Simulated Acid Rain on Crops

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SIMULATED ACID RAIN ON CROPS

AUTHORS: M.D. Plocher[1], S.C. Perrigan[1], R.J. Hevel[1], R.M. Cooper[1], and D.N. Moss[2], Department of Crop Science, Oregon State University.

PREFACE: The research described in this report was funded by Oregon State University and the United States Environmental Protection Agency under cooperative agreement No. CR-808864-01 and was planned in cooperation with US-EPA researchers J.J. Lee and G.E. Neely. The purposes of this report are to document the work performed under this cooperative agreement and to make the information obtained available to interested parties.

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[1]Research assistants, Department of Crop Science, Oregon State University.

[2]Professor and principal investigator, Department of Crop Science, Oregon State University.

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Abstract

In 1981, simulated H_2SO_4 acid rain was applied to alfalfa and tall fescue, and a 2:1 ratio of H_2SO_4:HNO_3 acid rain was applied to alfalfa, tall fescue, barley, wheat, potato, tomato, radish, and corn crops growing in the open field at Corvallis, Oregon. Careful attention was given to effects of the acid rain on the appearance of the foliage, and the effects on yield were measured. The simulated acid rain treatments had no effect on foliage of any crops. The yield of corn was reduced at pH 4.0 but was not affected by rain of pH 3.5.

Because the effect of pH 4.0 rain on corn yield was the only significant effect noted in the 1981 studies, in 1982, more extensive studies of the effect of simulated H_2SO_4/HNO_3 rain on corn were conducted. No significant effects of acid rain were found on foliage appearance, or on yield of grain or stover in the 1982 studies.

The results of these tests, combined with results of earlier studies, suggest that acid rain *per se* is not a serious problem for crop production. This report is the final report of a research project which has studied the effects of acid rain on many different crops.

INTRODUCTION

Before these experiments few crops had been exposed experimentally to acid precipitation (Cohen et al., 1981). In 1979, 1980, 1981, and 1982, studies were conducted by the Oregon State University Crop Science Department at the Department's Schmidt Research Farm near Corvallis to determine foliar and yield responses by crops exposed to simulated acid precipitation.

During the 1979 growing season, 28 different crop cultivars from 24 species were grown in pots in closed top chambers and exposed to simulated sulfuric acid (H_2SO_4) rain treatments. Yield and quality characteristics of these crops were measured. Yields of approximately two-thirds of the surveyed crops were not affected by simulated H_2SO_4 rain treatments of varying pH and, of the remaining crops, equal numbers exhibited stimulatory and inhibitory yield responses. Thus, in general, acid rain treatment did not appear to either inhibit or stimulate crop productivity (Cohen et al., 1981).

In 1980, 15 crop species were exposed to simulated sulfuric and sulfuric-nitric (H_2SO_4-HNO_3) acid rain, both in the open field and in pots in chambers (Cohen, et al., 1982). Yields of seven of the 15 crop cultivars were not affected by either H_2SO_4 or H_2SO_4-HNO_3 rain. The remaining crops showed both stimulatory and inhibitory responses. 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 by acid rain treatments. Yields of field-grown alfalfa, tall fescue, radish, and spinach were not significantly affected by H_2SO_4-HNO_3 rain simulants but a yield decrease occurred in mustard greens exposed to pH 3.0 H_2SO_4-HNO_3 rain. Corn grain dry weight was reduced at pH 4.0 in H_2SO_4 rain. After adjustment for differences in ear number by covariance analysis, however, no significant effect was identified (means within ±3 percent of the control). Thus the effect at pH 4.0 was on ear number. In contrast, rain of pH 3.0 or 3.5 had no significant effect on yield or yield components of corn.

In chamber experiments in 1980 (Cohen et al., 1982), all crops except lettuce and onion showed foliar injury from acid rain. This contrasts sharply with results obtained with field grown plants where, in 11 studies of six crops, only alfalfa and spinach showed any acid rain foliar injury, and in those two crops, foliar injury was minimal, rarely exceeding 1-2 percent of total leaf area. In the chambers in 1980, root crops exhibited both yield stimulation and depression but all leaf crops showed yield depression in response to acid precipitation. These results supported the conclusions of the 1979 study.

This report describes work done in both 1981 and 1982. In 1981, the crop survey was continued to determine sensitivity to simulated H_2SO_4-HNO_3 rain of several important crop species grown in a field environment. In addition, studies were designed to determine if different cultivar responses existed within selected crops. The alfalfa and tall fescue studies of 1980 were continued in 1981 to examine cumulative effects of acid rain that might occur in these perennial crops and to see if response to H_2SO_4 acid rain differed from the response to H_2SO_4-HNO_3 rain.

The only significant effect of acid rain on crop yield in the 1981 studies was found in corn. Therefore, in 1982, all experiments were conducted on field corn. Different cultivar responses to H_2SO_4-HNO_3 rain were examined with more treatments over a narrower pH range than used in 1981. The effect of rain composition was investigated further using H_2SO_4, HNO_3, and three treatments with different H_2SO_4:HNO_3 ratios but the same pH. In addition, an experiment was designed to determine whether plant response to individual rain events of a constant pH 4.0 treatment differed from response to a series of individual rain events over a range of pH's that averaged 4.0 for the season.

1981 MATERIALS AND METHODS

All experiments were conducted at Oregon State University Crop Science Department's Schmidt Farm near Corvallis. The soil at Schmidt Farm is a Willamette silt loam with a well drained surface layer about 60 cm thicker over a silty clay subsoil. Pre-study soil test results are listed in Table 1. Field preparation consisted of plowing, discing, and harrowing. The seedbeds were then cultivated with a rotary tiller and hand-raked to give a uniform seedbed.

The yield response of 10 crop cultivars to simulated acid rain was studied in the field in 1981. Alfalfa (*Medicago sativa* cv. Vernal) and tall fescue (*Festuca arundinaceae* cv. Alta) were tested with both simulated H_2SO_4 and H_2SO_4-HNO_3 rains. Corn (*Zea mays* cv. Pioneer 3992), barley (*Hordeum vulgare* cv. Steptoe), wheat (*Triticum aestivum* cv. Fieldwin), potato (*Solanum tuberosum* cv. Russet Burbank and Kennebec), tomato (*Lycopersicon esculentum* cv. New Yorker) and radish (*Raphanus sativus* cv. Cherry Belle and Scarlet Knight) were exposed only to the H_2SO_4-HNO_3 rain. All crops were exposed to simulated acidic rains of approximately pH 4.0, 3.5, 3.0, and pH 5.6 (control).

Table 1. Pre-study soil test results for 1981.

	pH	P	K	Mg	B	Ca	Lime requirement
	ppm					MEQ/100g	ha^{-1}
Wheat/Barley	6.3	42	207	1.8	.55	13.6	6.5
Potato	5.8	39	243	1.7	.51	9.3	6.0
Tomato	5.8	46	279	1.9	.51	11.2	6.2
Radish	5.7	59	174	1.2	.63	10.5	6.1
Corn	5.8	52	202	1.5	.53	9.8	6.1

Background ion concentrations for rain simulations were derived from precipitation data averaged over seven years from Hubbard Brook, New Hampshire (Likens and Borman, 1972). Rain simulants were prepared from a stock solution of deionized water with 0.220 mg/l Ca^{2+}, 0.216

mg/l NH_4^+, 0.115 mg/l Na^+, 0.078 mg/l K^+, 0.060 mg/l Mg^{2+}, 0.539 mg/l SO_4^{2-}, 0.744 mg/l NO_3^-, and 0.425 mg/l Cl^- added. The control rain consisted of stock solution in equilibrium with atmospheric CO_2 resulting in a pH of approximately 5.6. Acid treatments were prepared by adding 3.6 N H_2SO_4 and 1.8 N HNO_3 to the control rain to achieve the desired pH and acid equivalent ratios. The H_2SO_4-HNO_3 rain pH treatments were achieved using the acids in a 2:1 H^+ equivalent ratio.

Rain treatments were applied through stainless steel nozzles calibrated for even distribution over the plot study area at a rate of 0.7 cm/hr (see appendix for a designation of the nozzles and chambers). Rain events were 100 minutes/day, 2 days/week for a total rainfall of 2.2 cm/week. The pH of the rain solutions was checked during each rain event using an Orion 901 Research Microprocessor Ionanalyzer calibrated to standard pH buffer solutions of 4.01 and 7.00.

A randomized complete block design with four treatments (pH levels) and four replications was used for all studies. Each plot was a 1.8 m square area within a 3-m diameter circle defined by the placement site of the rain application chambers. The circle was centered in a 5-m by 4.5-m crop area, which gave 1-m borders on the ends and between chamber sites. A split plot design was used with barley, wheat, radishes, forages, and potatoes, with crop or cultivar making up the subplot. These designs are discussed under the heading of the individual crops. Sixteen portable cylindrical chambers measuring 3 m in diameter and 2.4 m in height were placed over the plots during a rain event. The chambers had open tops. The walls were formed of polyvinyl chloride tubing covered with Monsanto 602 plastic. The entire structure was then covered with a a horticultural shade cloth to simulate cloud cover while allowing free air movement through the chamber top. The four chambers within each replicate block were rotated within the block from one rain event to the next to reduce variation associated with possible chamber differences. As the plants grew, the chambers were placed on extensions to maintain uniform rain distribution pattern at the top of the crop canopy.

Forage Crops

The forage crop plots were planted in a split plot with rain pH constituting the main plots and forage species the subplots. The main plot area consisted of 10 rows each of 'vernal' alfalfa and 'alta' tall fescue spaced 15-cm apart and 5-m long, the alfalfa to the north and the tall fescue to the south in each plot. The circular rain exposure sites were laid out in the center of the main plots so the 1.8-m square calibrated rain area contained 6 rows of each species. The two adjoining center rows were left as border and 5 rows, 1.8 m long, were harvested. Thus, the harvested plot area was 1.35 m^2 for each subplot.

Alfalfa H_2SO_4 and tall fescue H_2SO_4 and H_2SO_4-HNO_3 study plots from the 1980 crop season (Cohen et al., 1982) were well established. However, the 1981 alfalfa H_2SO_4-HNO_3 plots were damaged extensively by gophers over the winter and were tilled under. The damaged area was replanted using the same methods and plot layout used in 1980 (Cohen et al., 1982). The alfalfa seed was inocculated with _Rhizobium meliloti_ before planting.

After planting the alfalfa H_2SO_4-HNO_3 study, both alfalfa studies were fertilized with 44.8 kg/ha S broadcast and 6.7 kg/ha B applied with a boom sprayer and followed by irrigation. Both tall fescue studies received 56 kg/ha N and 44.8 kg/ha S by broadcast application. Manual weed control was performed as needed. Malathion and Sevin were used for insect control and Maneb fungicide was used to control downy mildew. There was an initial harvest of the H_2SO_4 rain-treated alfalfa plots on May 7, before the 1981 rain treatment began. The yield of the initial harvest was not included in the crop response yield data.

The alfalfa and fescue H_2SO_4 and fescue H_2SO_4-HNO_3 plots received the first simulated rain exposures May 14 (Table 2). The first treatment exposure for the H_2SO_4-HNO_3 alfalfa (new planting) was June 25. Natural and simulated rainfall were supplemented with sprinkler irrigation (Table 3) when soil moisture content indicated need (Lorenz and Maynard, 1980).

The alfalfa H_2SO_4 rain studies were harvested on July 2, August 5, and October 21, and the alfalfa H_2SO_4-HNO_3 study was harvested on October 10. All harvests were at about the 10% blossom stage. The tall fescue H_2SO_4 rain studies were harvested July 16-17 and October 14-15,

Table 2. A summary of the treatments and application dates for the 1981 studies of the effect of acid rain on crops

Crop	Cultivar	Rain type	Total fertilizer application kg/ha $N-P_2O_5-K_2O-S-B$	Seeding	First rain event	Last rain event	Total # rain events	Harvest date
Alfalfa (Medicago sativa)	Vernal	1:0	0-0-0-44.8-6.7	5/19/80	5/14/81	10/20/81	44	5/07, 7/02, 8/05, 10/21[1]
		2:1	0-0-0-44.8-6.7	5/26/81	6/25/81	10/08/81	30	10/10
Tall Fescue (Festuca arundinaceae)	Alta	1:0	56-0-0-44.8-0	5/20/80	5/14/81	10/15/81	42	5/06, 7/16-17, 10/14-15[2]
		2:1	56-0-0-44.8-0	5/20/80	5/21/81	10/13/81	33	5/04, 5/17, 10/16[2]
Barley (Hordeum vulgare)	Steptoe	2:1	78-67-67-24-0	4/27-28/81	5/21/81	08/10/81	24	8/12/81
Wheat (Triticum aestivum)	Fieldwin	2:1	78-67-67-24-0	4/28/81	5/21/81	08/27/81	28	8/31/81-9/01/81
Potato (Solanum tuberosum)	Russet Burbank	2:1	224-134-168-47-0	5/13-14/81	6/02/81	09/01/81	27	9/02, 9/16[3]
	Kennebec	2:1	224-134-168-47-0	5/14-15/81	6/02/81	09/01/81	27	9/02, 9/16-17/81[3]
Tomato (Lycopersicon esculentum)	New Yorker	2:1	84-112-90-31-0	4/17/81	6/05/81	10/20/81	33	8/10, 10/05, 10/06/81[4]
Radish (Raphanus sativus)	Cherry Belle	2:1	56-1112-112-40-1	9/25/81	10/2/81	11/10/81	12	11/12/81
	Scarlet Knight	2:1	56-112-112-40-1	9/25/81	10/2/81	11/10/81	12	11/12/81
Corn (Zea mays)	Pioneer 3992	2:1	224-134-134-45-1	6/01-02/81	6/12/81	10/02/81	33	10/26-27/81

[1]Harvest dates for pre-rain havest, harvest 1, harvest 2, harvest 3

[2]Harvest dates for pre-rain harvest, harvest 1, harvest 2

[3]Tops harvested 9/2/81, Tubers 9/16-17/81

[4]Seventeen fruit harvests beginning 8/10/81, ending 10/05/81, tops 10/06/81

Table 3. Summary of 1981 natural and simulated rainfall and irrigation

Study	$H_2SO_4:HNO_3$ ratio	Natural rainfall: from emergence to harvest (cm)[1]	Natural rainfall: on same days as simulated (cm)[2]	Total simulated rainfall (cm)	Average pH of natural plus simulated rainfall[3], treatment pH 3.0	3.5	4.0	5.6	Total irrigation (cm)
Alfalfa	1:0	26.3	4.3	49.1	3.1	3.6	4.1	5.5	43.9
	2:1	8.1	.8	35.7	3.1	3.5	4.0	5.5	38.1
Tall Fescue	1:1	26.3	4.3	49.1	3.1	3.6	4.1	5.5	43.9
	2:1	27.7	3.1	38.0	3.2	3.7	4.2	5.5	43.9
Barley	2:1	13.0	.8	26.7	3.1	3.6	4.1	5.5	8.1
Corn	2:1	10.4	3.0	36.8	3.1	3.6	4.0	5.5	45.9
Potato	2:1	6.9	1.8	30.0	3.0	3.5	4.0	5.5	20.0
Radish	2:1	17.6	6.3	13.3	3.3	3.8	4.2	5.5	0
Tomato	2:1	12.0	1.2	36.7	3.1	3.5	4.0	5.5	27.6
Wheat	2:1	13.1	.8	31.1	3.1	3.6	4.1	5.5	8.1

1. Includes all natural rain from the date seedlings emerged from soil until harvest (date of transplant for tomatoes and first acid rain exposure for 1:0 alfalfa and 1:0 and 2:1 tall fescue).

