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Simulated Acid Rain Effects On Cool-Season Forage Grasses

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General Summary

Three approaches to determination of relative sensitivities of cool-season forage grasses to simulated acid precipitation were evaluated: (1) short duration (10-day) exposure of seeds and seedlings in a germination chamber, (2) medium duration (eight-week) exposure of mature forage grass clones in a greenhouse environment, (3) long duration (two-year) exposure of mature grasses in a field environment. Even though germination chamber experiments proved the most rapid and sensitive method for determining cool-season forage grass sensitivity to acid precipitation, it is doubtful that these tests would be diagnostic of mature forage response in field environments. Responses of forages to acid precipitation under differing managements (field vs. greenhouse) appear to vary.

Inhibition of radicle elongation (on soil and filter paper media) and delayed seed germination (on filter paper) of cool-season forage grasses with increasing rain acidity were evident in germination studies. The order of tolerance to increased rain acidity was (from greatest to least) tall fescue, orchardgrass; timothy, bluegrass. Visible injury of both tall fescue and orchardgrass in the greenhouse increased quadratically with decreased rain pH. Decreased rain pH did not affect the yield of tall fescue, but increased the yield of orchardgrass. The effect of rain pH on nutrient concentrations in tall fescue and orchardgrass foliage was inconsistent among blocks in time and among harvests within blocks. Nitrogen concentrations of orchardgrass, however, frequently demonstrated linear increases with decreased rain pH. The acidity levels causing foliar damage, however, were substantially greater than ambient levels. Additionally, the minimum drop volume producing damage at pH 3.0 is a relatively large drop size (based on our observations of both natural

and simulated rain in the field) and would not usually be encountered in field situations.

Changes occurring within the soil system in the field following acidic rainfall additions may have influenced orchardgrass seedling viability and seedling dry weight. Both seedling viability and dry weight were greatest with pH 3.1 simulated rainfall and decreased with higher or lower rainfall pH. Increased NO_3 levels in increasingly acidic simulated rainfall may have stimulated seedling response. The interactive effect of increasing NO_3 levels (beneficial) and increasing H (potentially detrimental) on the response of seedlings to simulated acid rain through time was effectively modeled with germination-mortality functions.

Three cultivars each of orchardgrass and tall fescue were subjected to four pH levels (4.3, 3.7, 3.1, 2.5) of simulated acid precipitation for two growing seasons in the field. Ambient precipitation was not excluded. Forage yields on individual harvest dates were not affected by rainfall pH. Variations in yields between cultivars mainly reflected differences in maturity. Forage was analyzed for N, S, P, K, Ca, and Mg. The principal effect of increased rainfall acidity on forage nutrients for any one harvest date was an increase in S concentration. Orchardgrass forage was affected more frequently than tall fescue. Repeated measures analysis indicated crop yields, forage S, and forage K were modeled with cubic responses, first increasing, then declining and increasing as pH decreased.

The conclusions drawn are tempered by the recognition that current natural precipitation is less acid on an annual basis than most of the levels employed in these studies.

Acknowledgments

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Part 1. Effects of Simulated Acid Rain on Cool-Season Forage Grasses: Greenhouse and Germination Chamber Experiments

Kien T. Luu[1], Jeff D. Wolt[2], John H. Reynolds[3], and Cynthia L. Lucas[4]

Rainfall averaging less than pH 4.5 has been identified throughout much of the eastern United States (Cogbill and Likens 1974, Hileman 1981). The cool-season forage grasses — tall fescue, orchardgrass, Kentucky bluegrass and timothy — have received little attention with regard to their sensitivity to acid precipitation, even though forage is an important component of agronomic systems in many regions of the United States and Canada that are subject to acid precipitation.

Workers in Oregon (Cohen et al. 1981, Lee et al. 1981) studied the effects of simulated acid rain on tall fescue, orchardgrass, bluegrass, perennial ryegrass, and timothy in pots and in field chambers. Also in Oregon, Cohen et al. (1982) studied Alta tall fescue and Potomac orchardgrass, and Plocher et al. (1985) studied Alta tall fescue. These reports indicated relative insensitivity of tall fescue and orchardgrass to acid precipitation.

Walker (1982) reported a possible acid precipitation influence on grass seedling establishment after seven to ten days of exposure to H_2SO_4-acidified water (pH 2.6). Seed germination of red fescue at pH 2.6 was two-thirds of that observed at pH 5.7. Germination of Kentucky bluegrass and Chewings fescue seed at pH 2.6 was nil. Haun et al. (1988) counted orchardgrass seedling numbers in the field for two weeks and found no effect of simulated rain pH on maximum seedling viability. Increased acidity (pH 4.3 to 3.1)

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General Introduction

Research into the effects of acid precipitation on yield and quality of cool-season forage grasses is disproportionately low in relation to the importance of these forages in regions of the United States where the consequences of acid precipitation are of great concern. Crop sensitivity to acid precipitation is dependent on the conditions under which experiments are conducted, the crop parameters evaluated, and the particular dose-response function used to interpret the results. Most crop sensitivity studies utilize simulated rain, the composition of which influences the results.

