weight basis; $\frac{K}{Mg+Ca}$ ratios were calculated on a meq basis.

[b]Standard error of the mean.

[c]Significance level of the F-test for treatment effects with * denoting $P \leq 0.05$.

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

Root Crops

Sharp reductions in root yield caused by simulated sulfuric acid rain treatments were observed for all three root crops studied. Carrot was most sensitive, exhibiting significantly reduced root fresh and dry weights at all three acid rain pH levels (-27 to -44%) and top dry weight at pH levels 3.5 and 3.0 (Table 13). Carrots grown in acid rain treatments were generally shorter and thinner, i.e., a greater percentage of these carrots fell into the smaller length and shoulder-diameter size classes (Table 13). (It should be noted that pale leaf color and fungal leaf spot were observed for carrot in all treatments when plants were about six weeks old. These symptoms were corrected with foliar urea-maneb sprays. Consequently, it is possible that interactions between acid rain treatment and early nutrient or disease stress may have produced more severe effects than would occur under optimal growth conditions.) Reductions in beet top growth and root fresh and dry weights (-43 to -45%) occurred at pH 3.0, and a greater percentage of 3.0 beets were less than 2.5 cm. diameter (Table 14).

Radish was grown in three experiments. Both planting date and chamber type differed for the first two experiments. In the third, radish was planted on the same date in all three chamber types (Table 15). In general, both root fresh and dry weights were significantly reduced at pH 3.0 (-36 to -75%), and top dry weight also tended to be lower at this acid rain treatment level, compared with the control. Significant reductions in radish top and root weights at higher acid rain pH levels (i.e., 3.5 and 4.0) occurred only for plants grown in large round chambers. The objective of the third experiment was to examine possible chamber-type differences by comparing relative treatment responses among the three chamber types. We could not meet this objective because a heavy slug infestation occurred. Significantly, in all three chamber types, we observed no slug damage to plants in 3.0 treatment chambers but considerable (LRC) to severe (SQC) damage in control chambers; damage in 3.5 and 4.0 chambers was intermediate. Similar differential slug damage was also observed in a previous study (Lee et al., in press). These observations suggest that pest-acid rain interactions may be important.

Compared with control plants, relative reductions in root growth exceeded reductions in top growth of these crops. For instance, at pH 3.0, mean reductions of 46, 45, and 54% occurred in root dry weights of carrot, beet, and radish (Experiment 1), respectively, while corresponding mean reductions of 33, 10, and 16% occurred in top dry weights of these crops. Greater relative reduction of root growth might be caused by acid rain effects which limit root growth directly and are associated with soil factors; i.e., reduced rhizosphere pH might lead to increased aluminum and/or manganese availability and result in toxicity. Alternatively, a secondary effect on root growth through restricted carbohyrate supply from the plant top might occur if acid rain treatments were to adversely affect production of carbohydrate in leaves and/or its translocation to the root.

Table 13. Effects of simulated sulfuric acid rain on growth of 'Danvers Half-Long' carrot.

Treatment	Top dry weight	Root fresh weight	Root dry weight	Shoulder-diameter size classes < 1.9 cm.	Shoulder-diameter size classes 1.9-3.2 cm.	Shoulder-diameter size classes > 3.2 cm.	Length size classes < 10.2 cm.	Length size classes 10.2-15.2 cm.	Length size classes 15.2-20.3 cm.	Length size classes > 20.3 cm.
	g			%						
5.6	8.39	138.54	13.36	4.2	31.2	64.6	12.5	31.2	41.7	14.6
4.0	6.86	100.56*	9.18**	25.0*	48.6	26.4**	24.3	24.3	49.3	2.1
3.5	5.78**	76.87**	7.55**	24.0*	44.0	32.0**	36.0*	30.0	26.0	8.0
3.0	5.60**	76.94**	7.15**	30.4**	39.1	30.4**	47.8**	17.4	28.3	6.5
S.E.[a]	0.56	11.63	1.10	6.3	7.0	6.7	6.7	6.6	7.2	3.7
F[b]	**	**	**	*	N.S.	**	**	N.S.	N.S.	N.S.

[a]Standard error of the mean.

[b]Significance level of the F-test for treatment effects with * and ** denoting $P \le 0.05$ and 0.01, respectively.

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

Table 14. Effects of simulated sulfuric acid rain on growth of 'Detroit Dark Red' beet.

Treatment	Top dry weight	Root fresh weight	Root dry weight	Beet diameter size classes < 2.5 cm.	Beet diameter size classes 2.5-3.8 cm.	Beet diameter size classes > 3.8 cm.
	g			%		
5.6	10.03	55.07	10.38	16.0	40.0	44.0
4.0	10.08	59.98	11.40	4.0	48.0	48.0
3.5	10.81	56.25	10.65	16.0	42.0	42.0
3.0	9.01*	31.30**	5.73**	42.0**	40.0	18.0**
S.E.[a]	0.34	5.78	1.14	6.9	7.5	10.2
F[b]	**	**	**	**	N.S.	**

[a]Standard error of the mean.

[b]Significance level of the F-test for treatment effects with ** denoting $P \le 0.01$.

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

Table 15. Effects of simulated sulfuric acid rain on growth of 'Cherry Belle' radish.

Treatment	Top dry weight	Root fresh weight	Root dry weight
	g		
Experiment 1 - LRC, planted April 19, 1979			
5.6	1.94	43.23	2.66
4.0	2.08	39.67	2.30*
3.5	1.83	35.68**	2.09**
3.0	1.63*	18.86**	1.21**
S.E.[a]	0.10	1.74	0.10
F[b]	*	**	**
Experiment 2 - SRC, planted May 25, 1979			
5.6	1.65	39.40	2.36
4.0	1.64	35.43	2.17
3.5	1.59	34.03	2.09
3.0	1.45	17.04**	1.17**
S.E.	0.10	2.69	0.15
F	N.S.	**	**
Experiment 3 - planted September 26, 1979			
SQC			
5.6	1.29	18.07	1.08
4.0	1.43	28.26	1.64
3.5	1.53	25.48	1.51
3.0	1.44	10.75	0.69
S.E.	0.12	4.40	0.22
F	N.S.	*	*
LRC			
5.6	2.00	47.74	2.54
4.0	1.84	54.51	2.91*
3.5	1.67**	34.86**	1.96**
3.0	1.32**	11.66**	0.77**
S.E.	0.09	2.74	0.13
F	**	**	**
SRC			
5.6	1.55	26.79	1.71
4.0	1.33	23.09	1.48
3.5	1.58	27.62	1.72
3.0	1.33	10.13**	0.72**
S.E.	0.09	2.38	0.13
F	N.S.	**	**

[a]Standard error of the mean.