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

3. Volume weighted average (computed using crop growth season natural rainfall).

and the H_2SO_4-HNO_3 studies were harvested July 15 and October 16. All forage plots were cut to a stubble height of 7.5 cm.

Subsamples of the forages for chemical analysis were taken at the final harvest. A subsample of 100 stems per plot from the final alfalfa harvest was separated into leaf plus petiole, and to stem fractions, from which percent leafiness was calculated. Percent crude protein (CP), acid detergent fiber (ADF), total sulfur (S), potassium (K), phosphorus (P), calcium (Ca), magnesium (Mg), manganese (Mn), iron (Fe), copper (Cu), boron (B), zinc (Zn), and aluminum (Al) were determined on samples from the third harvest of H_2SO_4 rain-treated alfalfa and from the second harvest of both H_2SO_4 and H_2SO_4-HNO_3 rain treatments in tall fescue. The H_2SO_4-HNO_3 rain alfalfa was analyzed for CP and ADF only.

The fescue samples for chemical analysis consisted of 15 g (fresh weight) of tissue from each of the five study rows per plot. Tissue, oven dried at 60°C for 48 hours, was ground to pass through a 0.5-mm screen. Percent crude protein was calculated by multiplying percent nitrogen (N) by 6.25. Acid detergent fiber 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 percent N using a standard Kjeldahl procedure (AOAC, 1975) and ADF using the method 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 Isaac (1972) and the 10 other elements using direct reading emission spectrometry as described by Chaplin and Dixon (1974).

Cereal Crops

The response of spring wheat and barley to simulated H_2SO_4-HNO_3 rain was measured in 16 contiguous plots, planted in a split plot design, with pH comprising the main plots and 'Steptoe' barley and 'Fieldwin' wheat comprising the split plots. The calibrated rain areas, 1.8-m square, contained five harvest rows of each species separated by one border row of each species. Row spacing was 15 cm. Thus, the harvested subplot area was 1.35 m^2.

Seeds were planted 1 cm apart at 2-cm depth. The plots were fertilized, following recommendations based on soil analysis (Table 1), with 78-67-67-24 kg/ha N-P_2O_5-K_2O-S incorporated before planting. Weeds were removed by hand. Malathion and Bayleton were used to control insects and fungal diseases, respectively. Loose smut (Ustilago nuda) infected heads of barley were rogued as they appeared.

Plots received the first H_2SO_4-HNO_3 rain May 21 (Table 2). Additional irrigation was applied (Table 3) when moisture in soil cores from plot areas outside the simulated rainfall area indicated less than 50 percent field capacity (Lorenz and Maynard, 1980).

Barley was harvested August 12-13. Wheat was harvested August 31-September 1. Tillers per plot were counted. The plants were harvested at ground level. Heads were removed and bagged separately from the straw. Samples were dried at 60°C and dry weights were measured for heads and straw. Heads were then threshed, the grain weighed, and kernels counted.

Potato

'Kennebec' and 'Russet Burbank' potatoes were compared to see if cultivars differed in their response to H_2SO_4-HNO_3 rain. Sixteen contiguous plots were planted in a strip using a split plot design with rain pH as the main plots and cultivars as split plots. The split plot consisted of equidistant hills on 45-cm centers (approximately 48,200 plants/ha) with each cultivar making up one half of the harvest area. The cultivars were bordered on the plot edges and ends by two hills on all sides. The harvested subplot consisted of eight hills of a given cultivar in an area of 1.6 m^2.

Seed pieces weighing approximately 50 g were treated with Captan five percent dust and planted on May 13-15, one seed piece per hill, at ten cm depth. Fertilizer, based on soil analysis, was broadcast and incorporated at the rate of 224-134-168-47 kg/ha N-P_2O_5-K_2O-S. Dyfonate granules at 4.5 kg/ha were incorporated with the fertilizer to control wireworms. A pre-emergent herbicide, 1.1 kg/ha EPTC (Eptam), was applied and additional weed control was done by hand. Malathion and Sevin were used for insect control.

Plots received the first rain treatment exposure June 2. Supplemental irrigation was applied when soil cores from plot areas outside the simulated rainfall area indicated less than 50 percent field capacity (Lorenz and Maynard, 1980). After senescence, the potato vines were harvested on September 2. The tubers were left to age in the soil until September 16-17. Boundaries of the 1.8-m square harvest area were cut precisely with a shovel blade. All partial potatoes cut with the shovel blade within the study area were bagged separately. Whole potatoes were classed by weight (less than 110 g, 110-170 g, 170-230 g, 230-280 g, and more than 280 g). Fresh weights for each class per variety per plot were measured. Potato tubers and vines were oven-dried at 60°C and dry weights were measured.

Tomato

The response of field grown 'New Yorker' tomatoes to simulated H_2SO_4-HNO_3 rain was measured in 1981. Seeds were planted in 5-cm pots on a mist bench April 17. On June 3, plants 36-43 cm in height were selected and transplanted in the field in rows 75 cm apart, in an east-west strip of 16 contiguous 3 x 5 m plots. Transplants were spaced 60 cm apart in each row. The calibrated rain area contained two study rows of three plants each in a 2.7 m^2-harvest area. The harvest plot was surrounded by two border plants on all sides. Based on soil analysis, 6,720 kg/ha lime and 56, 112, 90, and 31 kg/ha of N, P_2O_5, K_2O, and S fertilizer, respectively, were incorporated into the soil (Table 1). An additional 28 kg/ha N was applied as a foliar spray on July 2. Manual weed control was provided as needed.

The first H_2SO_4-HNO_3 rain event was June 5. Sprinkler irrigation was applied when soil moisture in the plot outside of the simulated rainfall area decreased to 50 percent field capacity (Lorenz and Maynard, 1980).

Ripe tomatoes were harvested twice weekly beginning August 10. Final harvest of all fruit was October 5. Tomatoes were counted, weighed, and size classed as < 6.4 cm, 6.4-7.6 cm, and > 7.6 cm in diameter. An assessment of fruit abnormalities was conducted at each harvest. Vines were cut at ground level on October 6, dried at 60°C for 48 hours and then weighed.

Radish

'Cherry Belle' and 'Scarlet Knight' radishes were exposed to simulated H_2SO_4-HNO_3 rain. Radishes and mustard greens were hand seeded September 25 in a split plot design with pH as main plots and species as subplots. The 1.5 x 3 m radish subplot was further split with the sub-subplot being cultivars. The mustard greens did not mature and were not harvested. Radish plant spacings of 15 cm between rows and 7.6 cm within each row were used. One border row of 'Scarlet Knight' separated the radish and mustard greens. Two 1.8 m rows each of 'Scarlet Knight' and 'Cherry Belle' were designated study rows within the calibrated spray area. The harvested sub-subplots for each radish variety had an area of 0.55 m^2. A border of 'Cherry Belle' radish was planted outside the calibrated area. Between cultivar border rows were not necessary because of similarities in plant characteristics. Based on soil analysis, (Table 1) 6,720 kg/ha lime and 56, 112, 112, 40, and 1 kg/ha N, P_2O_5, K_2O, S, and B fertilizer were broadcast and incorporated before planting. Dyfonate granules at 4.75 kg/ha were incorporated with the fertilizer to control wireworms. The first H_2SO_4-HNO_3 treatment exposure was October 2 (Table 2). Plots were weeded by hand as needed. Simulated and natural rainfall (Table 3) provided enough moisture for crop growth and additional irrigation was not needed. Radishes were harvested November 12 when roots had reached marketable size. At harvest, root fresh weight and top and root dry weights were measured.

Corn

The response of hybrid field corn cultivar 'Pioneer 3992' to H_2SO_4-HNO_3 simulated rain was studied. Harvest plots consisted of four rows spaced 0.5 m apart and 1.8 m long. Corn was hand seeded June 1 and 2 using a planting dibble to maintain uniform seed depth. Seeds were planted in hills 30 cm apart in rows 50 centimeters apart. This grid pattern insured equal plant numbers in the calibrated spray areas of all plots. Three seeds were planted per hill and thinned to a single plant per hill after emergence, providing a plant population of approximately 64,200 plants ha^{-1}. Each plot consisted of four east-west rows of six plants. Plots were bordered by three east-west rows outside the calibrated rain area and separated from each other by a minimum of four hills in the row. Before planting, 6,720 kg/ha lime and 224, 134, 134, 45, and 1 kg/ha N, P_2O_5, K_2O, S, and B fertilizer were broadcast and incorporated. Plots were hand weeded as necessary. Supplemental sprinkler irrigation was applied to meet the requirements of border plants outside the calibrated acid rain spray areas (Table 3). Frequency of irrigation was determined by evaluating moisture content of soil cores using methods of Lorenz and Maynard (1980).

The corn was harvested on October 26-27. Ear fresh weights, dry weights, grain dry weights, kernel counts, and total top dry weight per plot were measured. Data for single-eared plants were recorded separately from those for multiple-eared plants, tiller-eared plants and plants without ears.

STATISTICAL ANALYSES

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

1981 RESULTS AND DISCUSSION

Forage Crops Yield Data

'Vernal' alfalfa exposed to H_2SO_4 rain for a second crop year showed no significant differences between treatments for top dry weight or leafiness. Likewise, the H_2SO_4-NO_3 rain treatments, which were applied in 1981 only, showed no significant differences in yield or percent leafiness (Table 4). The H_2SO_4-NO_3 study was a new planting and was harvested only once.

Table 4. The effects of simulated 1:0 and 2:1 sulfuric-nitric acid rain on top dry weight production and percent leafiness of 'Vernal' alfalfa grown in the field in 1981

	1:0 rain					2:1 rain	
	Top dry weight, g m^{-2}				Leafi-	weight	Leafi-
pH	1	2	3	Total	ness, %	g m^{-2}	ness, %
5.6	486	402	168	1,056	40	270	47
4.0	449	385	175	1,009	40	270	47
3.5	523	430	193	1,146	40	259	52
3.0	468	377	133	978	43	246	50
SE[b]	22.2	18.9	11.9	48.7	1.6	11.0	2
F[c]	NS	NS	NS	NS	NS	NS	NS

[b]Standard error of the mean.

[c]Significance level of the F-test.

'Alta' tall fescue showed no significant differences in yield between treatments when exposed to H_2SO_4 rain for a second crop year (Table 5). However, the tall fescue treated with H_2SO_4-HNO_3 rain exhibited a significant decrease of 9% in top dry weight at the first harvest at pH 3.5 (Table 5). There was no significant difference among treatments at the second harvest or in the combined top dry weights for both harvests.

This one example of a statistically significant response in tall fescue is probably an anomaly, since the significant decrease occurred only at pH 3.5, at one harvest only. In that same experiment there was no effect on yield of rain of pH 3.0. If acid rain were affecting growth, the effect should have been more severe at the lower pH. Also one would expect to have seen an effect at other harvests.

Table 5. The effects of simulated 1:0 and 2:1 sulfuric-nitric acid rain on top dry weight production (g m^{-2}) of 'Alta' tall fescue grown in the field in 1981

	1:0			2:1		
pH	Harvest 1	Harvest 2	Total	Harvest 1	Harvest 2	Total
5.6	383	306	689	390	244	634
4.0	397	304	701	369	257	626
3.5	399	293	692	354*	231	585
3.0	399	307	706	405	285	690
SE[b]	11.12	10.0	18.0	9.3	15.6	21.2
F[c]	NS	NS	NS	*	NS	*

[b]Standard error of the mean.

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

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

Forage Crops Tissue Analysis

Tissue analysis of stems and leaves of 'Vernal' alfalfa treated with H_2SO_4 rain showed a significant increase in sulfur content at pH 3.0 (Table 6). Because of the increase in sulfur content, the corresponding N:S ratio exhibited a significant decrease. The increase in sulfur content, though significant, represents only two tissue samples. No significant differences were found for pH 3.5 or pH 4.0 treatments and there were no significant differences between treatments for any element in 1980, the first year of this study (Cohen et al., 1982).

No differences were found in the 1981 alfalfa acid detergent fiber (ADF) content. This result contrasts with the 1980 result in which the sulfuric acid rain-treated plots showed an increase in ADF at all pH levels, compared to control.