This research determined the sensitivities of cool-season forage grass yields and quality parameters to simulated acid precipitation in field and greenhouse environments. Tall fescue, orchardgrass, Kentucky bluegrass, and timothy were tested. Primary emphasis was placed on tall fescue and orchardgrass because of their greater economic importance and their adaptation to the climatic conditions of the area.

surface soil (Humic Hapludult), and Etowah silt loam surface soil (Typic Paleudult). Sterilized 9-cm diameter petri dishes containing either Whatman No. 2 filter paper or 30 g air-dry, sterilized soil received 50 seeds each of Forager or Kentucky 31 tall fescue, Hallmark or Potomac orchardgrass, Climax or Clair timothy, Common or Kenblue bluegrass (100 seeds in the case of Kenblue bluegrass, which exhibited less than 50 percent germination). Filter paper treatments received 4 mL simulated acid rain, while soils, were thoroughly wet with simulated rain (5 and 8 mL for Statler and Etowah soils, respectively). The randomized complete block experiment with four replications contained a split-split plot arrangement of treatments with six simulated rain pH values (5.5, 4.0, 3.5, 3.0, 2.5, and 2.0) as the main plot treatments. Split and split-split plot treatments were four grass species and eight grass cultivars, respectively. Seeds were allowed to germinate in the dark in a germination chamber in which saturated atmospheric moisture conditions were maintained at 21.5°C. The number of seeds germinated, radicle length, and coleoptile length were measured at three and five days after seeding for filter paper media and at four and six days for soil media. Measurements on bluegrass were conducted two to four days later in each case because of slower germination rates. Root and coleoptile length measurements were based on five randomly selected seedlings per petri dish.

Data were subjected to analysis of variance (ANOVA) using the GLM procedure of SAS (1982). In all instances, the effect of species was significant ($P < 0.01$); therefore, data are reported by species. Polynomial regression analysis was used to test the trends of treatment responses.

In conjunction with the germination experiment, Etowah and Statler surface soils in petri dishes were treated as they were for the germination experiment, but did not receive seed. Following the final germination measurements, soil solutions were obtained from these soils by vacuum displacement and analyzed for pH, electrical conductivity (EC), and total concentrations of Ca, Mg, K, NO_3, SO_4, and Cl as described by Wolt and Graveel (1986). Data were analyzed by ANOVA as a randomized complete block design with four replications in order to evaluate simulated rain influence on soil solution composition.

Greenhouse Experiment

Mature clones of tall fescue and orchardgrass cultivars were divided by hand and single tillers were established in Cone-Tainer plastic containers (Ray Leach Nursery, Canby, Oregon) (4 cm x 22 cm; 167 cm^3) filled with Pro-Mix BX soil mixture (Premier Brands, Inc., New Rochelle, New York) in the greenhouse for twenty-one days and were clipped to a uniform 2.5 cm stubble height. Plants were then exposed to twice-weekly simulated rain treatments (0.76 cm per event) on a revolving table beneath a single stainless steel Fulljet ½HH30WSQ nozzle (Spraying Systems, Inc., Wheaton, Illinois) suspended 2 m above the plant canopy. Nutrients were supplied by weekly immersion of roots in modified one-half strength Hoagland's solution (Hoagland and Arnon 1950). Rainwater sampled at plant height was analyzed for pH, EC, and ionic composition.

The experimental design consisted of a randomized complete block imposed in a split-split plot arrangement of treatments with four replications. Main plot treatments were rainfall acidity level (ranging from pH 5.5 to 2.3). Split-plot treatments were two grass species (tall fescue and orchardgrass). Split-split-plot treatments were five grass cultivars (noncertified Kentucky 31, certified Kentucky 31, and Kenhy tall fescue and Hallmark and Potomac

Table 1-1. Germination and radicle and coleoptile length of bluegrass (B), tall fescue (F), orchardgrass (O), and timothy (T) germinated on filter paper, as a function of simulated acidity[†]

	Germination				Radicle				Coleoptile			
pH	B	F	O	T	B	F	O	T	B	F	O	T
	--------%--------				----------mm----------				---------mm---------			
					First Observation[♠]							
5.5	12	73	21	26	2.8	8.3	2.8	0.3	Measurements were not taken.			
4.0	14	72	20	23	2.6	7.3	2.1	0.2				
3.5	13	70	15	21	2.4	7.0	1.4	0.1				
3.0	20	69	13	17	1.5	6.5	1.0	0.1				
2.5	0	67	0	0	0.0	4.8	0.1	0.0				
2.0	0	0	0	0	0.0	0.0	0.0	0.0				
pH[§]	Q	Q	Q	Q	L	Q	L	Q				
pH x Cultivar[¶]	**	*	NS	**	**	**	NS	NS				
					Second Observation[#]							
5.5	34	92	65	51	11.0	30.8	16.5	2.6	6.6	22.9	9.1	2.6
4.0	31	91	66	50	9.7	27.7	14.8	2.2	5.0	21.7	7.7	2.3
3.5	30	91	56	45	9.2	27.8	14.0	1.7	5.3	21.4	8.5	2.5
3.0	20	88	52	37	9.2	25.7	11.9	1.0	6.3	20.3	6.8	1.6
2.5	0	88	20	1	0.0	17.6	0.3	0.0	0.0	19.4	2.3	0.0
2.0	0	0	0	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
pH	Q	Q	Q	Q	Q	Q	Q	Q	L	Q	Q	Q
pH x Cultivar	**	**	*	**	**	*	NS	NS	**	NS	NS	NS

[†]Arcsin transformed data (radians) used for statistical analysis.