[b]Significance level of the F-test for treatment effects with * and ** denoting $P \leq 0.05$ and 0.01, respectively.

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

Fruit Crops

Stimulation of fruit production at various acid rain treatment levels occurred in two of the three fruit crops studied. Significant increases in fruit fresh weight occurred at pH 3.0 in tomato and at all three acid rain treatment levels in strawberry.

Ripe 'Quinalt' strawberries were harvested twice weekly from August 2 until October 16 when weekly berry production had dropped off sharply. After final harvest of ripe berries, the remaining immature berries were also harvested. Treatments did not differ significantly in number of harvests or in number and fresh weight of unripe berries (data not shown). Ripe berries constituted approximately 90% of total berry fresh weight. Mean fresh weight increases of 51, 71, and 72% over the control occurred for ripe berries in the 4.0, 3.5, and 3.0 acid rain treatments, respectively (Table 16). These large increases resulted from both increased berry number and increased average berry fresh weight. Significant increases of 13 to 21% in top dry weight also occurred in all three acid rain treatments. Thus, an overall stimulation of aboveground strawberry plant growth occurred. Mean root dry weight, however, was 14 and 21% lower at pH levels 3.0 and 3.5, respectively; this reduction was significant at pH 3.5. Since the greatest increases in fruit production occurred in these two treatments, reduced root growth may have resulted from interorgan competition for assimilate. Reductions in root dry weight might also be caused by direct effects of acid rain on root growth.

Ripe fruits of 'Patio' tomato were also harvested twice weekly, from September 25 until October 25, and unripe fruits were picked at the last harvest. Ripe fruit fresh weight constituted 66 to 80% of total fruit weight. Total fruit and total seasonal ripe fruit fresh weights were significantly greater than the control at pH 3.0, by 11 and 31%, respectively (Table 17). This stimulation occurred through the production of a greater number of ripe fruits. A response in terms of average fruit fresh weight or size class distribution did not occur. Treatments did not differ significantly in unripe tomato number and unripe total or average fruit fresh weights. However, mean total unripe fruit fresh weight was considerably lower than the control at pH 3.0 (-30%), and unripe fruits were smaller in acid rain treatments. As in strawberry, a reduction in root dry weight occurred for the treatment in which fruit production was stimulated (pH 3.0 in tomato). This may be caused by interorgan competition or a direct effect of acid rain on root growth. Although tomato plant top dry weight was significantly greater at pH levels 4.0 and 3.5, no advantage for fruit production resulted.

'California Wonder' green peppers were harvested once, on September 24. At harvest, some peppers in all treatments were beginning to lose their green color and differences in fruit maturity were not apparent. Average per fruit fresh and dry weights were 37 to 45% and 37 to 58%, respectively, greater than the control in the acid rain treatments (Table 18). This increased average fruit weight resulted in 20% greater total fruit fresh weight at pH 3.5 ($P \leq 0.10$), but total fruit fresh weights at pH levels 4.0 and 3.0 were within 5% of the control because reductions in fruit number occurred in these treatments. The percentages of acid rain treatment peppers in the largest length and diameter size classes tended to be greater than the control, reflecting the gains in average fruit weight. Stimulation of top dry weight at pH 3.5 occurred. The greater average fruit weights seen in the 4.0 and 3.0 acid rain treatments may have resulted from reduced competition among a smaller number of developing fruits. At pH 3.5, the increased vegetative growth apparently sustained development of a comparable number of peppers (relative to the control) so that greater average ($P \leq 0.05$) and total pepper weights ($P \leq 0.10$) resulted. Unlike the strawberry and tomato data, pepper plant root dry weights did not differ significantly among treatments.

In all three fruit crops, fruit number was affected by acid rain at some treatment levels. In strawberry and tomato, increased fruit number accompanied increased ripe fruit weight. In strawberry, but not in tomato, stimulation in top dry weight occurred along with stimulated fruit production so that assimilate supply may have been of overriding importance. However, in pepper, fruit number was reduced in two acid rain treatments (though comparable total fruit production was maintained through development of greater average fruit weight). Possible direct effects of acid rain treatment on some aspect(s) of reproductive development (e.g., floral initiation and development, pollination, fertilization, and fruit development) may have occurred in these three crops.

Appearance, as well as fruit number and weight, affects marketable fruit yield. In tomato, but not in strawberry or pepper, fruit appearance was affected by acid rain treatment. Small, superficial, yellowish patches or spots were observed at pH levels 3.0 and 3.5 and, in some cases, these small yellow dots later turned black. Fruit injury from acid rain treatment was greatest at pH 3.0 (data not shown). Consequently, it is possible that marketable fruit yield may be adversely affected by acid rain treatment even when stimulation in terms of fruit number and weight has occurred.

Table 16. Effects of simulated sulfuric acid rain on fruit and dry matter production of 'Quinalt' strawberry.

Treatment	Total berry[a]		Ripe berry[a]			Top dry weight	Root dry weight
	Number	Fresh weight (g)	Number	Fresh weight	Average fresh weight		
				g			
5.6	51.9	129.26	36.6	113.04	3.05	40.00	36.17
4.0	62.7*	185.74**	48.8**	170.67**	3.45	45.03*	35.86
3.5	65.9**	215.15**	52.0**	193.90**	3.74**	48.45**	28.46**
3.0	62.9*	208.90**	50.1**	194.89**	3.87**	46.71**	31.26
S.E.[b]	3.7	15.66	3.3	15.24	0.18	1.41	1.93
F[c]	*	**	**	**	**	**	*

[a]Data for "ripe berry" number and fresh weight represent total seasonal ripe berry production; "total berry" data include unripe berries at final harvest.

[b]Standard error of the mean.

[c]Significance level of the F-test for treatment effects with * and ** denoting $P \leq 0.05$ and 0.01, respectively.

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

Table 17. Effects of simulated sulfuric acid rain on fruit and dry matter production of 'Patio' tomato.

Treatment	Total berry Number	Total berry Fresh weight	Ripe berry Number	Ripe berry Fresh weight	Ripe berry Average fresh weight	Unripe berry Number	Unripe berry Fresh weight	Unripe berry Average fresh weight
		g		g	g		g	g
5.6	9.4	443.58	3.7	302.88	77.77	5.7	140.70	28.39
4.0	10.6	438.55	4.1	288.93	67.69	6.5	149.63	21.46
3.5	7.9	431.16	3.2	304.69	87.58	4.6	126.47	23.82
3.0	9.9	494.69*	5.6**	396.67**	71.73	4.3	98.02	21.52
S.E.[a]	0.8	17.16	0.5	19.96	6.02	0.7	18.20	4.04
F[b]	N.S.	*	**	**	N.S.	N.S.	N.S.	N.S.