Table 6. The effects of simulated sulfuric acid rain on concentration of crude protein (CP), acid detergent fiber (ADF), and 11 mineral elements for two analyses[a] of 'Vernal' alfalfa grown in the field in 1981

Treatment pH	Leaves and stems separated												
	CP	ADF	S	K	P	Ca	Mg	Mn	Fe	Cu	B	Zn	Al
	%							ppm					
5.6 leaves	23.2	16.9	0.29	0.97	0.25	2.90	0.27	60.5	548	5.00	76.5	12.0	501
3.0 leaves	23.8	15.9	0.38	1.02	0.25	2.95	0.27	55.5	462	5.00	85.5	10.5	385
5.6 stems	10.4	45.1	0.13	1.01	0.20	1.21	0.26	21.5	312	3.00	21.0	5.0	288
3.0 stems	11.0	43.0	0.17	1.17	0.25	1.34	0.23	18.5	202	3.00	26.0	12.5	204
SE[b]	2.4	5.2	0.04	0.06	.01	0.31	.01	7.3	58	.42	11.1	1.6	49
CV[c]	40	49	47	17	13	42	15	53	43	30	60	45	41
F[d]	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS

Treatment pH	Leaves and stems combined												
	CP	ADF	S	K	P	Ca	Mg	Mn	Fe	Cu	B	Zn	Al
	%							ppm					
5.6	15.7	32.2	.23	1.1	.25	2.55	.23	41.0	236.5	3.5	56.0	12.0	208.0
4.0	16.3	34.9	.22	1.0	.24	2.55	.24	39.2	308.0	4.2	50.2	11.0	248.2
3.5	16.0	34.5	.21	1.0	.23	2.39	.25	35.7	354.0	4.2	47.0	9.0	315.7
3.0	15.7	32.2	.32*	1.0	.25	2.62	.29	42.5	312.5	5.0	52.0	11.5	221.5
SE[b]	0.2	1.0	0.02	0.0	.01	.04	.01	1.6	28.5	0.2	2.5	0.7	29.6
CV[c]	5	10	23	8	7	6	16	15	32	15	17	23	39
F[d]	NS	NS	*	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS

[a]Concentrations are expressed on a dry weight basis for both separated and combined leaves and stems.

[b]Standard error of the mean.

[c]Coefficient of variation for the mean (percent).

F[d]Significance level of the F-test with * denoting $P \leq 0.05$.

*Symbol after table values denotes significant differences from control means with $P \leq 0.05$ for two-sided t-test.

Analysis of alfalfa tissue from H_2SO_4-HNO_3 rain treatments in 1981 showed no significant differences between treatments (Table 7). This, too, differs from 1980 when the first harvest of the H_2SO_4-HNO_3 rain treatment showed an increased N content at pH 4.0 and increased S at pH 3.0, and the second harvest had a significant increase in ADF at pH 3.5.

Table 7. The effects of 2:1 sulfuric-nitric acid rain on concentration of crude protein (CP) and acid detergent fiber (ADF) of 'Vernal' alfalfa grown in the field in 1981

Separated leaves and stems			Combined leaves and stems		
Treatment	CP (%)	ADF(%)	Treatment	CP (%)	ADF (%)
5.6 (leaves)	21.8	17.5	5.6	15.9	31.8
3.0 (leaves)	20.3	16.9	4.0	15.7	30.6
5.6 (stems)	9.6	46.7	3.5	16.2	30.4
3.0 (stems)	8.5	46.4	3.0	15.4	33.1
			SE[b]	0.1	0.6
			CV[c]	3	7
			F[d]	NS	NS

[a]Concentrations are expressed on a dry weight basis for separated and combined leaves and stems.

[b]Standard error of the mean.

[c]Coefficent of variation for the mean.

[d]Significance level of the F-test.

'Alta' tall fescue tissue showed no significant treatment effects for CP, ADF, S, P, K, Mg, Cu, B, Zn, or Al for either H_2SO_4 or H_2SO_4-HNO_3 simulated rains (Table 8). However, compared to the control, Ca content was significantly lower ($P \leq .01$) at pH 3.0 and pH 3.5 in the H_2SO_4 rain treatments. The 1980 second harvest H_2SO_4-HNO_3 samples had a significant decrease in Ca at pH 4.0 but not at pH 3.0 or pH 3.5. Thus, the data suggest that acid rain does decrease Ca content in tall fescue under some conditions. In the H_2SO_4-HNO_3 treatments, there was a significant increase in Fe at both pH 3.0 and pH 3.5. These differences, although significant, again represent only two tissue samples.

Table 8. The effects of 1:0 and 2:1 simulated sulfuric-nitric acid rain on uptake and concentration of crude protein (CP), acid detergent fiber (ADF), and 11 mineral elements in 'Alta' tall fescue grown in the field in 1981

1981 1:0	CP	ADF	S	K	P	Ca	Mg	Mn	Fe	Cu	B	Zn	Al
	%							ppm					
5.6	9.68	36.0	.28	1.52	.32	.36	.21	96.5	448.2	.88	3.25	7.00	651
4.0	9.35	7.0	.28	1.51	.31	.34	.22	95.7	345.5	.75	2.75	6.75	510
3.5	9.43	36.9	.29	1.50	.31	.32**	.20	102.0	531.7	.75	3.50	7.50	804
3.0	9.54	37.6	.31	1.50	.29	.28**	.20	105.2	606.5	.88	2.50	6.75	914
S.E.[b]	.14	.3	.01	.04	.01	.01	.01	2.1	60.3	.06	.29	.48	102
CV[c]	6	3	16	10	9	10	12	9	50	31	38	28	57
F[d]	NS	NS	NS	NS	NS	**	NS	NS	NS	NS	NS	NS	NS
1981 2:1													
5.6	10.31	33.90	.30	1.70	.33	.35	.20	83.50	161.2	.75	4.00	8.75	315
4.0	9.61	34.33	.29	1.58	.33	.35	.20	88.25	287.7	.75	3.75	8.25	378
3.5	9.77	35.56	.30	1.58	.35	.33	.22	88.50	333.7*	.87	3.50	7.50	471
3.0	9.78	35.52	.31	1.59	.32	.29**	.21	93.25	396.2**	.87	3.25	7.25	567
S.E.[b]	.13	.57	.01	.04	.01	.01	.01	2.35	36.2	.06	.30	.44	58
CV[c]	5	7	13	10	8	9	12	11	49	31	33	22	53
F[d]	NS	NS	NS	NS	NS	**	NS	NS	*	NS	NS	NS	NS

[a]Concentrations are expressed on a dry weight basis.
[b]Standard error of the mean.
[c]Coefficient of variation for the mean (percent)
[d]Significance level of the F-test 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 the two-sided t-test.

No foliar acid rain injury was observed in alfalfa or in the H_2SO_4-HNO_3 tall fescue experiments. Slight foliar acid rain injury was observed on H_2SO_4 treated tall fescue but only at pH 3.0. In that treatment, whitish spots, sometimes associated with a brown halo, appeared on some leaves, especially along the leaf margins. Injury amounted to less than one percent of leaf area and was not noted before June 22 or after September 22.

Cereals

No significant differences of any kind were found in the cereal studies (Table 9). There was no foliar injury. The grain dry weight, non-grain head dry weight, stubble dry weight, total top dry weight, head number, tiller number, percent fertile tillers, and dry weight per kernel of 'Fieldwin' wheat and 'Steptoe' barley were not affected by simulated H_2SO_4 acid rain treatments (Table 9).

Potato

Acid rain did not affect any measured trait of either 'Russet Burbank' (Table 10) or 'Kennebec' (Table 11) potatoes. Likewise, there was no foliar injury from acid rain treatment on either variety.

Tomato

'New Yorker' tomato plants showed no significant differences in treatment response for mature fruit fresh weight, number of mature fruit, average fresh fruit weight of mature fruit, total fresh weight of immature fruit, total number of immature fruit, total fruit fresh weight, total fruit number, and total top dry weight (Table 12). The number of mature fruit in each of the three diameter size classes was not significantly different for any pH treatment when analyzed for early season (August 10-24), mid-season (August 31-September 17), and late season (September 21-October 5) harvests. However, the number of mature fruit greater than 7.6 cm in diameter for all harvests combined was significantly greater at pH 3.0 (F-test $P = 0.02$, t-test $P \leq 0.01$).

Foliar injury from acid rain occurred only at pH 3.0. On those plants, a small amount of white circular flecking covering less than one percent of the leaf area was observed on July 24, 31, and August 6.

Table 9. The effects of simulated sulfuric acid rain on dry weight production (g m^{-2}), number of tillers and heads per m^2, and percent fertile tillers of 'Fieldwin' wheat and 'Steptoe' barley grown in the field in 1981

pH	Grain dry wt	Straw dry wt	Non-grain head dry wt	Total dry wt	Harvest index, %	Tiller number	Number of heads	% Fertile tillers
				Wheat				
5.6	269	599	126	994	.18	516	448	87.7
4.0	263	634	118	915	.16	472	442	94.9
3.5	260	606	122	988	.37	489	411	83.1
3.0	256	574	120	950	.15	479	437	91.0
SE[b]	14.8	25.0	3.7	32.6	.10	15.6	22.5	4.3
F[c]	NS	NS	NS	NS	NS	NS	NS	NS
pH				Barley				
5.6	370	366	94	930	.40	444	395	89.8
4.0	396	491	96	983	.40	453	410	91.6
3.5	411	495	99	1005	.41	461	411	89.0
3.0	379	469	92	940	.40	452	381	84.2
SE[b]	11.2	22.5	5.9	37.0	.08	11.5	15.7	2.2
F[c]	NS	NS	NS	NS	NS	NS	NS	NS

[b]Standard error of the mean

[c]Significance level of the F-test.

Similar appearing insect injury masked acid rain treatment differences after that date. No acid rain injury to the fruit occurred at any of the treatment levels.

Table 10. The effects of simulated sulfuric acid rain on the yield of Russet Burbank potatoes grown in the field in 1981

Treatment	Tuber FW ($kg\ m^{-2}$)	Tuber DW ($kg\ m^{-2}$)	Av. tuber FW (g)	Av. tuber DW (g)	Vine DW ($kg\ m^{-2}$)	Total DW ($kg\ m^{-2}$)
5.6	6.52	1.61	80	19.6	0.24	1.85
4.0	6.20	1.60	81	20.9	0.22	1.82
3.5	6.30	1.62	80	20.5	0.22	1.84
3.0	6.53	1.66	79	20.0	0.24	1.90
SE[a]	0.24	0.06	3.6	.9	0.02	0.08
F[b]	NS	NS	NS	NS	NS	NS

[a]Standard error of the mean.

[b]Significance level of the F-test.

Table 11. The effects of simulated sulfuric acid rain on the yield of Kennebec potatoes grown in the field in 1981

Treatment	Tuber FW ($kg\ m^{-2}$)	Tuber DW ($kg\ m^{-2}$)	Av. tuber FW (g)	Av. tuber DW (g)	Vine DW ($kg\ m^{-2}$)	Total DW ($kg\ m^{-2}$)
5.6	6.26	1.42	124	28	0.28	1.70
4.0	6.40	1.60	134	33	0.27	1.87
3.5	5.93	1.39	149	35	0.29	1.68
3.0	6.75	1.64	144	35	0.30	1.94
SE[a]	0.34	0.10	6.5	2	0.01	0.11
F[b]	NS	NS	NS	NSN	NS	NS

[a]Standard error of the mean.

[b]Significance level of the F-test.

Table 12. The effects of simulated sulfuric acid rain on fruit fresh weight, top dry weight, and the number of fruit[a] of 'New Yorker' tomatoes grown in the field in 1981

Treat-ment	Fruit fresh weight ($kg\ m^{-2}$) mature	immature	total	Top DW ($kg\ m^{-2}$)	Immature fruit per m^{-2}	Mature fruit per m^2 6.4 cm diam	Mature fruit per m^2 6.4-7.6 cm diam	Mature fruit per m^2 7.6 cm diam	Total fruit per m^{-2}
5.4	7.89	1.75	9.64	0.20	32	53	18	6	109
4.0	7.88	2.26	10.14	0.21	37	53	16	7	113
3.5	8.35	1.97	10.32	0.22	28	53	20	6	107
3.0	8.70	1.86	10.56	0.20	31	50	18	9**	108
SE[b]	0.43	0.32	0.58	0.01	2.9	2.5	1.6	0.6	4.7
F[c]	NS	NS	NS	NS	NS	NS	NS	*	NS

[a]Mature fruit were divided into three categories, 6.4, 6.4-7.6, and 7.6 cm.

[b]Standard error of the mean.

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

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

Radish

Simulated H_2SO_4-HNO_3 acid rain treatments had no significant effect on the yield of 'Cherry Belle' or 'Scarlet Knight' radishes grown in the field in 1981 (Table 13). Similar results for 'Cherry Belle' were found in the 1980 field studies.

Some injury to the cotyledons of both varieties was observed at pH 3.0, but not in other treatments. In the pH 3.0 treatment, irregular shaped gray spots in areas of rain drop accumulation covered less than two percent of the surface area. No acid rain injury was observed on any true leaves.

Corn

In 1981, for the second year, the effect of H_2SO_4-HNO_3 acid rain on 'Pioneer 3992' field corn yield and yield components was evaluated. In 1980, corn exposed to pH 4.0 had a lower grain yield than did the control plots ($P < .05$). However, rain of pH 3.5 and 3.0 had no significant effect on yield and there was no injury to foliage by acid rain. It appeared that the pH 4.0 treatment had fewer two-eared plants but since no significant effects were found at other pH levels, the grain yield reduction at pH 4.0 was unexplained. The same treatments were repeated in 1981 to check the 1980 results. Table 14 lists the yield and yield components of 'Pioneer 3992' field corn exposed to H_2SO_4-HNO_3 simulated acid rain in 1981. Surprisingly, there was again a trend toward a depression in yield of corn at pH 4.0, although the difference was not significant ($P = .08$). However, there was a highly significant ($P < .01$) decrease in stover weight at pH 4.0 and a less obvious decrease at pH 3.5 and 3.0. These results differed from 1980 in that the effect was much more pronounced on stover production than it was on grain yield.