[♠]Five days postseeding for bluegrass, and three days postseeding for other grasses. Coleoptiles were too small to measure in first observation.

[§]Effects of pH are not significant (NS) or polynomial regression is significant at the 5 (*) percent level and is linear (L) or quadratic(Q).

[¶]Effects are significant at the 1 (**) or 5 (*) percent level or are not significant (NS).

#Ten days postseeding for bluegrass, and six days postseeding for other grasses.

decreasing rain pH. The rain pH x cultivar effect was significant only for bluegrass.

To better clarify the occasional significant rain pH x cultivar effect, polynomial regressions for individual cultivars were performed for all parameters with significant interactions. Kenblue bluegrass demonstrated a linear decline in germination and radicle length (at first observation) and coleoptile length (at second observation) with decreased rain pH, while the response of common bluegrass was quadratic. Clair timothy had a linear decline in germination (at first observation) with decreased rain pH, while the response of Climax timothy was quadratic. For other cultivars within species, the effect of rain pH was always quadratic (data not presented). Delayed germination was apparent when the results of the first and second observation were compared at pH 2.5 vs. pH greater than 2.5 (Table 1-1). For example, at first observation, no germination of timothy and orchardgrass was found at pH 2.5, but at pH greater than 2.5 germination was evident. Three days later (second observation), germination of these two grasses was observed at pH 2.5, indicating that increased acidity of rain water delayed germination. Delayed germination and suppressed root growth of the grasses with increasing acidity is perhaps indicative of relative species sensitivity to acid rain. From the results using filter paper, the tolerance to decreased rain pH was greatest in fescue, then orchardgrass, then timothy, and least in bluegrass.

Germination on Soil. On the Statler sandy loam, there was no effect of simulated rain acidity on germination with the exception of a decline in the percent germination of timothy with increased acidity at first observation (Table 1-2). Simulated rain did not affect coleoptile growth, but it

On the Etowah silt loam, there was a linear trend of decreasing germination of orchardgrass, timothy (at first observation), and bluegrass (at second observation) with increasing acidity of simulated rain. No effect of simulated rain acidity was found on germination of tall fescue and on coleoptile growth of all grass species (Tables 1-2 and 1-3). Treatments significantly influenced root growth of all grasses in Etowah soil. Root growth was linearly decreased in bluegrass, tall fescue, and timothy and quadratically decreased in orchardgrass with decreasing simulated rain pH (Table 1-3).

In soil, generally there was no pronounced influence of acidity on germination and coleptile growth of the grasses. Root growth, however, was significantly depressed by increasing acidity of simulated rain in soil media. In contrast to the results obtained on filter paper, there was seldom a significant interaction between rain pH and cultivar on germination or radicle and coleoptile growth from seed germinated on soil media.

The grasses responded differently at different simulated rain pH in these germination tests on filter paper and soil media. The pronounced reduction of root growth and germination at specific thresholds of rain pH for each grass species suggests that root length and germination may be useful parameters for predicting sensitivity (e.g., biological responsiveness) of these grasses to acid rain.

Displaced solutions from both soils (Table 1-4) demonstrated linear or quadratic increases in Ca, Mg, and SO, with increased simulated rain acidity. These shifts in soil solution composition, however, may not be indicative of rain-induced alterations of the soil environment, which could explain the observed reduction in root elongation. A two-week delay between the measurement of root length and displacement of soil solutions may have obscured transient shifts in soil solution composition, which could influence radicle development. Drying of soils during the six- and ten-day term of the experiment may have increased soluble salts in solution sufficiently to inhibit radicle elongation. The varied electrical conductance (EC) of the Etowah soil versus the Statler soil did not influence germination or root elongation, however, so some mechanism other than simple salt toxicity was operative in this study.

The observed inhibition of root growth and delayed germination may be a transitory effect. Direct seeding of orchardgrass in a field environment did not show any significant effect of simulated rain pH on maximum seedling numbers, but simulated rain pH did influence seedling viability over time (Haun et al. 1988).

Greenhouse **Experiment**

Both tall fescue and orchardgrass demonstrated similar quadratic trends of increased foliar injury with decreased rain pH (Table 1-5). For fescue, the rain pH x cultivar interaction was significant, but all three fescue cultivars had similar quadratic responses (data not presented).