	Top dry weight	Root dry weight	Ripe berry size classes < 5 cm.	Ripe berry size classes 5-6.3 cm.	Ripe berry size classes > 6.3 cm.	Unripe berry size classes < 5 cm.	Unripe berry size classes 5-6.3 cm.	Unripe berry size classes > 6.3 cm.
	g	g	%	%	%	%	%	%
5.6	34.48	5.06	48.4	47.7	3.8	80.1	19.8	0
4.0	38.41**	4.95	48.9	51.1	0	95.8	4.2**	0
3.5	38.54**	5.11	35.9	61.7	2.4	92.1	5.5*	2.4
3.0	35.76	4.31**	53.7	43.4	2.8	99.1	0.8**	0
S.E.	1.09	0.21	9.0	9.0	2.0	5.8	4.3	1.2
F	*	*	N.S.	N.S.	N.S.	N.S.	*	N.S.

[a]Standard error of the mean.

[b]Significance level of the F-test for treatment effects with * and ** denoting $P \leq 0.05$ and 0.01, respectively.

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

Table 18. Effects of simulated sulfuric acid rain on fruit and dry matter production of 'California Wonder' green pepper.

Treatment	Total fruit: Number	Total fruit: Fresh weight	Total fruit: Dry weight	Average fruit: Fresh weight	Average fruit: Dry weight	Top dry weight	Root dry weight
		g					
5.6	5.9	193.12	12.72	36.86	2.38	9.26	5.70
4.0	4.1*	202.71	13.46	50.34	3.38*	9.99	6.21
3.5	5.4	232.22	14.83	52.03	3.26*	10.65**	5.83
3.0	4.1*	201.97	14.39	53.63	3.76**	8.27	5.26
S.E.[a]	0.5	11.58	0.75	4.72	0.29	0.37	0.27
F[b]	*	N.S.	N.S.	N.S.	**	**	N.S.

	Length size classes: < 5 cm.	Length size classes: 5-6.3 cm.	Length size classes: > 6.3 cm.	Diameter size classes: < 3.8 cm.	Diameter size classes: 3.8-5 cm.	Diameter size classes: > 5 cm.
	%					
5.6	51.4	26.7	21.8	31.5	25.8	42.7
4.0	34.6	33.3	32.0	16.2	21.7	62.1
3.5	32.2	33.8	34.1	13.0	19.6	65.7
3.0	34.2	11.3	54.4**	14.6	18.4	66.9
S.E.	6.0	6.8	7.1	5.6	6.2	7.3
F	N.S.	N.S.	*	N.S.	N.S.	N.S.

[a]Standard error of the mean.

[b]Significance level of the F-test for treatment effects with * and ** denoting $P \leq 0.05$ and 0.01, respectively.

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

Cole Crops

Data for the three cole crops studied are summarized in Table 19. In broccoli, the "marketable top" portion consisted of the immature flowering head cut 127 mm below its top. Leaves were removed and combined with the remaining "non-marketable" stem and leaf portion. In cauliflower, the marketable head was cut directly below the lowest flowering lateral and leaves were included with the non-marketable, remaining stem. Cabbage was cut directly below the head, leaving the non-marketable stem. In all three crops, the non-marketable portion was removed at soil level.

No significant treatment effects on marketable top fresh or dry weights of these three crops occurred, and marketable yields were extremely low in all treatments (Table 19). In broccoli, mean marketable top dry weight was 24% lower than the control at pH 3.0 ($P \leq 0.10$), mean root dry weight was 20% greater (N.S.), and total dry weight was very comparable. Consequently, dry matter partitioning may have been affected by acid rain treatment. Vegetative growth, i.e., root production, may have persisted at the expense of reproductive development at pH 3.0, or an inhibitory effect on reproductive development might have allowed greater root growth. In cabbage, non-marketable top dry weight at pH 3.5 was significantly lower than the control by 28%. Though not significantly different than the control, mean marketable top dry weight was 47% greater at pH 3.5 and mean root dry weight was 17% lower. Unlike broccoli, relatively more dry matter may have gone into marketable top weight at pH 3.5 with less available for stem and, possibly, root growth.

Leaf Crops

The leafy vegetable crops 'Lucullus' Swiss chard, 'Bibb' and 'Great Lakes' lettuce, 'Southern Giant Curled' mustard greens, and 'Improved Thick Leaf' spinach were grown ('Great Lakes' lettuce was harvested before full head formation had occurred, because cool temperatures for this late-season planting had greatly slowed growth.) Mean leaf fresh and dry weights of mustard greens were 15 to 30% and 10 to 31%, respectively, lower than the control in the acid rain treatments (Table 20). These reductions in leaf fresh weight were significant at pH levels 4.0 and 3.0 and in dry weight at pH 3.0. Significant reductions in leaf dry weight of 'Great Lakes' lettuce occurred at pH levels 3.0 and 3.5 (Table 20). Mean leaf fresh and dry weights were from 14 to 19% and 12 to 21%, respectively, lower than the control in the acid rain treatments. Leaf production of chard, 'Bibb' lettuce, and spinach was not sensitive to acid rain simulants (Tables 20 and 21).

At harvest, acid rain injury was visible on leaves of lettuce, Swiss chard, spinach, and mustard greens. Marketability of the latter three crops was reduced by this injury at pH 3.0. In lettuce, injury consisted of necrotic spots. In Swiss chard, mustard greens, and spinach, white flecking occurred. If similar responses were to occur in field-grown plants, acid rain might reduce marketable yield through effects on crop appearance rather than by reduced weight.

Although spinach leaf, stem, and root production were not sensitive to acid rain treatment, time of flowering did appear to be affected (Table 21). Flower presence and/or bolting (stem elongation) were noted at harvest. Flowering at pH levels 3.5 and 3.0 occurred earlier than in the control or at pH 4.0.

Table 19. Effects of simulated sulfuric acid rain on yield and dry matter production of 'Italian Green Sprouting' broccoli, 'Golden Acre' cabbage, and 'Early Snowball' cauliflower.