Because of these decreases in corn stover production, the total plant dry weights were significantly less than the controls in treatments pH 3.0, 3.5, and 4.0. No other effects of acid rain on corn were seen. The grain yields were not significantly different between treatments although the average yield at pH 4.0 again appeared to be depressed. There was no foliar injury on corn from acid rain.

Table 13. The effects of simulated sulfuric acid rain on root weights, top dry weights, total dry weights, and number of plants per plot of 'Cherry Belle' and 'Scarlet Knight' radish grown in 1981

'Cherry Belle' Radish (plot basis) treatment	Root fresh wt ($g\ m^{-2}$)	Root dry wt ($g\ m^{-2}$)	Top dry wt ($g\ m^{-2}$)	Total dry wt ($g\ m^{-2}$)	Plants per m^2
5.6	487	28	22	50	87
4.0	431	25	22	47	87
3.5	496	29	24	53	87
3.0	496	29	24	53	88
SE[a]	25	1.4	1.0	2.3	1.3
F[b]	NS	NS	NS	NS	NS

'Scarlet Knight' Radish (plot basis) treatment	Root fresh wt ($g\ m^{-2}$)	Root dry wt ($g\ m^{-2}$)	Top dry wt ($g\ m^{-2}$)	Total dry wt ($g\ m^{-2}$)	Plants per m^2
5.6	618	37	29	66	87
4.0	615	36	67	67	86
3.5	686	40	33	73	89
3.0	582	35	31	66	89
SE[a]	24	1.3	0.9	2.2	1.0
F[b]	NS	*	NS	NS	NS

[a]Standard error of the mean.

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

Table 14. The effects of 2:1 simulated sulfuric-nitric acid rain on ear weight, grain dry weight, stover dry weight, and kernel number of 'Pioneer 3992' corn grown in the field in 1981

Treatment	Total ear FW g m^{-2}	Grain DW g m^{-2}	Stover DW g m^{-2}	Biomass yield g m^{-2}	Kernels m^{-2}
5.6	2070	854	980	1834	898
4.0	1780	738	799**	1537**	810
3.5	1922	785	880**	1665*	827
3.0	1967	822	908*	1729	860
SE[a]	65	28	23	48	17
F[b]	NS	NS	**	**	NS

[a]Standard error of the mean.

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

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

Since, in 1980, the pronounced effect of acid rain at pH 4.0 was to reduce the number of two-eared plants, we analyzed the 1981 yield component data for single-eared plants alone. The results are shown in Table 15. About 80% of the plants in 1981 had only one ear and there was no difference among treatments on the degree of prolificacy. However, when only single-eared plants were considered in the analysis, there was a significant decrease in grain yield per plant at pH 4.0 ($P < .05$). Thus, qualitatively the 1981 results differed from the 1980 results in how the rain treatment affected yield components, but the results were similar for the two years in that slightly acid precipitation did affect the crop, whereas more acidic precipitation did not.

Because these results occurred in two years, it was decided to study the response of corn in more extensive field studies in 1982. All the acid treatments appeared to have a reduced biomass production in 1981. Thus, it seems possible that, among field crops, corn may be especially sensitive to acid precipitation.

Table 15. The effects of 2:1 simulated sulfuric-nitric acid rain on yield components of single-eared plants of 'Pioneer 3992' corn grown in the field in 1981

Treat-ment	One-eared plants %	Grain dry wt g/plant	Stover dry wt g/plant	Grain plus stover dry wt g/plant	Kernels per ear
5.6	82	129	153	282	130
4.0	81	112**	124**	236**	121
3.5	79	125	141	266	126
3.0	78	127	145	272	128
SE[a]	5	3.9	4.8	8.5	3.6
F[b]	NS	*	**	*	NS

[a]Standard error of the mean.

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

*,**Symbols after table values denote significant differences from the control mean with $P \leq 0.05$ and 0.01, respectively.

1981 SUMMARY AND CONCLUSIONS

Yields of 8 of 10 crops were not affected by exposure to H_2SO_4 or H_2SO_4-HNO_3 rain treatments in 1981. Only the forage yield of 'Alta' tall fescue and stover yield of 'Pioneer 3992' field corn exposed to H_2SO_4-HNO_3 rain showed significant yield differences between treatments. In tall fescue, the forage yield was depressed at pH 3.5 at one harvest only. Yields were not affected at other harvests or for other pH treatments. Also, tall fescue showed no significant differences between H_2SO_4 rain treatments for two harvests in 1981. (This is in contrast to 1980 when the first harvest and the total of two harvests were significantly greater in simulated rain of pH 3.5 and pH 4.0.)

The lack of significant yield differences after the first harvest of 1980 suggests that there was no cumulative effect of H_2SO_4 rain on tall fescue yield. Although the first harvest of the H_2SO_4-HNO_3 rain treatments in 1981 showed a significant decrease in yield at pH 3.5, this decrease was not seen in the second harvest and the total yields of the two harvests were not significantly different among treatments. The H_2SO_4-HNO_3 treated tall fescue had no significant yield differences between treatments for individual or combined harvests in 1980. Thus, there was no clear effect of acid rain on yield of tall fescue.

'Vernal' alfalfa exposed to H_2SO_4 rains during two growing seasons exhibited no significant differences between treatments for top dry weight at any of five individual harvests. These results suggest that H_2SO_4 has no cumulative effect on yield of 'Vernal' alfalfa.

Though some individual harvest tissue samples for fescue and alfalfa showed significant differences between treatments for mineral or fiber contents, results were not consistent among successive harvests over the two years of the experiment. Thus, our data did not show any clear effect of acid rain, either positive or negative, on the composition of the forage.

Field grown 'Steptoe' barley, 'Fieldwin' wheat, 'Russet Burbank' and 'Kennebec' potatoes, 'New Yorker' tomatoes, 'Cherry Belle' and 'Scarlet Knight' radishes showed no significant differences in yield between H_2SO_4-HNO_3 simulated rain treatments in 1981.

The effect of acid rain on corn is less clear than for the other crops. In 1980, there was a significant reduction in grain yield in the pH 4.0 H_2SO_4-HNO_3 acid rain treatment but not at other pH values. In contrast, in 1981, there was much less effect of acid rain on plot grain yields. However, there was a significant effect of pH 4.0 rain on grain yield of single-eared plants. When all plants were included in the analysis, the effect was not statistically significant ($P = .08$). However, there was a decrease of 16% in stover yield at pH 4.0 and a smaller decrease in the more acidic treatments.

Since an effect of pH 4.0 rain on corn grain or stover yield was observed in two years, the final year of these studies was devoted only to corn.

1982 MATERIALS AND METHODS

In 1982, experiments concentrated on the response of corn (Zea mays L.) to acid precipitation. Three studies were conducted. Experiment one examined the response of two early maturing cultivars, 'Pioneer 3992' and 'Northrup King PX39' to H_2SO_4-HNO_3 rain. Experiment two studied the response of 'Pioneer 3992' to acid rain of varying H^+ equivalent ratios of H_2SO_4:HNO_3. The third experiment exposed 'Pioneer 3992' to treatments in which pH varied from event to event, but the season-long average pH was the same for all treatments.

The background ion concentrations for all experiments were based on weighted average ion concentrations for National Atmospheric Deposition Program sites in New York, Pennsylvania, and Ohio from June 1 to September 30, 1979 (P. Irving, personal communication). Rain simulants were prepared from a stock solution of deionized water with 0.165 mg/l Ca^{2+}, 0.169 mg/l Na^+, 0.031 mg/l K^+, 0.035 mg/l Mg^{2+}, 0.258 mg/l NH_4^+, 1.114 mg/l SO_4^{2-}, 0.457 mg/l NO_3^-, 0.107 mg/l Cl^-, and 0.007 mg/l PO_4^{3-} added. The control rain consisted of stock solution in equilibrium with atmospheric CO_2 resulting in a pH of approximately 5.4.

Rain treatments were applied through stainless steel spraying nozzles calibrated for uniform distribution over the calibrated spray area at a rate of 1.4 cm/hr. During each rain event, rain was on for five minutes and then off for five minutes, giving a total delivery equal to 0.7 cm/hr. Rain events were 100 minutes/day, 2 days/week for a total rainfall of 2.2 cm/week. A sample of rain solution was collected for each treatment throughout each rain event (Table 16). The pH was then checked using an Orion 901 Research Microprocessor Ionalyzer calibrated to standard pH buffer solutions of 4.01 and 7.00.

Twenty-four portable exposure chambers were placed over the plots to apply the simulated rain. Each chamber consisted of a closed top polyvinyl chloride framework 4.6 m in diameter and 2.5 m tall (see Appendix for details of chamber construction). This framework was covered with woven polypropylene fabric to reduce disturbance of the rain distribution by wind. This cover allowed free air exchange and

Table 16. Summary of amount and acidity of natural and simulated rainfall and irrigation for the 1982 corn experiments

Experiment No.		Natural rainfall: from emergence to harvest[1]	Natural rainfall: on same day as simulated rainfall[2]	Total simulated rainfall	Average[3] pH of simulated plus natural rainfall: treatment pH						Total irrigation
		------ cm ------			3.5	3.7	3.9	4.1	4.3	5.4	--cm--
#1	West block 'Pioneer 3992'	12.0	3.0	33.0	3.68	3.88	4.04	4.26	4.45	5.27	30.2
	East block 'Pioneer 3992'	12.0	3.0	33.0	3.65	3.87	4.05	4.26	4.44	5.44	29.5
	West block 'Northrup King PX39'	15.8	3.0	33.0	3.72	3.91	4.07	4.29	4.48	5.27	30.2
	East block 'Northrup King PX39'	15.8	3.0	33.0	3.68	3.91	4.09	4.29	4.47	5.43	29.5
							4.0			5.4	
					2:1	3:1	1:1	1:0	0:1		
	'Pioneer 3992'	11.6	1.9	30.8	4.12	4.15	4.13	4.11	4.12	5.40	29.4
			4.0SV		4.0HV		4.0C	5.4			
	'Pioneer 3992'	11.6	1.9	30.8	4.16		4.25		4.34	5.50	29.9

1. Includes all natural rain from the date seedlings emerged from soil until harvest (simulated rainfall did not begin until after emergence).
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).

simulated cloud cover so that rain was not applied in direct intense sun. For a rain event, a chamber was placed upon a base consisting of a 4.6 m-diameter tubular steel ring and eight 1.8-m tubular aluminum uprights. The chamber base was raised on the uprights as necessary as the corn grew to keep the calibrated spray area always at the top of the crop canopy. Chambers were placed over the plots by hand until August 3, then a mechanical crane was used for chamber placement and removal. The chambers were rotated among treatments for successive rain events to eliminate systematic variability contributed by chambers and nozzles. A chamber was on a plot only during the rain event and then was removed.

Thermocouples, protected from rain contact, were suspended below the rain delivery nozzles in four randomly selected chambers. Temperatures from these four chambers and two ambient locations were recorded before, during, and after each rain event (Table 17). The temperature within the chambers was about 4°C cooler than the ambient during the rain events, as one would expect.

Table 17. Air temperature (°C)[1] for the 1982 simulated acid rain events[2]

	Before	During	After
Ambient	20.3	22.1	22.8
Chamber 2	20.6	17.9	18.2
Chamber 10	19.9	17.3	17.8
Chamber 14	22.1	19.3	18.8
Chamber 18	24.8	18.8	19.9

1. Temperature probes suspended in the center of four randomly selected chambers. Two ambient sites were measured using thermometers.

2. Mean of 116 rain events, ambient represents mean of two sites.

Field preparation for the 1982 experiments consisted of plowing and discing. Before the corn plots were established, the soil at the site had a pH of 4.8 (Table 18). Therefore, an application of 4345 kg/ha lime was plowed in and an additional 4345 kg/ha was disced in, as was an application of 231, 101, 50, 30, and 9 kg/ha N, P_2O_5, K_2O, S, and Mg. The field was then cultivated with a rotary tiller and harrowed before planting. Atrazine at 1 kg/ha and Lasso at 2.2 kg/ha active ingredient were applied as pre-emergent herbicides after planting.

Corn was seeded by hand May 28 to June 1 in two blocks with 34 north-south rows per block. The rows were spaced at 50 cm with plants within rows spaced at 30 cm. This planting arrangement provided a plant population of approximately 67,000 plants per hectare. Each plot consisted of 17 rows, with 20 plants per row. Eight rows to the outside of the block and three to the inside served as east-west borders for the 3.35 m-diameter circular calibrated study area. Four rows served as borders north and south. Within the calibrated rain area, 60 plants per plot, in two rows each of 8, 10, and 12 plants, served as study plants (Figure 1).

The first simulated rain events were applied June 14 and June 15. Sprinkler irrigation (Table 16) was applied when the moisture in soil cores from plot border areas indicated less than 50 percent field capacity (Lorenz and Maynard, 1980).

The plots were harvested by hand. Single-eared plants per row were harvested and informmation recorded together as one sample per plot. All other plants within a plot were harvested and data were taken individually on each plant. Fresh weights were taken for all mature ears. All plant material was dried at 60°C for 48 hours. Dry weights were taken for ears, kernels (grain dry weight), and stover. A 1,000-kernel subsample from the single-ear plants of each plot was then counted and the dry weight recorded. Leaf tissue from single ear plants of each plot of Experiment 1 was selected at random, harvested, dried, ground, and analyzed for concentrations of sulfur (S), potassium (K), phosphorus (P), calcium (CA), magnesium (Mg), manganese (Mn), iron (Fe), copper (Cu), boron (B), zinc (Zn), and aluminum (Al). The Plant Analysis Laboratory, Oregon State University, determined total S using a Leco

Table 18. Pre-study field soil characteristics[a] for the 1982 corn experiments

pH	Lime req. m.t./ha	P	K	B	Na	Zn	Mn	Cu	SO_4	OM	K	Ca	Mg	Na	CEC
		ppm									meq/100 g				
4.8	11.5	32.9	148	0.92	98.9	0.97	31.1	0.98	4.90	3.31	0.38	4.11	0.58	0.43	20.7

[a]Mean values for 35 field samples.