Increased acidity had no effect on relative yields in tall fescue (Table 1-5). Relative yields of orchardgrass, however, were increased quadratically with increased acidity of simulated rain. Lee et al. (1981) also found no influence of acid rain on yield of Alta tall fescue; whereas, potomac orchardgrass had a higher yield with pH 3.0 rain than with control rain (pH 5.6). In contrast, Cohen et al. (1982) reported that dry matter yield of Potomac orchardgrass was not significantly affected by acid rain; however, early stimulatory but transitory effects of acid rain on yield of Alta fescue were recognized. The yield increase of orchardgrass in this study may be due to the beneficial effect of N from acid rain. Others have reported that the

Table 1-6. Mean N and S concentrations of tall fescue and orchardgrass grown in the greenhouse, as a function of simulated rain pH (sampled from block 1)

Rain pH	Tall fescue Harvest 2 N	Tall fescue Harvest 2 S	Orchardgrass Harvest 2 N Potomac	Orchardgrass Harvest 2 N Hallmark	Orchardgrass Harvest 1 S Hallmark
	g kg^{-1}				
5.5	36	3.0	44	42	4.0
3.4	42	3.0	41	46	3.6
2.8	44	3.8	57	47	4.0
2.3	42	4.7	50	48	3.6
pH†	L	NS	NS	NS	NS
pH x Cultivar♣	NS	NS	*		NS

†Effects of pH are not significant (NS) or polynomial regression is significant at the 5 percent level and is linear (L).
♣Effects are significant at the 5(*) percent level or are not significant (NS).

applied N to influence yield under the conditions of this experiment.

Samples from block 1 (Table 1-6) indicated that N concentration of tall fescue increased ($P < .01$) linearly with increasing acidity of simulated rain. For orchardgrass, the rain pH x cultivar interaction was significant, so the main effect of pH on orchardgrass species was not interpreted. Both Potomac and Hallmark orchardgrass had a trend of increased N concentration as acidity of simulated rain increased, but this trend was not significant.

There was no difference in S concentration of either fescue or orchardgrass due to acid rain treatments, even though SO_4 level also increased as pH decreased. Studies from Oregon have shown acid rain did not affect S concentrations of Alta tall fescue (Cohen et al. 1981, 1982; Plocher et al. 1985).

Samples from block 2 (Table 1-7) did not differ in N, P, K, Ca, and Mg concentrations of either tall fescue or orchardgrass in harvest 1, but, in harvest 2, N and K concentrations of tall fescue were quadratically increased, while Ca and P concentrations of orchardgrass were linearly decreased with increasing acidity of simulated rain. There was no influence of acid rain on Mg concentrations of the grasses in either harvest. During the first year of their studies, Cohen et al. (1981) found no significant effect on mineral concentrations of Alta tall fescue. In the second year, there were also no differences in mineral concentrations at harvest 1, though Ca and P concentrations in Alta fescue tissues at harvest 2 were decreased with increased rain acidity. This suggests that grasses may require long-term exposure before acid rain has a significant effect on forage quality.

SUMMARY

Germination Tests

Inhibition of radicle elongation (on soil and filter paper media) and delayed seed germination (on filter paper) of cool-season forage grasses with increasing rain acidity was greatest in fescue, then orchardgrass, then timothy, and least in bluegrass. Effects on radicle growth and germination rate, however, were not translatable into an ultimate effect on germination percentage or yield.

Greenhouse Experiment

Visible injury of both tall fescue and orchardgrass quadratically increased with increased rain acidity. Decreased rain pH did not affect tall fescue yields but quadratically increased orchardgrass yields. The effect of

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RESULTS AND DISCUSSION

Figure 2-1 (a-e) shows the relationship between acidity and droplet size over time as the volume of drops was reduced by evaporation and/or absorption from the original volume of 50 µL. The change in raindrop pH as the volume changed was essentially identical for simulated acid raindrops placed on orchardgrass and tall fescue leaves ('compare Figure lb with Figure 1d and Figure lc with Figure le).

Simulated rain (pH 3.0) caused foliar necrotic spots on orchardgrass when the initial drop volume was 40 µL (4 mm diameter drops) but not with smaller drop volumes (Table 2-1). Apparently, the ions became more concentrated as the solution dried from the larger drops and caused damage. Fescue was unaffected by pH 3.0 simulated rain at all volumes used. With pH 2.5 simulated rain, a minimum drop volume of 15 µL (2.3 mm diameter) was necessary for necrotic spots to form on fescue. Initial drop volumes of 7 µL (1.8 mm diameter) placed on orchardgrass leaves produced necrotic spots 33 percent of the time with pH 2.5 simulated rain. The threshold H dose for foliar lesion development was greater than 40 picoequivalents for tall fescue as compared with greater than 20 picoequivalents for orchardgrass.

These data indicate differing sensitivities of mature tissue of orchardgrass and tall fescue to acid precipitation. The pH causing foliar damage, however, is substantially lower than would be encountered in the field. Additionally, the minimum drop volume producing damage at pH 3.0 (40 µL) is a relatively large drop size, based on observations of both natural (Laws and Parsons 1943) and simulated (Haun 1987) rain and would not be typically encountered in field situations. Haun (1987) used a ground-based precipitation probe to characterize simulated rainfall generated in our field