Treatment	Marketable top weight[a] Fresh	Marketable top weight[a] Dry	Nonmarketable top[a] dry weight	Total top dry weight	Root dry weight	Total dry weight
	g					
'Italian Green Sprouting' broccoli						
5.6	44.63	6.06	29.67	35.74	12.27	48.00
4.0	39.77	5.53	29.21	34.83	10.00	44.74
3.5	40.90	5.37	33.50	38.87	10.42	49.30
3.0	33.26	4.58	29.49	34.07	14.78	48.85
S.E.[b]	2.95	0.40	2.14	2.12	1.24	2.31
F[c]	N.S.	N.S.	N.S.	N.S.	*	N.S.
'Golden Acre' cabbage						
5.6	240.81	31.34	41.61	72.95	14.16	
4.0	242.70	27.54	37.32	64.86	12.89	
3.5	353.91	35.56	29.99**	65.55	11.80	
3.0	218.05	25.91	43.65	69.56	16.62	
S.E.	41.91	4.09	2.60	3.41	1.83	
F	N.S.	N.S.	**	N.S.	N.S.	
'Early Snowball' cauliflower						
5.6	69.62	6.36	24.47	30.92	6.29	
4.0	83.33	8.10	26.59	34.69	6.57	
3.5	101.64	8.86	25.08	33.94	7.02	
3.0	71.73	6.43	27.58	34.01	7.44	
S.E.	11.55	0.94	1.80	1.59	0.49	
F	N.S.	N.S.	N.S.	N.S.	N.S.	

[a]See text for descriptions of "marketable" and "non-marketable" crop portions.

[b]Standard error of the mean.

[c]Significance level of the F-test for treatment effects with * and ** denoting $P \leq 0.05$ and 0.01, respectively.

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

Table 20. Effects of simulated sulfuric acid rain on leaf and root weights of 'Lucullus' Swiss chard, 'Great Lakes' lettuce, 'Bibb' lettuce, and 'Southern Giant Curled' mustard greens.

Treatment	Swiss chard			'Great Lakes' lettuce			'Bibb' lettuce			Mustard greens		
	Leaf weight Fresh	Leaf weight Dry	Root dry wt.	Leaf weight Fresh	Leaf weight Dry	Root dry wt.	Leaf weight Fresh	Leaf weight Dry	Root dry wt.	Leaf weight Fresh	Leaf weight Dry	Root dry wt.
	g											
5.6	99.72	16.66	13.35	171.88	13.04	1.54	129.97	6.13	1.33	59.28	7.30	2.06
4.0	93.39	17.14	12.87	146.96	11.48	1.26	134.31	6.54	1.25	49.22*	6.26	2.17
3.5	103.24	17.40	13.21	138.55	10.29**	1.32	132.64	5.95	1.17	51.55	6.54	1.85
3.0	90.03	16.30	13.11	146.28	10.39**	1.10	131.84	6.42	1.04	41.71**	5.04**	1.77
S.E.[a]	7.27	0.91	1.36	9.53	0.59	0.12	4.71	0.18	0.08	3.16	0.39	0.17
F[b]	N.S.	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 for treatment effects with ** denoting $P \leq 0.01$.

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

Table 21. Effects of simulated sulfuric acid rain on leaf fresh weight, dry matter production and flowering category of 'Improved Thick Leaf' spinach.

Treatment	Leaf weight		Non-marketable	Total top	Root	Flowering category	
	Fresh	Dry	stem dry wt.[a]	dry wt.	dry wt.	No flower	Flower/ bolted
	g					%	
5.6	32.32	3.58	0.65	4.23	1.63	92.9	7.1
4.0	28.99	3.50	0.82	4.32	1.78	92.9	7.1
3.5	31.98	3.68	0.81	4.49	1.61	78.6	21.4
3.0	27.44	3.33	0.69	4.02	1.40	57.1	42.8
S.E.[b]	2.33	0.31	0.06	0.35	0.24		
F[c]	N.S.	N.S.	N.S.	N.S.	N.S.		

[a]Plants were harvested 2.5 cm above the soil line for leaf weight determination; dry weight of the remaining stem portion is shown.

[b]Standard error of the mean.

[c]Significance level of the F-test for treatment effects.

OTHER CROPS

Onion

Fresh and dry bulb weights of Sweet Spanish-type onion were not affected by acid rain treatment (Table 22), nor was the size-class distribution of bulbs (data not shown). Shoot production was stimulated at pH 3.0, relative to the control, as shown by the 30% greater top dry weight. However, this stimulation apparently was not translated into greater bulb production.

Pea

Pod plus pea fresh and dry weights, pea fresh and dry weights, and dry weights of the stem plus leaf and root portions of 'Marvel' pea were not affected by acid rain treatment (Table 23). Pod dry weight was 9% lower than the control at pH 3.0, although, in contrast, acid rain treatment pod plus pea dry weights were virtually identical to the control (within 3%).

Potato

'White Rose' potato was chosen in this study as an example of an important tuber crop. Relative to the control, mean total tuber fresh weight was 7 and 11% greater at pH levels 4.0 and 3.5, respectively, but was 8% lower at pH 3.0 (Table 24). Only the increase at pH 3.5 was statistically significant. On a dry weight basis, a significant reduction at pH 3.0 was observed. Tubers were assigned to two size classes, class "A" tubers ($\geq$ 4.8 cm) and class "B" tubers (< 4.8 cm diameter). The smaller "B" tubers comprised more than 90% of total tuber fresh and dry weights. The significant reduction in dry weight of "B" tubers was responsible for the reduction in total tuber production at pH 3.0. On average, fewer "B" tubers (and, consequently, fewer total tubers) were formed at pH levels 3.0 and 3.5. However, these tubers had greater average fresh weight than those of the control. Presumably, the formation of fewer tubers resulted in reduced competition among tubers for available resources during tuber growth and, subsequently, in greater average fresh weight of "B" tubers. The significant stimulation in top (leaf plus stem) dry weight which occurred at pH 3.5 (Table 24) may also have contributed to this effect through greater photosynthate production and availability to pH 3.5 tubers. Although the substantially greater average "B" tuber fresh weight at pH 3.5 more than compensated for reduced tuber number (so total tuber fresh weight exceeded that of the control), this did not occur at pH 3.0. In the pH 3.0 treatment, mean tuber number was reduced to a greater extent, yet a relatively greater compensatory average "B" tuber gain in fresh weight did not occur. This may have been caused by a lack of stimulation of top dry weight at pH 3.0 and a resulting inadequate photosynthate supply to support such compensation.

Tuber number in potato is, in part, a function of main stem number (Ivins and Milthorpe, 1963). A main stem is a semi-independent plant which has arisen from the planted mother tuber. The significant reduction in tuber number at pH 3.0, therefore, appears to be related to the concurrent, though not statistically significant, reduction in stem number ($P \leq 0.10$) (Table 24). Consequently, reduced tuber production at pH 3.0, both in terms of tuber number and total weight, may have occurred indirectly following a direct acid rain effect on stem number. To test whether this indirect effect might occur, effects of acid rain treatment on potato sprouting and on tuber production should be examined separately in future studies. Significant reductions in root dry weight in the pH 3.5 and 3.0 treatments also occurred. The severe reduction in pH 3.0 root growth (-31%) might reflect the reduction in stem number. Reduced root growth may also have affected tuber production indirectly by limiting nutrient and water supply to the plant top, redu-ducing photosynthesis, and subsequently, limiting sucrose supply to developing tubers.