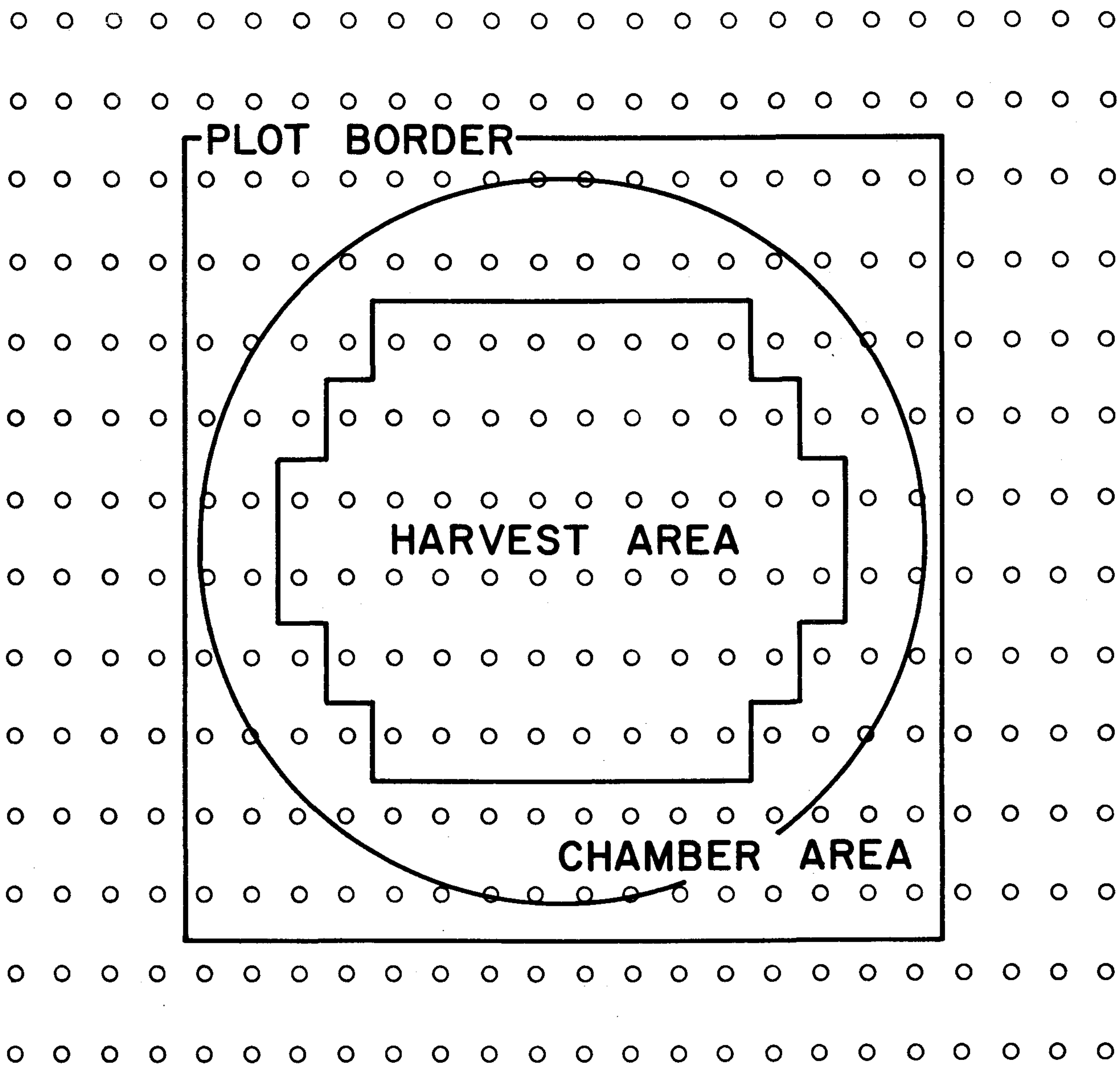

Figure 1. A sketch of the 1982 corn plots showing the location of the acid rain chambers and the plot harvest areas.

Sulfur Analyzer as described by Jones and Isaac (1972) and the 10 other elements using direct reading emission spectrometry as described by Chaplin and Dixon (1974).

Post-harvest soil samples were collected for analysis as shown in Table 19.

A randomized complete block design was used for all three experiments. A one-way analysis of variance (ANOVA) was used to compare treatments in all three experiments. When the resulting pH-treatment F test was significant ($P \leq 0.05$), two-sided t tests were used to determine which acid treatment means differed significantly ($P \leq 0.05$) from the control.

Experiment 1 consisted of 48 plots in two parallel north-south strips, each strip being two plots wide and 12 plots long. In each strip, there were 12 treatments - six pH levels for each of two cultivars, 'Pioneer 3992' and 'Northrup King PX 39'. Simulated rains were applied to all plots in a strip at the same time. Then the chambers were moved and rain applied to the second strip. Each variety in Experiment 1 was exposed to rains of pH 3.5, 3.7, 3.9, 4.1, 4.3, and 5.4 (control). The pH levels 3.5 through 4.3 were attained by adding 3.6 NH_2SO_4 and 1.8 $NHNO_3$ to the control rain. All acid rain treatments had an H_2SO-HNO_3 ratio of 2.37:1. The 'Pioneer 3992' plots of Experiment 1 were harvested October 20, 21, and 22. The 'Northrup King PX39' plots were harvested October 27, 28, and 29.

In Experiment 1, four plots, 'Pioneer 3992' block 3, pH 3.5, 4.1, and 4.3, and 'Northrup King PX39' block 3, pH 4.1, were destroyed when a heavy wind overturned a chamber. Data from those plots were not included in the analysis.

Experiment 2 consisted of 24 plots of 'Pioneer 3992' in one north-south strip, two plots wide and 12 plots long. The treatments were randomly assigned to six plots within each of four replicate blocks. In addition to a control of pH 5.4, the plots received pH 4.0 simulated rain treatments of H_2SO_4 alone, HNO_3 alone, and H_2SO_4-NO_3 in ratios of 3:1, 2:1 and 1:1. Experiment 2 was harvested October 13, 14, and 15.

Table 19. Soil analysis results at the conclusion of the 1982 corn experiment

Study	Treatment		Soil pH	ppm P	ppm K	ppm B	ppm Zn	ppm Mn	ppm Cu	ppm S	MEQ/100 g Ca	MEQ/100 g Mg	MEQ/100 g CEC[a]	OM[b]
Experiment 1														
'Northrup	pH													
King Px39'	3.5		6.2	35	123	.26	.49	.76	1.0	34.7	12.2	.62	17.3	3.7
	3.9		5.9	34	131	.28	.37	17.4	.99	34.7	10.2	.35	16.4	3.5
	4.3		6.3	53	201	.26	.33	9.6	.91	35.7	12.3	.83	17.3	3.8
	5.4		5.7	33	86	.18	.34	11.4	.70	38.0	9.7	.40	15.6	3.1
'Pioneer	3.7		6.4	42	158	.20	.41	9.5	.94	34.4	11.9	.57	16.8	3.6
3992'	4.1		4.7	29	100	.20	.50	28.6	.66	46.4	3.9	.30	14.3	3.0
Experiment 2		S-N												
'Pioneer	pH	Ratio												
3992'	4.0	3:1	5.2	29	101	.17	.58	24.0	.70	49.5	7.7	.47	15.7	3.2
	4.0	2:1	4.7	31	90	.20	.80	32.0	1.0	34.3	4.5	.59	15.2	3.3
	4.0	1:1	6.0	40	164	.20	.44	10.5	.86	29.9	11.5	.54	15.9	3.6
	4.0	1:1	5.0	35	117	.17	.62	23.6	1.0	28.8	5.9	.51	15.7	3.4
	4.0	0:1	5.0	38	105	.20	.58	27.4	.98	34.3	5.8	.50	15.7	3.4
	5.4	2.37:1	5.7	49	191	.23	.44	11.6	1.3	29.4	9.4	.41	16.2	3.4
Experiment 3														
'Pioneer	pH	VAR[c]												
3992'	4.0	0	5.1	24	86	.16	.82	35.0	.68	25.6	6.2	.78	15.2	2.5
	4.0	2	5.0	28	86	.17	.82	40.6	1.1	26.7	5.8	.64	18.3	3.2
	4.0	1	6.8	26	98	.20	.48	10.6	1.1	10.9	13.3	.67	16.6	3.0
	5.4	0	4.9	21	78	.19	.84	43.0	1.0	45.7	4.0	.69	14.8	2.6

[a]Cation Exchange Capacity.

[b]Percent Organic Material.

[c]pH variation level: 0 (constant), 1 (slight variation), 2 (high variation).

Experiment 3 consisted of 24 plots of 'Pioneer 3992' in one north-south strip, two plots wide and 12 plots long. Treatments were randomly assigned to four plots within each of six replicate blocks. The $H_2SO_4:HNO_3$ acid ratio for Experiment 3 was 2.37:1. Two treatments, the pH 5.4 (control) and the pH 4.0 (constant), were the same for all rain events. The other two treatments received a rain of one pH at one event and a rain of a different pH at the next event. In one variable pH 4.0 treatment, events ranged from pH 3.5 to 5.4 but averaged 4.0 for the season. In a second, more variable pH 4.0 treatment, events ranged from pH 3.1 to 5.4 and averaged 4.0 for the season. The variable pH treatments were based on pH frequencies for events at University Park, Pennsylvania, and Champaign-Urbana, Illinois, from May 15 through October 15, 1981 (Dana and Rothert, 1983). Experiment 3 was harvested October 15, 19, and 20.

1982 RESULTS AND DISCUSSION

'Pioneer 3992' and 'Northrup King PX39' field corn showed no significant differences in response to any simulated acid rain treatment in any of the three experiments conducted in 1982.

Seventy-eight percent of the 'Pioneer 3992' and 94 percent of the 'Northrup King PX39' plants in Experiment 1 produced single ears. Total ear fresh weight, total ear dry weight, total grain dry weight, total top dry weight, and total dry weight were not significantly affected by simulated acid rain treatment for either variety (Tables 20 and 21). Additional analysis for single-eared plants on a per plant basis did not show any significant differences between treatments (Tables 22 and 23). Tissue analysis of leaves from single-eared plants from each plot showed no significant differences between treatments for S, K, P, Ca, Mg, Mn, Fe, Cu, B, Zn, and Al content (Table 24).

Table 20. The effects of 2:1 sulfuric-nitric simulated acid rain events with different pH levels on ear fresh weight, ear dry weight, top dry weight, and grain dry weight of 'Pioneer 3992' grown in the field in 1982

pH	Total ear weight fresh	Total ear weight dry	Total stover dry weight	Total grain dry weight
	g/m²			
3.5	1,759	973	788	759
3.7	1,778	990	767	766
3.9	1,725	977	735	759
4.1	1,659	905	720	701
4.3	1,730	968	701	745
5.4	1,690	919	714	715
SE[a]	30.7	19.6	16.2	15.0
CV[b]	30	32	33	32
F[c]	NS	NS	NS	NS

[a]Standard error of the mean.

[b]Coefficient of variation of the mean (percent).

[c]Significance level of the F-test.

Table 21. The effects of 2:1 sulfuric-nitric simulated acid rain events with different pH levels on ear fresh weight, ear dry weight, top dry weight, and grain dry weight of 'Northrup King PX39' corn grown in the field in 1982

pH	Total ear weight fresh	Total ear weight dry	Total top dry weight	Total grain dry weight
	g/m^2			
3.5	1,946	783	1,171	600
3.7	1,986	795	1,180	601
3.9	1,907	740	1,180	555
4.1	1,884	728	1,198	548
4.3	1,886	752	1,212	566
5.4	1,957	759	1,167	567
SE[a]	35.1	16.7	13.9	21.7
CV[b]	21	26	22	28
F[c]	NS	NS	NS	NS

[a]Standard error of the mean.

[b]Coefficient of variation of the mean (percent).

[c]Significance level of the F-test.

Table 22. The effects of 2:1 sulfuric-nitric simulated acid rain events of different pH levels on single-eared plant stover and grain dry weight and kernel number per plant for 'Pioneer 3992' corn grown in the field in 1982

pH	Stover weight g/plant	Grain dry weight g/plant	Kernel No. kernel/plant
3.5	122	118	528
3.7	121	119	518
3.9	118	118	514
4.1	118	113	495
4.3	113	114	519
5.4	113	113	515
SE[a]	1.6	1.3	7.7
CV[b]	16	12	7
F[c]	NS	NS	NS

[a]Standard error of the mean.

[b]Coefficient of variation of the mean (percent)

[c]Significance level of the F-test.

Table 23. The effects of 2:1 sulfuric-nitric simulated acid rain events of different pH levels on single-eared plant stover and grain weight, and kernel number per plant for 'Northrup King PX39' corn grown in the field in 1982

pH	Stover weight g/plant	Grain dry weight g/plant	Kernel No. kernel/plant
3.5	185	95	478
3.7	186	95	511
3.9	184	88	469
4.1	190	88	460
4.3	185	90	432
5.4	182	89	474
SE[a]	2.3	1.6	8.6
CV[b]	15	21	9
F[c]	NS	NS	NS

[a]Standard error of the mean.

[b]Coefficient of variation of the mean (percent)

[c]Significance level of the F-test.