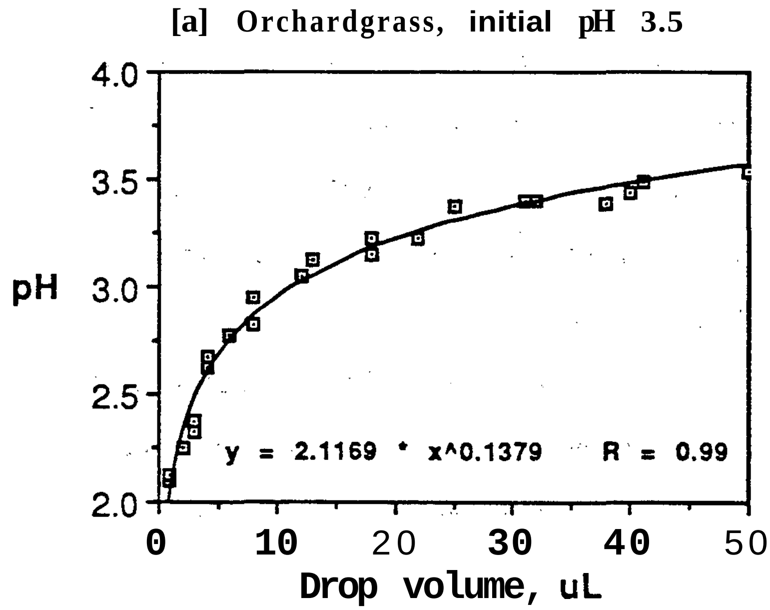

Figure 2-la. The relationship of pH to droplet volume for simulated raindrops (initial volume 50 µL, initial pH 3.5) placed on orchardgrass leaves monitored for 3.5 or 4 hours.

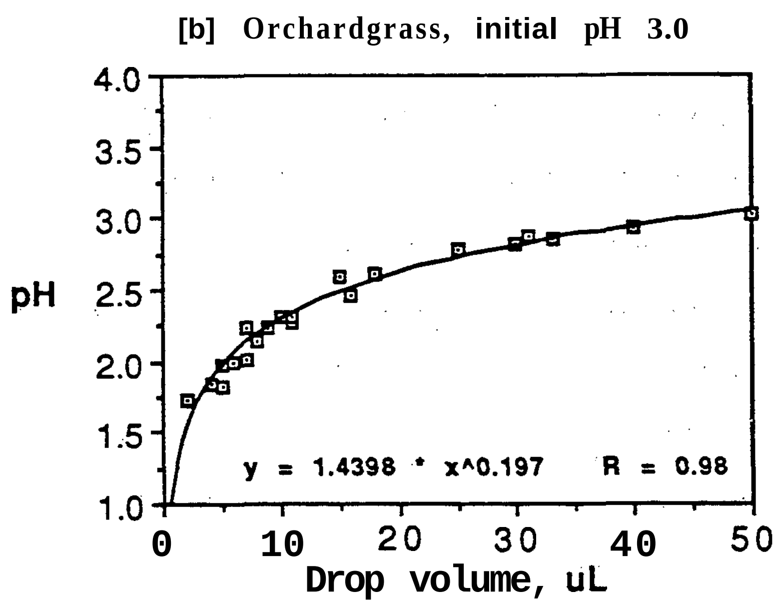

Figure **2-lb.** The relationship of pH to droplet volume for simulated raindrops (initial volume 50 µL, initial pH 3.0) placed on orchardgrass leaves and monitored for 3.5 or 4 hours.

Table 2-1. Effects of simulated acid rain (pH 3.0 and 2.5) droplet volume on foliar lesion development of Potomac orchardgrass and Kenhy tall fescue

Rain pH	Drop Volume	Acid Dose	Orchardgrass	Tall Fescue
	μL	Picoequivalents	Number of foliar lesions per 9 drops	
3.0	40	40	9	0
	30	30	0	0
	20	20	0	0
	15	15	0	0
	10	10	0	0
	7	7	0	0
2.5	15	47	9	9
	10	32	4	0
	7	22	3	0

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offer some buffering protection from acidic precipitation (McLaughlin et al. 1983). Establishment practices for small-seeded forages, however, may leave a large portion of the seeds on or near the soil surface within the upper 1.5 cm of the seedbed (Decker and Taylor 1985). Under such conditions the buffering effect of soil on acidic deposition may be lessened.

Haun et al. (1988) monitored viability of orchardgrass seedlings concurrently with simulated acid rainfall application (pH 4.3 to 2.5) and noted that pH 3.1 simulated rainfall tended to result in increased seedling viability in comparison with other rainfall pH. In addition, statistical procedures were used to ascertain whether the generalized response of orchardgrass seedlings to simulated acid rain could be effectively modeled with an asymptotic germination-mortality function.

MATERIALS AND METHODS

A field experiment was conducted in the fall of 1985 at the University of Tennessee Plant Science Field Laboratory, Knoxville, to investigate the response to simulated acid rain when orchardgrass was germinated on two unfertilized Ultisol surface soils. The experimental configuration was a randomized complete block design with a split plot arrangement of treatments. Main plot treatments had four simulated rain pH values (4.3, 3.7, 3.1, and 2.5) in four replications. The range of simulated rainfall selected had been identified as the region of maximum biological response in previous controlled environment studies. Split plot treatments were Etowah silt loam (fine-loamy, siliceous, thermic Typic Paleudults) and Statler variant sandy loam (fine-loamy, mixed, mesic Humic Hapludults) surface soils.