Table 22. Effects of simulated sulfuric acid rain on bulb fresh weight and dry matter production of Sweet Spanish onion.

Treatment	Bulb weight Fresh	Bulb weight Dry	Top dry weight
	g		
5.6	410.11	29.10	15.54
4.0	424.28	31.80	14.53
3.5	457.44	33.31	16.81
3.0	411.99	32.12	20.14**
S.E.[a]	22.55	1.58	1.15
F[b]	N.S.	N.S.	**

[a]Standard error of the mean.

[b]Significance level of the F-test for treatment effects with ** denoting $p \leq 0.01$.

**Symbol following dry weight value denotes significant difference from control mean with $P \leq 0.01$ for two-sided t-test.

Table 23. Effects of simulated sulfuric acid rain on pea, pod, and dry matter production of 'Marvel' pea.

Treatment	Pod Number	Pod + pea weight Fresh	Pod + pea weight Dry	Pea weight Fresh	Pea weight Dry	Pod dry weight	Stem + leaf dry weight	Root dry weight
		g						
5.6	14.6	60.78	11.20	21.55	4.21	7.00	13.61	2.23
4.0	13.9	61.65	11.18	22.57	4.48	6.70	14.18	2.04
3.5	14.2	60.38	11.40	21.13	4.08	7.32	13.59	2.17
3.0	13.9	59.37	10.81	22.37	4.46	6.35*	13.00	2.37
S.E.[a]	0.6	1.71	0.31	0.95	0.23	0.21	0.39	0.11
F[b]	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 for treatment effects with * denoting $p \leq 0.05$.

*Symbol following dry weight value denotes significant difference from control mean with $P \leq 0.05$ for two-sided t-test.

Table 24. Effects of simulated sulfuric acid rain on stem number, dry matter production, and tuber yield of 'White Rose' potato.

Treatment	Total tuber weight		"A" tuber weight[a]		"B" tuber weight			"B" tuber number	Total tuber no.	Stem no.	Top dry wt.	Root dry wt.
	Fresh	Dry	Fresh	Dry	Fresh	Dry	Average					
	g										g	
5.6	691.79	149.53	54.31	12.22	637.48	137.31	30.60	22.4	22.8	5.9	11.14	3.71
4.0	742.84	157.33	47.35	10.60	695.49	146.73	34.29	20.6	20.9	6.3	13.76**	3.65
3.5	765.00*	157.07	84.61	18.10	680.39	138.97	39.41**	18.0	18.6	5.2	14.14**	3.00*
3.0	637.58	128.62**	60.52	12.84	577.06	115.78*	38.06*	15.8**	16.3**	4.4	10.85	2.54**
S.E.[b]	21.14	4.86	33.16	7.15	34.95	7.23	2.32	1.7	1.5	0.5	0.65	0.25
F[c]	**	**	N.S.	N.S.	N.S.	*	*	*	*	N.S.	**	**

[a]Class "A" tubers were ≥ 4.8 cm diameter and class "B" tubers were < 4.8 cm. diameter.

[b]Standard error of the mean.

[c]Significance level of the F-test for treatment effects with * and ** denoting P ≤ 0.05 and 0.01, respectively.

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

CONCLUSIONS

Yield of approximately two-thirds of the crops surveyed was not affected by simulated H_2SO_4 rain treatment. Equal numbers of the remaining crops exhibited stimulatory and inhibitory yield responses. These results did not suggest that acid rain treatment either generally inhibited or stimulated crop productivity. Moreover, the acid rain simulant treatments used represent fairly extreme conditions in that they 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). Consequently, crops which did not exhibit yield inhibition under the conditions of this study would not be expected to show such a response to ambient acid rain under field conditions.

Crop response appeared to depend on crop species and crop product. For example, while forage yield of alfalfa and timothy was stimulated at some acid rain pH levels, yield of the remaining forage legume and grass species was not generally affected by acid rain treatment. Although dry matter yield of two horticultural leaf crops, mustard greens and head lettuce, was reduced, that of the remaining leaf crops was not affected. However, root and fruit crop species exhibited generalized responses (yield inhibition and stimulation, respectively) which appeared to be more closely associated with crop product than was seen for other crop product groupings.

Effects of simulated H_2SO_4 rain treatments on crop quality, as well as yield, were important. For example, although spinach leaf production was not affected by acid rain treatment, crop quality and marketability were adversely affected by the presence of foliar injury (pH 3.0). Similarly, quality and marketability of tomato were reduced by the presence of injury on fruits (pH 3.0). The size-class distribution of crops was also affected by acid rain treatment (i.e., carrot and beet), and effects on this quality factor paralleled those found for yield. Effects on nutritive value of fruit and vegetable crops, e.g. mineral and vitamin content, as well as crop product appearance and size, may also be important and should be examined. Future studies should also continue to evaluate effects of acid rain on mineral, protein, and fiber contents of forage crops. Comparable evaluation of effects on grain quality is also needed.

Since conclusions drawn from results of this study only pertain to its specific experimental conditions, further research is obviously needed before general statements regarding acid rain effects on crop quality and yield can be made. Objectives of subsequent studies should also include understanding the causes of observed yield and quality responses by examining effects on underlying morphological, physiological, and biochemical processes. Results of our initial crop survey suggest numerous hypotheses and areas for such research. For instance, for crops in which yield increases from acid rain treatment occurred, suggested study areas include effects on plant nutrition (e.g., alfalfa and strawberry) and reproductive development (e.g., strawberry and tomato). For crops in which crop product yield or other growth or dry matter reductions occurred, suggested study areas include effects on carbohydrate production, translocation, storage, and utilization (e.g., radish, mustard greens, potato, and ryegrass). Additional worthwhile study areas include dry matter partitioning, crop canopy development and/or senescence, foliar cation leaching and root reabsorption, crop-pest interactions, possible mechanisms of crop adaptation to acid rain stress, and interactions between acid rain and environmental factors such as temperature, light, soil type and pH, and liming and fertilizer practices. Finally, responses of different cultivars within a crop species may be different and should be examined in future experiments.

1979 STUDY-END SOIL ANALYSIS AND FOLIAR INJURY ESTIMATION

Soil samples were composited on a treatment basis after final harvest of crops. Complete soil analyses were performed by the OSU Soil Testing Laboratory for beet, peanut, ryegrass, and timothy. Basic cations, extractable SO_4-S, and pH were analyzed for other crops. The analytical methods used were described by Berg and Gardner (1978).