Table 24. The concentrations of 11 mineral elements in leaves of two corn cultivars treated with 2:1 sulfuric-nitric simulated rain of two different pH levels. The corn was grown in the field in 1982

Treatment	S	K	P	Ca	Mg	Mn	Fe	Cu	B	Zn	Al
	Pioneer 3992										
	%					ppm					
3.5	.22	1.45	.26	.82	.23	172.5	319.3	7.75	7.25	29.0	298.3
5.4	.21	1.32	.25	.92	.18	240.3	373.5	8.50	7.75	23.5	382.0
SE[a]	.02	.07	.02	.03	.02	17.3	40.1	.64	.42	1.9	51.3
CV[b]	21.7	14.8	20.5	8.6	28.5	23.7	32.7	22.3	16	20.3	42.7
F[c]	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
Treatment	Northrup King PX39										
3.5	.22	1.45	.35	.85	.25	269.5	463.0	8.0	6.25	46.5	501.0
5.4	.21	1.57	.39	.91	.26	279.8	372.3	8.5	7.00	46.8	340.3
SE[a]	.01	.11	.02	.03	.01	27.8	51.8	.60	.37	3.2	78.8
SV[b]	7.1	19.7	12.7	9.5	10.7	28.7	35.1	20.6	16.0	19.7	53.0
F[c]	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS

[a]Standard error of the mean.

[b]Coefficient of variation for the mean (percent).

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

'Pioneer 3992' was not significantly affected by the pH 4.0 rains of differing nitric/sulfuric acid ratios in Experiment 2. Table 25 shows that yields per m^2 of stover and grain were not affected by the treatments. Table 26 shows that stover and grain yield per plant of single-eared plants were likewise unaffected. Eighty-four percent of the population produced single ears.

Variation in acidity of individual rain events in Experiment 3 did not produce any significant differences in grain or biomass yield of 'Pioneer 3992' (Tables 27 and 28). Single ears were produced on 85 percent of the plants.

No foliar acid rain injury was observed in any of the three experiments in 1982.

Table 25. The effects of pH 4.0 acid rain events having differing nitric to sulfuric acid ratios on ear fresh weight and dry weight, and stover and grain dry weight of 'Pioneer 3992' corn grown in the field in 1982

Treatment		Total ear weight		Stover	Grain
pH	N-S ratio	Fresh	Dry	dry weight	dry weight
		g/m^2			
4.0	0:1	1,744	945	808	740
4.0	1:0	1,709	885	741	687
4.0	1:1	1,743	911	775	708
4.0	2:1	1,708	913	779	711
4.0	3:1	1,690	901	725	724
5.4	0:0	1,733	926	764	741
SE[a]		30.3	17.2	15.5	14.1
CV[b]		21	23	24	24
F[c]		NS	NS	NS	NS

[a]Standard error of the mean.

[b]Coefficient of variation of the mean (percent).

[c]Significance level of the F-test.

Table 26. The effects of pH 4.0 acid rain events of differing nitric to sulfuric acid ratios on single-ear plant stover and grain dry weight and kernel number per plant of 'Pioneer 3992' corn grown in the field in 1982

Treatment		Stover weight	Grain dry weight	Kernel No.
pH	N-S ratio	g/plant	g/plant	kernels/plant
4.0	0:1	121.0	112.9	515.4
4.0	1:0	111.9	101.1	504.0
4.0	1:1	119.9	106.8	506.3
4.0	2:1	119.9	109.5	511.5
4.0	3:1	116.5	111.6	514.8
5.4	0:0	119.1	112.8	507.9
SE[a]		1.8	1.3	8.7
CV[b]		18.0	16.0	8.0
F[c]		NS	NS	NS

[a]Standard error of the mean.

[b]Coefficient of variation of the mean (percent).

[c]Significant level of the F-test.

Table 27. The effects of variation in acidity of individual 2:1 sulfuric-nitric simulated acid rain events, but averaging pH 4.0, on stover and grain dry weights of 'Pioneer 3992' corn grown in the field in 1982

Treatment pH variation level	Stover dry weight	Grain dry weight
	g/m^2	
4.0 constant	669	665
4.0 slight variation	708	685
4.0 high variation	693	727
5.4 constant	747	729
SE[a]	12.8	14.9
CV[b]	22	25
F[c]	NS	NS

[a]Standard error of the mean.

[b]Ceofficient of variation of the mean (percent)

[c]Significance level of the F-test.

Table 28. The effects of variation in acidity of individual 2:1 sulfuric-nitric simulated acid rain events, but averaging pH 4.0, on single-eared plant stover and grain dry weight and kernel number per plant of 'Pioneer 3992' corn grown in the field in 1982

Treatment pH variation	Stover dry weight g/plant	Grain dry weight g/plant	Kernel No. kernels/plant
4.0 constant	109.8	113.6	513
4.0 slight	108.3	105.5	495
4.0 high	109.0	113.2	528
5.4 control	113.2	114.2	502
SE[a]	1.2	1.5	5.6
CV[b]	14	16	8
F[c]	NS	NS	NS

[a]Standard error of the mean.

[b]Coefficient of variation of the mean (percent).

[c]Significance level of the F-test.

GENERAL DISCUSSSION

Two years of growing similar crops in pots in chambers (1979, 1980) and in the field (Cohen et al., 1981, 1982) allow some general comparisons on crop responses to acid rain and on the responses of crops in different environments.

'Vernal' alfalfa, 'Alta' tall fescue, 'Russet Burbank' potato, 'Improved Thick Leaf' spinach, and 'Patio' tomato had no significant yield response to acid rain in pot-grown studies in chambers. Field studies of the same crops ('New Yorker' instead of 'Patio' tomato) showed similar lack of response. Thus, it seems clear that in the absence of other aerial pollutants, acid rain has little effect on yield or quality of these crops.

'Southern Giant Curled' mustard greens exhibited significant decreases in leaf weight at pH 3.0 and pH 4.0 in response to H_2SO_4 simulated rain when grown in pots in 1979. Field grown mustard greens showed no response to H_2SO_4 rain in 1980. However, mustard greens exposed to H_2SO_4-HNO_3 rain had decreases in yield at pH 3.0 and pH 4.0 in the field in 1980. Pot studies carried out in chambers showed significant decreases in yield at pH 3.0 and pH 3.5 for 'Cherry Belle' radish in the H_2SO_4-HNO_3 rain treatments and pH 3.0 in the H_2SO_4 rain treatment. In contrast, a significant increase in yield was seen for radishes exposed to pH 4.0 H_2SO_4 rain. These results on plants grown in pots in chambers were contradicted by two years of field-grown radishes with no significant differences in yield between treatments. The contrast in these comparisons suggests that great care is needed in interpreting results from plants grown in pots in chambers and those results should not be used to estimate crop response under field conditions.

Comparison of foliar injury from acid rain on potted plants in chambers versus that on field-grown plants indicates that the responses are quite different in the two conditions. Alfalfa, barley, tall fescue, potato, radish, tomato (leaves and fruit), and wheat all exhibited some acid rain foliar injury at pH 3.0 in 1980 pot studies (Cohen et al., 1982). In the field, only alfalfa exposed to H_2SO_4 rain had any visible injury, and that was only on less than one percent of the leaf surface, at one harvest only, and in one year only. In 1981 field studies, we observed foliar acid rain injury to foliage in H_2SO_4-HNO_3 exposed tomatoes in three plots and that was on less than 1 percent of the leaf surface. Likewise, we observed some injury in a few tall fescue plots on a few leaves. No tomato fruit exhibited acid rain injury and the injury on tall fescue was not apparent after September 22. Radish cotyledons showed acid rain injury at pH 3.0 H_2SO_4-HNO_3 treatment in 1981 in the field but no true leaves were injured. These tiny flecks, which we scored as acid rain foliar injury, would likely have gone unnoted in most experiments.

It is often assumed that foliar acid rain injury is an indication of yield loss. This has not been true for field-grown crops exposed to acid rain in these experiments in the few cases where there appeared to be some foliar injury. Even in chamber studies where foliar injury was more severe, the plant yields were seldom affected.

Among all the experiments in all crops during the several years of simulated acid rain testing in the fields the only statistically clear response was a reduction in corn stover weight in 1981. All acid treatments (pH 4.0, 3.5, and 3.0) showed reduced stover production compared to the control (pH 5.6) and the results were highly significant ($P \leqq 0.01$) for both the F test and for t tests for the means of the pH 4.0 and 3.5 treatments, compared to the control.

The response of corn to simulated acid rain has not been consistent from year to year, however. Nevertheless, the results do suggest that, among crop plants, corn may be particularly sensitive to acid rain. It is of particular interest that the sensitivity appeared to be greater to the mildly acidic rain of pH 4.0 than to the much more acidic rain of pH 3.5 and 3.0. Figure 2 shows the grain yield of 'Pioneer 3992' for the three years in which acid rain was applied in the field. The yield data for 1981 were quite variable so that the F test was not significant ($P=.08$); however, the similarity of pattern of the response curves in 1980 and 1981 suggests that the response pattern shown in Figure 2 for the two years was real. Although the results were not significantly different, the same general response pattern was observed in the means in 1982.

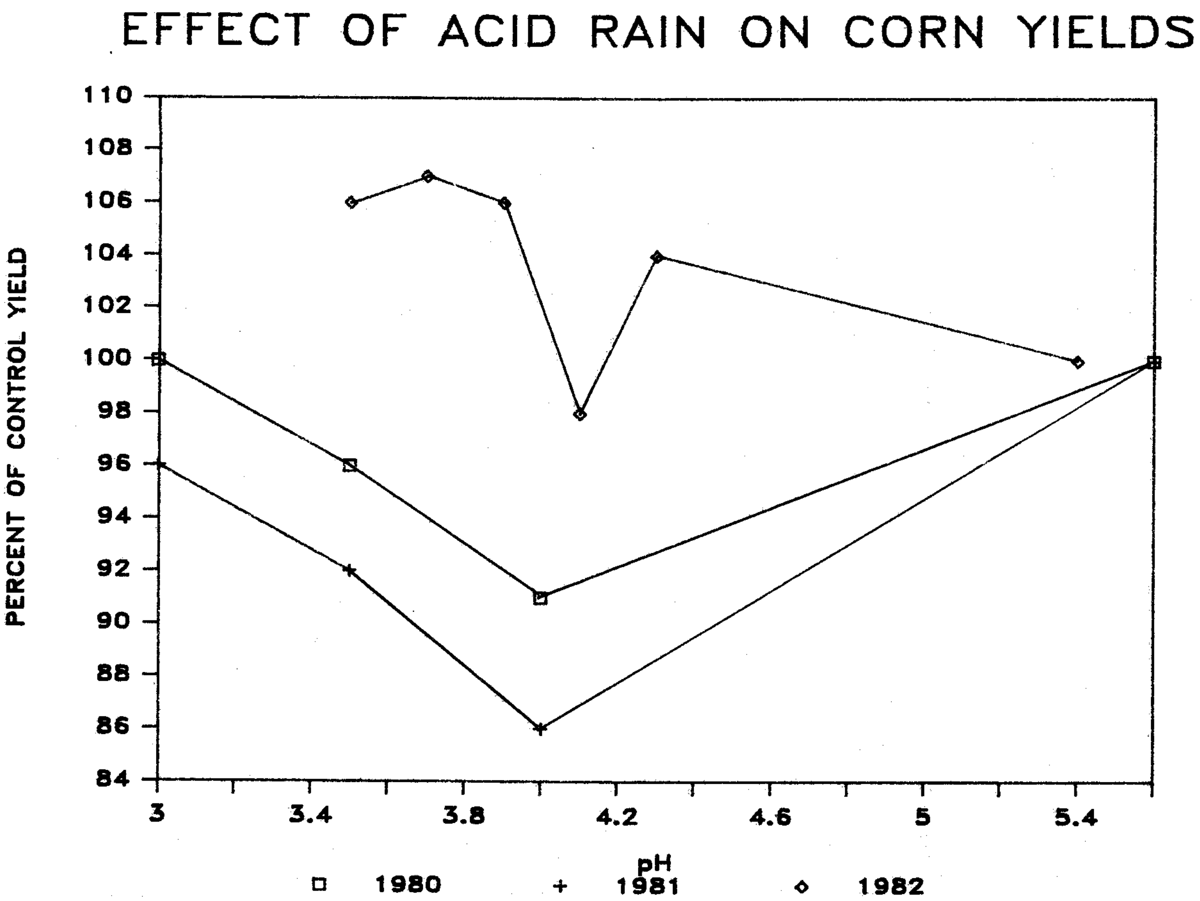

Figure 2. The grain yield of 'Pioneer 3992' at different pH of acid rain in 1980, 1981, and 1982.

In 1980, the effect of acid rain treatments on yield of corn appeared to be an effect on the number of two-eared plants in the treatments (Cohen et al., 1981). In 1981, there was no effect of acid rain on the degree of prolificacy. Thus, these effects of acid rain on the grain yield were dissimilar in the mechanism by which they were expressed in the plant and would not be particularly noteworthy had the yield of stover not been depressed in 1981. However, the depression of the stover yields by 19% at pH 4.0, 10% at pH 3.5, and 7% at pH 3.0 indicated that the carbohydrate production of the corn was affected by acid precipitation in 1981. This strenghtened the argument that the corn yield depression in 1980 was real. No explanation is apparent of why the depression in yield would have been greater at pH 4.0 than at the more acidic levels.

These results on corn were surprising, given the fact that other crops had shown no response to acid rain. Surprising, too, was the particular sensitivity to mildly acidic rain. Therefore, in 1982, the research concentrated on corn.

During the 1982 growing season, there were no significant effects of any kind from treating field-grown corn with simulated acid rain. The grain and biomass yields of all treatments were identical and there was no foliar or compositional effects of acid rain on the corn. Yet in 1980 and 1981, there were significant effects on either biomass or grain yield. Thus, these data support the conclusion that, under some conditions, corn is particularly sensitive to acid precipitation.

This document constitutes a final report on the research on acid rain by the Crop Science Department of Oregon State University. In general, studies over the past several years have shown that crop plants are amazingly tolerant of acid precipitation. Even repeated applications of precipitation of pH 3.0 throughout the entire growing season had no effect on the yield or appearance of most crops. The only exception was corn, as discussed above.

Perhaps we should not be surprised by these results. Plant foliage is equipped well by nature to tolerate acid precipitation. The leaves and stems are covered with wax (the cuticle) which excludes acid precipitation from contacting living cells. The stomata, the route of entry and egress of gases such as water vapor, oxygen, and carbon dioxide, close in the presence of acids. If acid rain were to begin to penetrate a stomatal opening, it would contact first a stomatal guard cell. Guard cells can absorb acids and an increase in the acidity of the guard cell contents causes water to be transported out of the cell, it loses turgor, and the stoma closes. Thus, one would expect foliage to be relatively tolerant of acids.