Soil properties, plot establishment, and simulated rainfall application have been previously summarized (Haun et al. 1988). Test plots received 8.7

cm of simulated acid rain in 19 one- to three-minute duration applications (0.23 cm min^{-1}) over the 29-day term of the experiment. Ambient rainfall was not excluded.

Potomac orchardgrass (95 percent germination) was surface-seeded on September 10 in all test plots at 2,150 seeds m^{-2} (200 seeds per subplot) and simulated rainfall applications were initiated. Simulated rainfall application was discontinued from days 22 through 27 after seeding due to heavy ambient rainfall.

Total number of seedlings was determined by counting throughout the term of the experiment. Seedlings were counted upon the emergence of either the radicle or the coleoptile from the seed covering or soil surface, whichever was observed first. Seedlings were first observed on the sixth day following seeding and daily counts were made through day 16. Thereafter counts were conducted every other day for the remainder of the 29-day term of the experiment. Since daily counts did not include seedlings that may have germinated and subsequently died, the counts are representative of seedling viability rather than germination per se.

Seedling germination and seedling mortality can both be modeled as sigmoidal functions with the mortality function lagging in time relative to the germination function (Figure 3-1a). A common mathematical expression of the sigmoidal function is the logistic growth curve which is expressed as:

$$y = \frac{a}{1 + br^{a}} \qquad [1]$$

If y_1 and y_2 represent two sigmoidal functions describing germination and mortality, respectively, their difference (Δy, the shaded portion in Figure 3-1a) represents seedling viability. A convenient model for seedling

Table 3-1. Best fit germination-mortality functions for relative seedling viability (predicted maximum seedling viability = 100) as a function of days from seeding.+

Rain pH	Replication	a	b	r_1	r_2	"R^2-like" statistic♣
4.3	1	-79.8	19.824	0.994	0.593	0.980
	2	-176.5	3.315	0.930	0.799	0.977
	3	-113.0	5.422	0.922	0.600	0.971
	4	-78.5	107.907	0.876	0.355	0.993
3.7	1	-70.6	62.824	0.900	0.388	0.989
	2	-1260.1	3.804	0.883	0.869	0.988
	3	-72.7	47.807	0.893	0.441	0.962
	4	-113.8	2.648	0.967	0.724	0.963
3.1	1	-114.9	8.541	0.968	0.437	0.983
	2	-110.6	8.228	0.999	0.517	0.990
	3	-237.2	6.671	0.914	0.817	0.962
	4	-114.4	11.833	0.956	0.606	0.987
2.5	1	-91.5	10.014	0.982	0.388	0.966
	2	-123.3	2.719	0.975	0.641	0.961
	3	-81.7	245.088	0.816	0.143	0.986
	4	-105.5	6.634	0.968	0.703	0.959

$$^{+}\hat{y} = \frac{a}{1 + br_1^{d}} - \frac{a}{1 + br_2^{d}},$$

where $\hat{y}$ = seedling viability; a, b, r_1, and r_2 are empirically fit; and d = days from seeding.

$$^{♣}\text{"}R^2\text{-like" statistic} = 1 - \left(\frac{\text{residual sum of squares}}{\text{corrected total sum of squares}}\right)$$

however, were good estimates for a given combination of replication and simulated rainfall pH. The "R^2-like" statistic (Table 3-1) was greater than 0.95 for all estimated functions. The goodness-of-fit between predicted and actual seedling viability is illustrated in Figure 3-2. When analyzed by MANOVA, seedling viability as predicted from these functions was significantly affected by simulated rainfall pH (P=0.08). The analysis of predicted

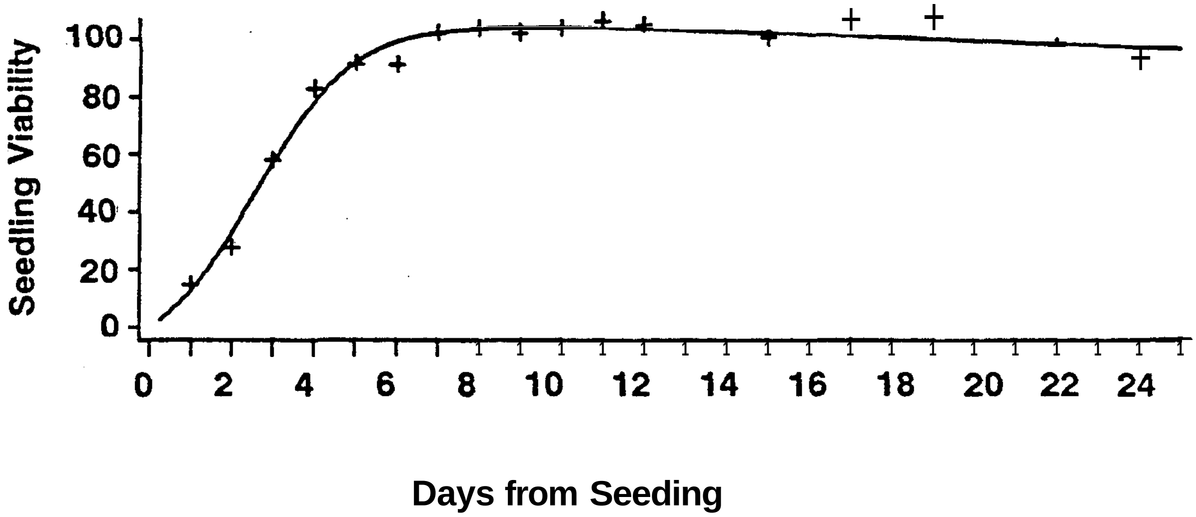

Figure 3-2. Comparison of seedling viability as a function of days from seeding for predicted (solid line) vs. actual (+) results. Data are for pH 3.1, replication 1