Although statistical analysis of the data was not possible since only one aggregate sample per treatment was tested, several points are noteworthy. Relative to the controls, lower soil pH at 3.0 was found for several crops, e.g., peanut, timothy, ryegrass, bluegrass, tall fescue, and orchardgrass (Tables 25 and 26). The pH difference which was found, however, was generally within the error/sensitivity range for pH measurement and, in two cases, pH at 3.0 was actually greater than the control (i.e., strawberry and 'Bibb' lettuce). Consequently, the data did not indicate a general trend of reduced soil pH for lower pH acid rain treatments. However, soil pH may have been altered in some of the longer-duration crops, such as the grasses, and this possibility should be examined more closely in subsequent studies.

Evidence of soil SO_4-S accumulation at lower treatment pH was seen for all crops, except radish in Experiment 3, LRC. This trend was particularly apparent at pH 3.0. No other treatment-related trends were identified for the other measured soil parameters.

Visual estimates of percent foliar injury caused by simulated acid rain treatment were made several times during the growth of each crop. Estimates were made to the nearest 5%, except any injury, no matter how slight, was rated as 5%. Although foliar injury at final harvest was observed for most crops at pH levels 3.0 and 3.5, the amount of leaf area affected was generally small, i.e., 5% or less (Table 27). Mean foliar injury at harvest exceeded 10% at pH 3.0 in only four crops, cauliflower, mustard greens, radish, and spinach. No injury at final harvest was observed for three crops, carrot, onion, and strawberry. Leaf senescence at final harvest prevented estimation of foliar injury for barley, Swiss chard, oat, potato, tomato, and wheat. No foliar injury was observed in barley, oat, and wheat before harvest (Table 28).

Table 25. 1979 Study-end Complete Soil Analysis Results

Sample Number	Treatment		pH	Lime Req.	ppm P	ppm K	meq/100 g Ca	meq/100 g Mg	meq/100 g Na	ppm SO_4	% OM	CEC	% Total N	ppm NO_3-N	ppm NH_4-N	Free $CaCO_3$
	Beet															
33		3.0	5.6	6.6	20	101	10.3	5.0	1.0	38.2	1.88	18.6	.05	2.03	4.39	1.14
34		3.5	5.7	6.7	17	90	10.8	5.3	0.58	34.5	1.88	18.6	.05	1.71	3.96	0.90
35		4.0	5.6	6.7	25	94	10.2	5.0	0.51	35.3	2.08	17.3	.05	1.93	3.86	1.48
36		5.6	5.7	6.6	18	98	10.6	5.2	0.41	29.0	1.98	19.0	.05	0.64	4.82	1.55
	Peanut															
41		3.0	5.8	6.8	23	137	11.5	5.7	0.31	22.3	1.19	19.4	.06	5.76	2.98	1.24
42		3.5	5.9	6.8	23	144	11.6	5.7	0.30	19.8	1.03	18.6	.06	5.33	3.09	1.38
43		4.0	6.0	6.8	21	132	11.0	5.3	0.30	15.3	0.93	18.6	.06	3.84	2.67	1.46
44		5.6	6.1	6.8	21	132	11.1	5.6	0.29	11.2	1.24	19.2	.06	4.16	2.88	1.17
122	dup	3.5	6.0	6.8	20	148	11.2	5.8	0.31	17.8	1.27	19.1	.06	1.71	5.33	1.07
	Timothy															
25		3.0	5.8	6.7	19	129	11.1	5.0	0.60	46.8	1.93	17.2	.05	0.86	1.82	1.31
26		3.5	6.1	6.8	20	129	10.9	5.0	3.8	24.7	2.14	17.4	.06	1.18	1.82	1.41
27		4.0	6.1	6.7	20	148	11.0	5.0	2.2	14.2	2.08	17.3	.06	0.62	1.18	0.93
28		5.6	6.2	6.7	20	133	10.6	5.0	1.7	17.8	2.29	17.3	.05	0.11	0.96	0.98
123	dup	3.5	6.0	6.8	18	168	11.1	5.3	0.28	20.4	1.40	18.5	.06	0.64	2.56	0.79
	Ryegrass															
105	Ch 4	3.0	6.1	6.8	17	109	11.7	5.8	0.28	18.4	0.57	18.4	.06	0.64	1.49	0.92
106	11	3.0	5.9	6.7	18	117	10.7	5.4	0.29	16.4	1.24	18.4	.06	0.75	1.39	1.07
107	5	3.5	6.4	6.9	17	117	10.9	5.6	0.38	7.7	1.14	19.0	.05	0.21	2.03	1.52
108	12	3.5	6.3	6.8	15	121	11.4	5.8	0.30	7.5	1.47	18.8	.06	0.21	1.49	1.57
109	3	4.0	6.3	6.8	14	101	10.1	5.2	0.25	4.7	1.29	19.2	.05	0.21	1.71	1.14
110	10	4.0	6.3	6.9	16	121	11.2	5.6	0.27	5.8	1.40	21.3	.06	0.53	1.71	<0.75
111	6	5.6	6.4	6.9	14	117	11.3	5.7	0.31	2.4	1.58	18.9	.06	0.43	5.33	0.88
112	13	5.6	6.4	6.8	14	129	11.6	5.9	0.29	5.8	1.50	18.9	.06	0.64	2.77	1.57
120	dup 4	3.0	6.1	6.8	16	109	10.7	5.4	0.29	15.2	1.27	19.3	.06	0.43	1.39	0.95
121	dup 3	4.0	6.3	6.8	16	113	10.8	5.5	0.28	4.9	1.42	18.8	.06	0.85	1.07	1.05
	Pepper															
124	BF*	3.0	5.3 (5.4)	6.7	21	191	10.3	4.9	0.23	35.4	0.98	17.2	.07	44.83	3.30	1.07
125	AF*	3.0	5.3 (5.2)	6.7	23	254	11.2	5.2	0.21	32.1	1.03	18.2	.07	52.98	2.45	1.48
126	BF	5.6	5.6 (5.5)	6.8	19	199	10.7	5.1	0.23	18.4	1.34	17.1	.07	39.76	3.20	1.17
127	AF	5.6	5.3 (5.3)	6.7	28	230	10.5	5.0	0.24	41.5	0.88	17.4	.07	47.54	2.98	0.91
	Tomato															
128	BF	3.0	5.5 (5.5)	6.9	21	203	11.0	5.3	0.25	46.2	1.19	17.9	.07	38.70	8.00	1.43
129	AF	3.0	5.0 (5.0)	6.6	36	234	10.4	5.1	0.23	65.2	1.09	17.8	.07	50.74	2.98	1.5
130	BF	5.6	5.7 (5.7)	6.9	21	195	10.0	4.8	0.24	30.4	1.24	18.3	.07	29.35	20.89	1.41
131	AF	5.6	5.1 (5.2)	6.7	31	226	10.0	4.8	0.25	46.7	0.83	17.7	.07	65.88	3.30	1.03

*BF Before Fertilizer Addition
*AF After Fertilizer Addition
[a]Data in parentheses are results of replicate tests.