Plant roots, on the other hand, may readily absorb acids, and soil acidity is a well known problem for plant growth. It is important to realize, however, that agriculture, since its early inception, has been managing soil aciditiy. In general, soils have a huge buffering capacity compared to the quantity of hydrogen ions incident on a soil surface from acid rain. Of much greater concern to soil managers is the normal flux of acid generated in the soil each year by natural processes and by the necessary applications of fertilizer. "Worst case" estimates suggest that acid rain could supply only about 1% of the normal hydrogen ion flux that would be generated yearly in a fertilized agricultural soil (Baham, John. Department of Soil Science, Oregon State University--private communication). Thus, agriculture has learned to manage soil acid fluxes much larger than those threatened by acid rain. Acid rain should not pose a serious problem for the soil manager because the soil buffers the acid when it first contacts the soil and the slow changes induced in the soil acidity by the precipitation are readily handled by the application of lime.

From a soil management point of view, a far more important aspect of acid rain may be the fertilizer value of the components of the rain. Every year the progressive farmer spends a significant portion of his budget on nitrogen fertilizer. The nitrate in acid rain provides part of the essential nutrients that crop plants need. In many areas the soils are also deficient in sulfur, and fertilizers must contain sulfur for crops to yield well. Thus, any assessment of the impact of acid rain on crop plants should consider the fertilizer value of the N and S in acid rain to adequately assess the role that acid rain plays in crop yields.

RECOMMENDATIONS

We recommend to the U.S. Environmental Protection Agency that further field tests should be performed on the response of corn to controlled applications of simulated acid rain. Those tests should be performed in an environment where corn is a major crop and where acid rain occurs naturally, because the responses we observed were not consistent from year to year. This suggests that the environment may be important in determining any response. Therefore, the studies should be conducted in an environment similar to that in which corn is grown as a commercial crop.

APPENDIX

This appendix describes the rain simulation chamber used in 1981 and 1982. Different designs were used each year to meet the needs of the particular experiment.

Natural rainfall is highly variable in composition, distribution, droplet size (Best, 1950), terminal velocity of the raindrops (Gunn and Kinger, 1949), intensity (Laws and Parsons, 1943), and duration. Thus, decisions had to be made as to the range for these factors in our experiments. Many different rainfall simulators have been developed to deal with specific traits of rainfall (Mutchler and Hermsmeier, 1965). For these experiments, composition and distribution were primary concerns. In the design, however, droplet size and terminal velocity were also considerations.

Our exposure chambers were designed to meet four criteria:

1. The simulated rainfall should have a uniform distribution of rain over the plot at an application rate of approximately 0.7 cm/hr.
2. The mean volume raindrop size and drop size distribution should be within the range ordinarily observed for natural rain.
3. The chambers should simulate cloud cover by reducing light intensity about 75 percent (Welch et al.).
4. The chambers should be portable and adaptable to plants of different heights.

The exposure chambers were designed in two basic parts, the structure and the rain delivery system. The rain delivery system delivered the rainwater to the plots, formed the raindrops, and distributed the raindrops uniformly over the harvest area. The structure provided support for the rain delivery system, shelter from the wind (required for uniform distribution of the rain over the study area), and support for the simulated cloud cover (shade cloth).

The 1981 Simulator

In 1981, the rain was provided by Delevan type R-D spray nozzles. They gave hollow cone spray patterns. We used a combination of an RD-1 cap, a #23 disc and a #2 cone, which gave us the desired rate of application. However, this combination gave patterns that were inconsistent from nozzle to nozzle and many nozzles were tested to find sufficient similar nozzles for our studies. The best results were obtained when the nozzles were operated at a pressure of 40 pounds per square inch.

Pairs of nozzles provided coverage of a 2 m x 2 m calibrated spray area. The enclosures were circular. The nozzles were located 2 m apart and 0.7 m into the chamber from the sides. The nozzles were held by a "hanger" that allowed adjustment of the nozzle to any orientation. The nozzles were oriented to deliver the simulated raindrops with an upward velocity. The rain then fell by gravity upon the plants (Figure A1).

Distribution was checked by collecting rain in containers placed at the intersections of a 0.3 m grid laid out over a 2 x 2 m area. Distribution for a pair of nozzles was accepted if no values were below 3.7 mm/hr or greater than 12.3 mm/hr. The coefficient of variation for raindrop distribution over the plot area was less than 25 percent and the average rate over the area fell between 5.9 mm/hr and 7.4 mm/hr. The distribution pattern for pairs of nozzles was adjusted by turning, tilting, and tipping the nozzles until an acceptable pattern was achieved. This was a difficult, time-consuming process.

The exposure chambers were 3.3 m in diameter with 2 m vertical walls plus an additional 0.6 m wall extension at the top which tapered inward to a diameter of 2 m (Figure A1). Extensions were added at the bottom of the chamber to adjust the height so that the top of the crop canopy was in the vertical zone where the spray distribution pattern was uniform. The tapered top of the chamber helped reduce wind turbulence in the chamber. The sides of the chamber were covered with clear polyethylene film. The top 2 m diameter circle was left open for ventilation. The entire chamber was then covered with a shade cloth. The cloth was sufficiently porous to allow ventilation through the opening

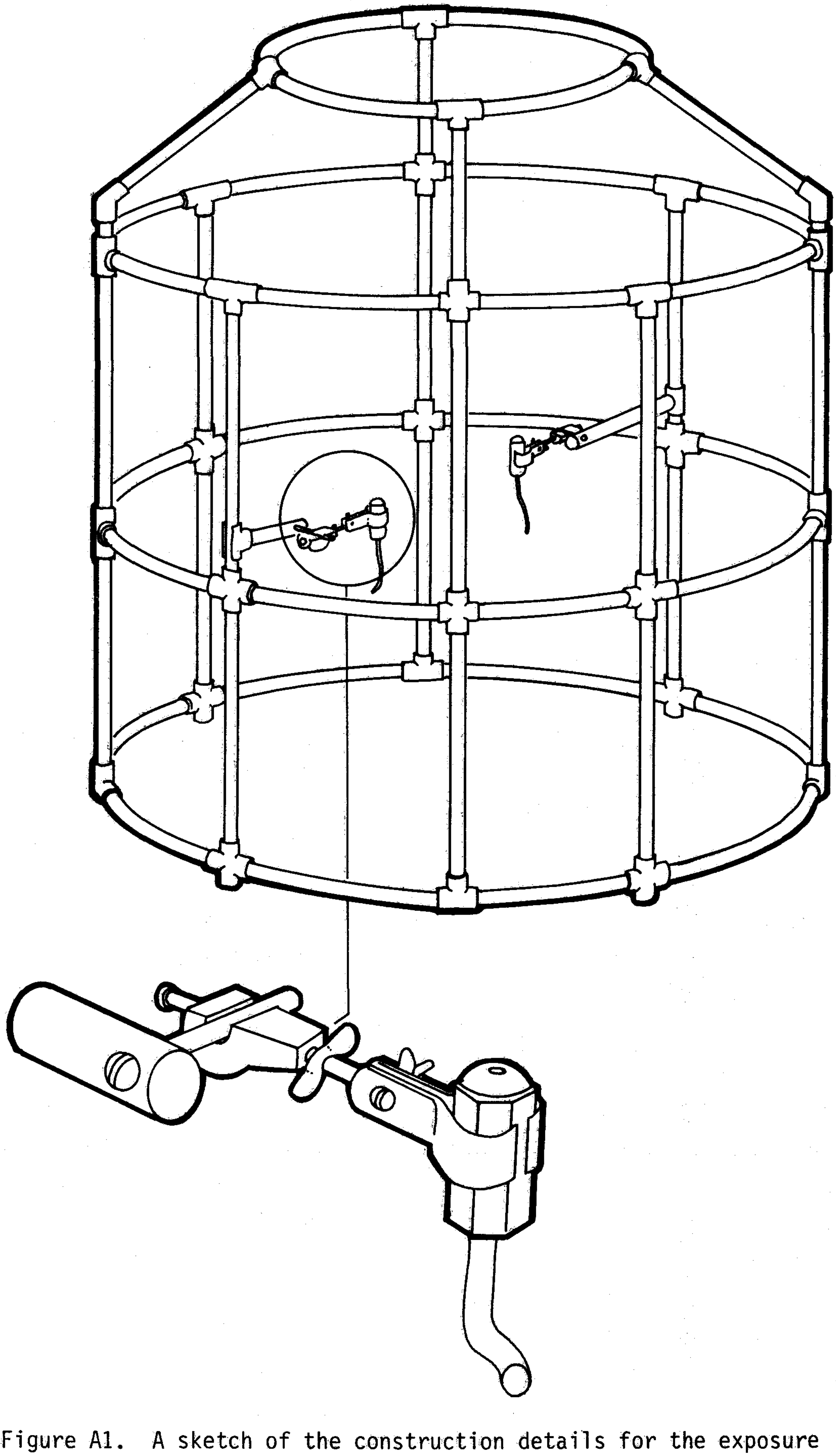

Figure A1. A sketch of the construction details for the exposure chambers used in 1981.

at the top of the chamber. The total weight of the chambers was approximately 20 kg.

The frame of the enclosure was made from 1.9 cm polyvinyl chloride (PVC) pipe and fittings (Figure A1). Hoops were made of class 1120 PVC pipe and the uprights and all the fittings, crosses, tees, and 45-degree elbows were schedule 40 PVC pipe. All joints were either glued or secured with a short section of hardwood dowel inserted both into the end of the pipe that goes into the fitting and into the fitting itself. These dowels were secured by a machine screws and nuts. Wires were strung diagonally across the frame to prevent it from flexing excessively in the wind.

The frame was covered with 6 mil polyethylene film (Monsanto 602). The film was held in place by Monsanto clear plastic tape.

The shade fabric was a black, woven polypropylene material (Chickopee brand) that provided 73 percent shade. It was porous enough to allow sufficient ventilation so that interior temperatures were close to ambient.

Mobile home anchors were screwed into the ground at the corners of the field plots. Tether lines attached to the middle hoop of the chamber were tied to the anchors when the chambers were on the plots. These tethers stabilized the chambers in wind.

The raindrops coming from the nozzles initially had a horizontal component to their trajectory. Therefore, distribution and density of rain drops changed with distance fallen. A uniform distribution occurred about 0.3 m below the nozzles (about 0.6 m above the bottom of the chamber). As crops grew taller, extensions were added at the base of the chamber to assure that the distribution of the rain was uniform at the top of the crop canopy. These extensions were circular frames of PVC pipe identical in construction to the sidewalls of the chamber proper. They consisted of two 3.1-m diameter, class 1120, PVC pipe hoops, supported by struts of schedule 40 PVC pipe of an appropriate length. For corn, a 1.1-m extension was used. These extensions were not covered in any fashion. Border rows of the crop provided a wind break and shade. When the crop was tall enough to begin to interfere with the spray pattern, the extensions were placed permanently in the crop. The chambers were then set on the extensions rather than on the soil.

The 1982 Simulator

The rain in 1982 was applied by a Spraying Systems 1/4 GG 10W spraying nozzle. This nozzle had a wide angle, solid cone spray pattern. The drop size and drop size distribution compare favorably with a moderately heavy natural rain (Best, 1976). Less than 2 percent of the drops were less than 700 microns in diameter, and less than 2 percent of the drops were greater than 5,500 microns in diameter. The mean volume diameter was 2,910 microns (Spraying Systems, Wheaton, IL). The best performance occurred at operating pressure of 8 to 10 pounds per square inch.

One nozzle was used in each enclosure to provide coverage for the calibrated spray area, a circle 3.4 m in diameter (about 9 m^2). A nozzle was suspended at the center of each chamber by a harness that allowed us to adjust the nozzle to the appropriate position and orientation. Nozzles were selected which gave uniform spray patterns and adjustments were not required to get uniform distribution over the harvest area.

Spray patterns were checked by collecting rain in containers placed at the intersections of a 0.3-m grid laid out over the 3.6-m diameter circular area. No values were below 7.4 mm per hour or greater than 24.6 mm per hour. The coefficient of variation was less than 25 percent, and the average rate over the harvest area was 13.3 mm per hour. This rate was twice as great as the desired application rate. An appropriate application rate was achieved by simulating rain for 5 minutes, then turning off the rain for 5 minutes, then back on for 5 minutes and so on.

As with the Delevan nozzle used in 1981, this nozzle gave each raindrop a horizontal velocity component. Density and distribution of drops were functions of the distance the drops had fallen. In this application a desirable rain pattern was developed as the drops were falling through the vertical interval 1 to 1.5 m below the nozzle when the nozzle was oriented upward. To keep the top of the plant canopy within this interval from the nozzle, the chamber was adjusted vertically as the plants grew. This adjustment was achieved by adding extensions to the base on which the spray chamber rested. This procedure allowed us to vary the height of the nozzle, relative to the ground, from about 1.5 to 4.5 m and allowed for a plant height to 3.5 m.

The adjustable chambers consisted of two cylinders, one inside the other (Figure A2). The nozzle was fixed at the center near the top of the inner cylinder. The nozzle did not move relative to this part of the chamber. The two cylinders were attached to each other by snap-bolts at the bottom of the inner cylinder that hooked to eyebolts on the frame of the outer cylinder. When the snap-bolts were not connected to the eyebolts, the inner cylinder was free to move vertically within the outer cylinder. Sets of eyebolts were spaced at one-foot intervals vertically on the outer frame. By attaching the snap-bolts to a set of eyebolts, the height of the nozzle relative to the ground could be adjusted.