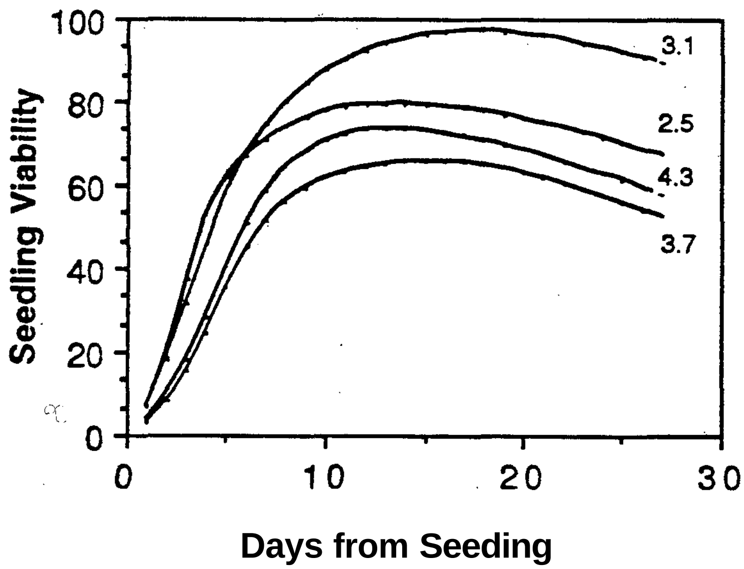

Figure 3-3. Germination-mortality functions describing seedling viability as a function of time as affected by simulated rainfall pH.

Part 4. Forage Yield and Quality of Orchardgrass and Tall Fescue Under Simulated Acid Precipitation

John H. Reynolds[1] and Jeff D. Wolt[2]

Cool-season forage grasses have received scant attention with regard to their sensitivity to acid precipitation, even though they are especially well-adapted to portions of the eastern United States that are of critical concern in relation to acid precipitation (Cowling 1983). Acid precipitation with pH less than 4.5 has been documented throughout much of the eastern United States (NADP 1987). Tall fescue is perhaps the most widely grown cool-season grass in the transition zone of the eastern United States, where it occupies from 12 to 14 million hectares (Buckner 1985). Orchardgrass is also widely grown in the eastern United States.

Soils typically cropped to perennial forage grasses in humid temperate regions manifest several characteristics that may predispose them to sensitivity to acidic deposition: acid reaction, cation exchange capacity less than 15 cmol(+) kg^{-1}, absence of natural carbonates, low buffer capacities, and low intensities of management (McFee 1983, Arthur and Wagner 1983).

The principal effects of acid precipitation on crop plants are induction of necrotic lesions, erosion of waxes, foliar leaching of nutrients, alteration of physiological and reproductive processes, and predisposition of plants to infection (Cowling 1982, Shriner 1980). Yields of agronomic crops may be either inhibited or stimulated by acid precipitation (Cohen et al. 1981, Cohen et al. 1982, Lee et al. 1982, Irving 1983, 1986). The

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hydrogen-ion effect of acid precipitation on vegetation is generally negative but may be masked by a counteractive beneficial effect of precipitation-borne sulfur and/or nitrogen (Shriner 1976). Noggle and Jones (1979) found tall fescue grown in S-depleted soils accumulated more than 30 percent of total vegetative S from atmospheric sources. The determination of crop sensitivity to acid precipitation is dependent on the conditions under which experiments are conducted (Jacobson et al. 1980), the crop parameters evaluated (Shriner 1980), and the particular dose-response function used in interpretation of results (Lee 1982). Most crop sensitivity studies utilize simulated acid precipitation, and factors such as duration and intensity of events (Shriner 1980), size distribution of simulated raindrops (Shriner et al. 1977), and rainwater composition (Cohen et al. 1982, Jacobson et al. 1980) will influence the results obtained.

Workers in Oregon (Cohen et al. 1981, Lee et al. 1981) studied the effects of simulated acid rain on tall fescue, orchardgrass, bluegrass, perennial ryegrass, and timothy in pots and in field chambers. Also in Oregon, Cohen et al. (1982) studied Alta tall fescue and Potomac orchardgrass, and Plocher et al. (1985) studied Alta tall fescue.