Table 26. 1979 Study-end Partial Soil Analysis Results

Sample Number	Treatment	pH	ppm SO_4-S	ppm K	meq/100 g Ca	meq/100 g Mg	meq/100 g Na
Alfalfa							
057	3.0	6.0	41.0	90	10.8	5.1	0.53
058	3.5	6.1	12.1	94	11.0	5.3	0.49
059	4.0	6.1	7.6	86	11.0	5.1	0.38
060	5.6	6.2	6.1	101	11.3	5.0	1.6
Bluegrass							
085	3.0	6.0	15.5	164	11.2	5.4	0.26
116	3.0	6.0	15.5	98	10.9	5.3	0.32
086	3.5	6.2	4.6	176	11.2	5.3	0.28
087	4.0	6.3	2.6	168	11.0	5.2	0.26
088	5.6	6.5	1.7	164	11.6	5.6	0.28
Carrot							
069	3.0	5.5	18.8	109	10.2	5.0	0.23
070	3.5	5.5	12.7	109	10.4	5.1	0.25
071	4.0	5.7	8.3	107	10.2	5.0	0.23
072	5.6	5.9	4.6	86	10.1	5.0	0.22
Clover							
049	3.0	5.7	32.0	94	11.1	4.9	0.33
050	3.5	6.0	15.0	105	11.5	5.2	0.42
051	4.0	5.8	29.7	90	10.8	4.9	0.33
052	5.6	5.9	12.6	98	11.2	5.1	0.31
Corn							
021	3.0	5.7	30.0	94	11.1	5.3	0.31
022	3.5	5.8	14.7	113	11.2	5.4	0.31
023	4.0	5.9	11.8	94	11.0	5.1	0.28
024	5.6	5.8	17.5	90	11.1	5.2	0.30
Cucumber							
045	3.0	5.5	28.5	90	10.8	5.0	0.35
046	3.5	5.7	14.2	98	10.7	5.1	0.34
047	4.0	5.9	6.4	113	11.2	5.4	0.32
048	5.6	5.8	10.1	105	11.0	5.2	0.32
Lettuce - Bibb							
089	3.0	6.2	23.3	285	13.5	5.8	1.8
090	3.5	5.9	14.1	105	12.4	6.0	0.29
091	4.0	6.0	16.9	109	12.5	6.0	0.30
092	5.6	6.0	12.3	117	12.5	6.0	0.30
115	5.6	6.0	16.4	94	11.9	5.7	0.36
Lettuce - Head							
093	3.0	6.0	15.3	105	11.7	5.6	0.25
094	3.5	6.2	7.2	105	11.4	5.5	0.23
095	4.0	6.3	5.8	129	12.7	6.2	0.25
113	4.0	6.1	6.5	109	12.1	5.8	0.26
096	5.6	6.3	5.8	113	12.3	5.9	0.26
Onion							
017	3.0	5.7	10.9	152	11.4	5.1	0.28
018	3.5	5.6	4.5	160	11.2	5.1	0.35
019	4.0	5.7	2.2	137	10.6	4.8	0.23
020	5.6	5.7	2.8	129	11.1	5.0	0.26
119	5.6	5.7	3.3	125	10.9	4.9	0.30
Orchardgrass							
037	3.0	5.8	30.0	105	10.6	4.7	0.28
038	3.5	6.1	14.5	125	10.6	4.7	0.28
039	4.0	6.1	11.2	129	10.6	4.7	0.25
117	4.0	6.1	14.5	144	10.0	4.5	0.38
040	5.6	6.1	8.7	125	10.0	4.4	0.30

1979 Study-end Partial Soil Analysis Results (Cont.)

Sample Number	Treatment	pH	ppm SO_4-S	ppm K	meq/100 g Ca	meq/100 g Mg	meq/100 g Na
	Pepper						
029	3.0	5.6	21.3	125	10.6	4.7	0.28
030	3.5	5.7	10.1	129	10.5	4.6	0.25
031	4.0	5.9	8.3	125	10.4	4.6	0.30
032	5.6	5.8	10.4	137	10.7	4.9	0.27
	Radish II - SRC						
073	3.0	5.7	13.0	140	11.8	5.6	0.27
074	3.5	5.8	10.2	133	12.3	5.9	0.28
075	4.0	5.9	3.4	129	12.1	5.8	0.29
076	5.6	5.9	4.7	129	11.8	5.6	0.30
	Radish II - SQC						
077	3.0	5.8	13.1	137	12.0	5.7	0.28
078	3.5	5.8	7.8	133	12.0	5.7	0.29
079	4.0	5.8	6.1	125	12.4	5.7	0.28
080	5.6	5.8	3.5	140	12.3	5.8	0.28
	Radish II - LRC						
081	3.0	5.9	15.4	148	12.6	5.9	0.28
082	3.5	5.9	9.4	129	11.9	5.7	0.27
083	4.0	5.8	10.0	133	12.3	5.8	0.29
084	5.6	5.9	15.0	133	12.5	6.0	0.29
	Soybean						
061	3.0	5.7	36.5	109	11.2	5.3	0.29
062	3.5	5.9	19.5	109	11.4	5.5	0.31
063	4.0	6.0	15.9	101	11.2	5.4	0.29
064	5.6	6.0	14.2	101	11.0	5.2	0.30
	Strawberry						
053	3.0	6.3	43.6	90	10.8	5.0	1.9
054	3.5	5.9	19.5	78	10.6	4.9	1.2
118	3.5	5.4	38.1	105	11.4	5.1	0.38
055	4.0	5.9	15.8	89	10.6	5.0	0.87
056	5.6	5.7	18.1	86	10.5	5.0	0.65
	Tall Fescue						
101	3.0	6.1	13.2	113	11.5	5.6	0.33
102	3.5	6.4	6.0	109	11.5	5.7	0.34
114	3.5	6.3	8.3	90	11.5	5.6	0.44
103	4.0	6.4	3.7	109	11.0	5.3	0.30
104	5.6	6.4	3.5	101	11.3	5.4	0.30
	Tomato						
065	3.0	5.5	29.7	78	10.2	4.7	0.30
066	3.5	5.6	12.9	82	10.9	5.1	0.33
068	4.0	5.7	22.1	86	10.1	4.7	0.31
067	5.6	5.5	19.3	90	10.3	4.7	0.33