The inner cylinder was 5 m in diameter (Figure A2). Initially the cylinder had a 2-m side-wall consisting of three hoops and two sets of struts. The shade cloth covered the chamber to the bottom of this side-wall. After the corn had exceeded 1 m in height, another 1 m of side-wall was added. This gave a total side-wall height of 3 m. The shade cloth did not cover this addition. All structural members were schedule 40 PVC 1.9-cm diameter pipe and fittings except the small hoop in the roof of the inner cylinder. This was made of class 1120 PVC 1.9 cm pipe. All joints were doweled and bolted as described for 1981 chambers.

The outer cylinder was slightly more than 5 m in diameter (Figure A2). The bottom hoop was constructed of rectangular steel (2.5 x 1.2 cm). This rigid hoop maintained the shape of the structure. The uprights of the outer cylinder were constructed of 2.5-cm tube drawn from 0.15-cm aluminum (6061-46). Each was 2 m long. The eyebolts were attached to these uprights. The uprights were supported by a zigzag frame of schedule 40 PVC 1.9-cm diameter pipe and fittings. The shade cloth was a woven polypropylene fabric (Chicopee brand). It provided about 90 percent shade. The fabric was porous and allowed ventilation

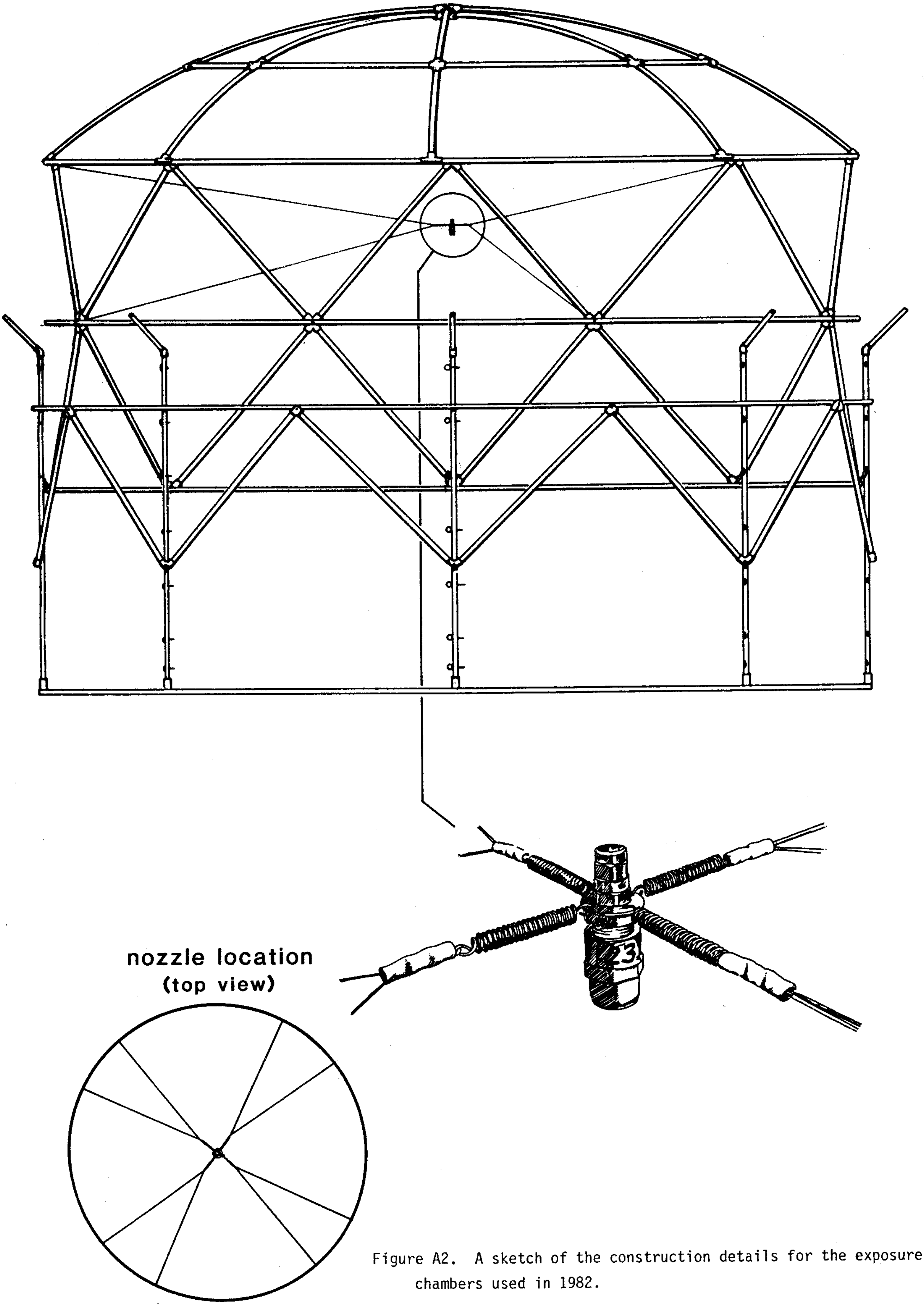

Figure A2. A sketch of the construction details for the exposure chambers used in 1982.

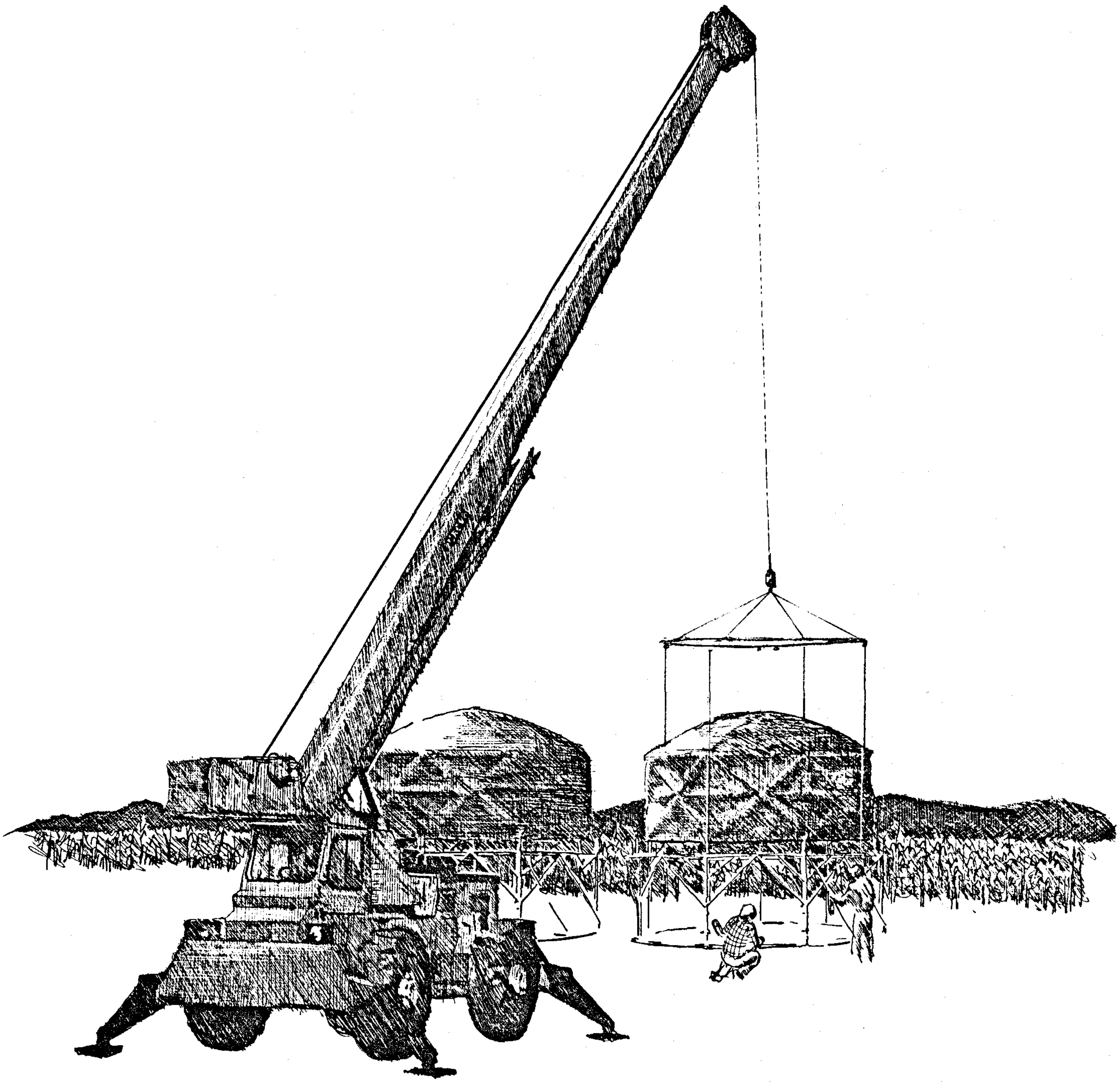

Figure A3. A sketch of the mechanical crane placing a chamber upon a plot in 1982.

enough that inside temperatures were close to ambient (Table 17), but provided an adequate wind shelter for the spray pattern. When the chambers were raised to accommodate the growing crop, there was a gap between the shade cloth and the ground. It was assumed that the crop provided the shade and the wind break in this gap. The shade cloth covering the chamber walls always extended at least one foot below the top of the crop canopy.

The nozzle was suspended in the center of the chamber by #40 braided Dacron line (Fig. A2). These lines were attached to the nozzles with springs which helped to dampen any vibrations in the structure that would tend to disturb the spray pattern. The springs were attached to, and the nozzle supported by, a stainless steel washer. At points of adjustment, the lines were run through electrical solderless butt connectors (#10-12 AGW). After adjustments were made and the nozzle was centered and leveled at the proper height the connectors were crimped to hold the lines in place.

The chambers were secured on the field plots during rain events to mobile home anchors by tether lines from the top of the chamber. After the corn was four feet in height, a mechanical crane was used to lift the chambers onto the plots (Figure A3).

The rain making and rain delivery to the plots were similar for both years. Rain was delivered to the plots by various pipes, tubing and other plumbing. Because of the corrosive nature of the rain solutions, and a desire to apply nothing to the study plants but the formulated rains, great care was used in selecting appropriate materials to be in contact with the rain solutions. With one exception, there was no evidence that any of them corroded or leached anything into the rain solutions. The following materials were used.

Of the plastics, polyvinyl chloride types I and II, polyethylene and polypropylene were all excellent. (Handbook of Plastics and Elastomers). Other polymers used were Teflon, as a coating on some parts, and viton, as "O" rings in the compression fittings (vendor recommendation). Where metal fittings or parts were required, only 316 stainless steel was used (Source Book on Stainless Steel). In 1981, the Delevan nozzles were 306 stainless steel. Some corrosion was observed on those nozzles.

REFERENCES

Association of Official Analytical Chemists. 1975. 12th edition. Methods of analyses. Washington, D.C.

Berg, M.G. and E.H. Gardner. 1978. Methods of soil analysis used in the soil testing laboratory at Oregon State University. Special Report 321. Oregon Agricultural Experiment Station, Corvallis, OR.

Best, A.C. 1950. The Size and distribution of raindrops. Quarterly Journal of Royal Meteorological Society 16:76.

Chaplin, M.H. and A.R. Dixon. 1974. A method for analysis of plant tissue by direct reading spark emission spectrometry. Applied Spectroscopy 28:5-8.

Cohen, C.J., L.C. Grothaus, and S.C. Perrigan. 1981. Effects of simulated sulfuric acid rain on crop plants. Results of 1979 crop survey. Special Report 619. Oregon Agricultural Experiment Station, Corvallis, OR.

Cohen, C.J., L.C. Grothaus, and S.C. Perrigan. 1982. Effects of simulated sulfuric and sulfuric-nitric acid rain on crop plants. Results of 1980 crop survey. Special Report 670. Oregon Agricultural Experiment Station, Corvallis, OR.

Dana, M.T. and J.E. Rothert. 1983. The MAP3S Precipitation Chemistry Network: Fifth Periodic Summary Report (1981). Publication No. PNL-4599, UC-11. Pacific Northwest Laboratory, Richland, WA.

Goering, H.K. and P.J. VanSoest. 1970. Forage fiber analyses. USDA Handbook No. 379.

Gunn, R., and G. Kinzer. 1949. The terminal velocity of fall for water droplets in stagnant air. Journal of Meteorology 6:(4) 243-248.

Harper, C. A. (editor). 1975. Handbook of Plastics and Elastomers. McGraw-Hill Book Company, N.Y.

Jones, J.B., Jr. and R.C. Isaac. 1972. Determination of sulfur in plant material using a Leco Sulfur Analyzer. Journal of Agricultural and Food Chemistry 20:1292-1294.

Laws, J.O. and D.A. Parsons. 1943. The relations of raindrop size to intensity. Transactions of American Geophysics Union 24:452-459.

Likens, G.E. and F.H. Borman. 1972. Nutrient cycling in ecosystems. In: Ecosystem structure and function, p. 25-47. Proceedings 31st Annual Biology Colloquium, Oregon State University Press, Corvallis, OR.

Lorenz, O.A. and D.N. Maynard. 1980. 2nd Edition. Knott's Handbook for Vegetable Growers. John Wiley and Sons. New York.

Matches, A.G. (ed.). 1973. Anti-quality components of forages. Crop Science Society of America Publication No. 4. Madison, WI.

Mutchler, C.K., and D.A. Hermsmeir. 1965. Review of rainfall simulators. Transactions ASAE 8:(1) 67-68.

Raynor, G.S. 1979. Meteorological and chemical relationships from sequential precipitation samples. p. 269-273. In: W. Licht, A.J. Engel, and S.M. Slater (eds.). American Institute of Chemical Engineering Symposium Series No. 188, Vol. 75. AIChE. New York.

Salisbury, F. B., and C. Ross. 1969. Plant Physiology. Wadsworth Publishing Co., Inc., Belmont, CA.

Source Book on Stainless Steel, 1976. ASME Engineering Bookshelf. The Periodical Publication Department, American Society of Metals.

Welch, R. M., S.K. Cox, and J.M. Davis. 1980. Solar Radiation and Clouds. American Meteorological Society, Boston, MA.