Table 27. Estimated mean percent foliar injury at final harvest caused by simulated sulfuric acid rain treatment of 1979 survey crops.[a,b]

Crop	Treatment pH 3.0	3.5	4.0
Alfalfa	4.3	0.4	0.0
Beet	5.0	1.2	0.2
Bluegrass[c]	5.0	3.6	0.4
Broccoli	5.0	3.2	0.0
Cabbage	4.3	0.0	0.0
Carrot	0.0	0.0	0.0
Cauliflower	14.6	0.4	0.0
Clover	5.0	0.0	0.0
Corn	5.0	0.0	0.0
Tall fescue[c]	7.9	5.0	0.0
Lettuce - Bibb	5.0	0.0	0.0
Lettuce - Head	4.6	0.0	0.0
Mustard greens	10.4	4.3	0.0
Onion	0.0	0.0	0.0
Orchardgrass	6.1	1.8	0.0
Pea	5.0	5.0	0.0
Pepper	5.0	0.0	0.0
Radish, Exp. 1	17.5	5.0	0.0
Radish, Exp. 2	15.4	5.0	0.0
Radish, Exp. 3, LRC	11.4	5.0	0.0
Radish, Exp. 3, SRC	7.9	4.3	0.0
Radish, Exp. 3, SQC	11.6	4.8	0.0
Ryegrass[c]	5.0	0.4	0.0
Spinach	11.8	4.0	0.0
Strawberry	0.0	0.0	0.0
Timothy	4.3	1.4	0.0

[a]Visual estimates of percent foliar injury were made to the nearest 5%, except any injury, no matter how slight, was rated as 5%.

[b]Leaf senescence at final harvest prevented estimation of foliar injury for barley, Swiss chard, oat, potato, tomato, and wheat.

[c]Estimates shown were made at the first of multiple harvests; leaf material was less abundant at the final harvest.

Table 28. Relative ratings of maximum foliar injury caused by simulated sulfuric acid rain treatment of 1979 survey crops.[a]

Crop	Treatment pH 3.0	3.5	4.0
Alfalfa	+	+	0
Barley	0	0	0
Beet	+	+	+
Bluegrass	+	+	+
Broccoli	+	+	0
Cabbage	+	0	0
Carrot	+	0	0
Cauliflower	++	+	0
Chard-Swiss	++	+	+
Clover	+	+	0
Corn	+	0	0
Tall fescue	+	+	0
Lettuce - Bibb	+	+	0
Lettuce - Head	+	+	0
Mustard greens	++	+	0
Oat	0	0	0
Onion	0	0	0
Orchardgrass	+	+	0
Pea	+	+	0
Pepper	++	+	+
Potato	+	+	0
Radish, Exp. 1	++	+	0
Radish, Exp. 2	++	+	0
Radish, Exp. 3, LRC	+	+	0
Radish, Exp. 3, SRC	+	+	0
Radish, Exp. 3, SQC	+	+	0
Ryegrass	+	+	0
Spinach	++	+	0
Strawberry	+	0	0
Timothy	+	+	0
Tomato	++	+	0
Wheat	0	0	0

[a]Adapted from Lee et al., 1980.

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

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

0 No apparent foliar injury caused by simulated acid rain.

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APPENDIX

Several additional studies were conducted. Data for these crops 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 the following tables are presented to document the fact that these studies were conducted under USEPA Contract No. 68-03-2702.

Appendix Table 1. Data collected for '5116 Cresta' cucumber planted July 17 and harvested October 1.

Treatment	Cucumber fresh weight			Cucumber dry weight			
	Total[a]	Mature	Immature	Total[a]	Mature	Immature	Aborted
	g						
5.6	28.43	7.20	21.23	1.43	0.32	1.11	0.22
4.0	41.18	28.73	12.45	1.69	0.88	0.81	0.44
3.5	160.29	131.24	29.05	5.01	3.72	1.29	0.30
3.0	90.80	56.64	34.16	2.96	1.53	1.43	0.39

	Dry weight		
	Stem + leaf	Total top	Root
	g		
5.6	27.83	29.48	1.69
4.0	27.09	29.23	1.57
3.5	27.43	32.75	1.66
3.0	27.98	31.34	1.67

[a]Total weights are summed for mature and immature cucumbers.

NOTE: Because of the late planting of this cucumber variety, nighttime temperatures during reproductive development were too low for normal plant growth. This resulted in minimal mature cucumber production and growth cessation and/or abortion of developing cucumbers.

Appendix Table 2. Data collected for 'Tennessee Red' peanut planted July 26 and harvested September 26.

Treatment	Top dry wt.	Root dry wt.	No. immature peanuts > 0.63 cm.	Plant number
	g	g		
5.6	13.99	4.51	2.9	1.0
4.0	12.50	4.09	2.9	1.0
3.5	10.49	3.70	1.5	1.1
3.0	11.41	3.37	1.9	1.0

Appendix Table 3. Data collected for 'OR 10' soybean planted July 26 and harvested September 25.

	Number			Dry weight				
Treatment	Nodes to pod 1	Nodes	Pods	Pod	Leaf	Stem	Total top	Root
				g				
5.6	4.2	12.0	38.4	13.60	4.44	3.41	21.45	3.00
4.0	4.2	12.1	34.4	9.73	4.06	2.70	16.49	2.64
3.5	4.1	11.5	38.2	10.86	4.15	3.22	18.23	2.72
3.0	4.3	12.0	32.0	11.22	3.81	2.66	17.70	2.38

NOTE: Since neither peanut nor soybean is adapted to growth in the Willamette Valley of Oregon, responses to acid rain cannot be evaluated at this location.

Appendix Table 4. Data collected for tobacco transplanted June 13 and harvested August 8.

Treatment	Flower bud wt.		Dry weight				Stem height
	Fresh	Dry	Leaf	Stem	Total top	Root	
	g						cm
5.6	3.37	0.55	27.64	15.93	44.12	9.10	93.1
4.0	2.99	0.45	28.38	16.70	45.52	10.71	90.8
3.5	2.56	0.37	26.73	16.80	43.90	10.23	90.6
3.0	2.11	0.31	26.72	14.69	42.14	10.24	81.4

	Percent flower bud elongation				
	0	1-25	26-50	51-75	76-100
5.6	70.0	15.7	5.7	3.9	5.4
4.0	67.9	12.9	8.9	4.3	6.1
3.5	83.2	7.9	3.9	1.4	3.6
3.0	88.6	6.8	2.1	0.4	1.8

NOTE: Severe symptoms of N deficiency occurred in tobacco and precluded assessment of acid rain response.