The foregoing experiments indicated relative insensitivity of tall fescue and orchardgrass to acid precipitation. However, because of the importance of these grasses to forage ecosystems of the eastern United States, a more comprehensive evaluation of their response to acid rain under conventional management in the humid temperate environment of the region is needed. The objective of this experiment was to show the relative sensitivities of orchardgrass and tall fescue cultivars in forage yield and quality to

Table 4-1. Weighted mean simulated rainfall composition from September 1984 through December 1986

Simulated Rainfall Treatment	pH	EC	NO_3	SO_4	NO_3:SO_4
	1984-85+				
		μmhos cm^{-1}	-- μmol L^{-1} --		mol ratio
4.3	4.10	33	33	35	0.94
3.7	3.60	81	76	79	0.96
3.1	3.10	289	255	273	0.93
2.5	2.60	1106	1012	1052	0.96
	1986♠				
4.3	4.22	20	12	16	0.75
3.7	3.61	63	49	65	0.75
3.1	3.09	248	203	227	0.89
2.5	2.63	900	886	896	0.99

+ Total Simulated rainfall applied in 1984-85, 414 mm; mean application, 4.1 ± 1.7 mm per event; other ions (μmol L^{-1}): Cl, 20; Ca, 12; Mg, 3.3; K, 3.8.

♠ Total simulated rainfall applied in 1986, 427 mm; mean application, 6.3 ± 1.1 mm per event; other ions (μmol L^{-1}): Cl, 28; Ca, 8; Mg, 1.9; K, 3.0.

maintained grasses in the vegetative state, analogous to frequent intensive grazing. Fertilization was restricted to NH_4NO_3 applied in March 1985 (34 kg N ha^{-1}), March and September 1986 (34 and 68 kg N ha^{-1}, respectively), and March 1987 (68 kg N ha^{-1}). A combination of chemical and mechanical weed control was used to maintain relatively pure forage grass stands throughout the duration of the experiment.

Seven harvests were made from April through November 1985, six harvests during 1986, and four harvests from April through July 1987. The 1987 yields

Table 4-2. Weighted mean ambient precipitation composition from September 1984 through December 1986

Year	Calendar Quarter+	pH	EC	NO_3	SO_4	Cl	Ca	Mg	K	$NO_3:SO_4$
			µmhos cm^{-1}	-------------		µmol L^{-1}	------------			mol ratio
84	4	4.46	26	31	36	17	22	4.0	5.1	0.87
85	1	4.27	22	32	14	14	15	4.1	2.0	1.12
85	2	4.06	33	28	39	13	14	2.0	2.4	0.73
85	3	4.04	69	22	31	9	4	0.7	0.6	0.70
85	4	4.27	26	12	20	7	3	0.9	1.1	0.60
84-85	Overall	4.19	37	25	31	12	11	2.2	2.7	0.81
86	1	4.06	36	27	33	19	8.8	1.5	20	0.82
86	2	4.05	37	42	39	8	7.3	1.6	3.4	1.08
86	3	4.05	23	26	29	11	9.3	1.7	1.8	0.90
86	4	4.21	18	17	21	12	3.0	1.0	5.0	0.81
86	Overall	4.10	26	25	28	13	6.7	1.5	8.0	0.89

+ Total ambient precipitation 1,261 mm in 1984-85 and 976 mm in 1986.

were used as an indication of residual effects of the treatments since no simulated rainfall was applied in 1987. Forage was harvested with a rotary mower to a 5-cm stubble height on each harvest date. Forage samples were dried at 65°C in a forced-air oven for determination of dry matter yield. Kentucky 31 tall fescue plots were contaminated with annual ryegrass, necessitating reseeding of these plots in spring 1985. Yields of this cultivar were therefore excluded for the first two harvest dates of 1985.

cultivars mainly reflected differences in maturity. Able is a later flowering orchardgrass cultivar than Hallmark or Potomac, so April yields of Able were smaller than the others. Forager is an earlier flowering fescue cultivar than Kenhy or Kentucky 31 so April 1986 yields were larger for this cultivar than for the others. Yields in the following cuts were sometimes reversed with Forager yielding less than Kenhy and Kentucky 31.

Analysis of plant responses to acid rainfall by each harvest date demonstrated little treatment effect due to the subtle nature of acid rain effects on plants and the relatively high variation in agronomic plot data (CV's frequently exceeded 20 percent). Repeated measures analysis (Sanders 1978) provides a more powerful statistical tool for evaluation of season-long effects of acid rainfall on forage responses. Yields were strongly affected by harvest date and by rainfall pH in the first and second years (Table 4-3). Rainfall of pH 3.1 tended to produce the lowest yield in both 1985 and 1986 as yields were modeled with cubic responses (Figure 4-1). The amounts of nutrients received from ambient and simulated precipitation are shown in Appendix Tables 7 and 8. It is not possible to determine during 1985 and 1986 whether the amount of N and S received from simulated rainfall treatment pH 2.5 was sufficient to counteract the acidity of that treatment. In the residual third year there were no effects of previous rainfall on yield although the yields appeared to decrease as the treatment pH was lower.

The principal effect of rainfall pH treatment on orchardgrass forage nutrients in 1985 was an increase in S as the pH was lowered (Table 4-4). Among the three cultivars, the later maturity of Able was reflected in higher P, Ca, and Mg in the first harvest (Table 4-5). On other harvest dates, no more than two elements had significant differences among cultivars.

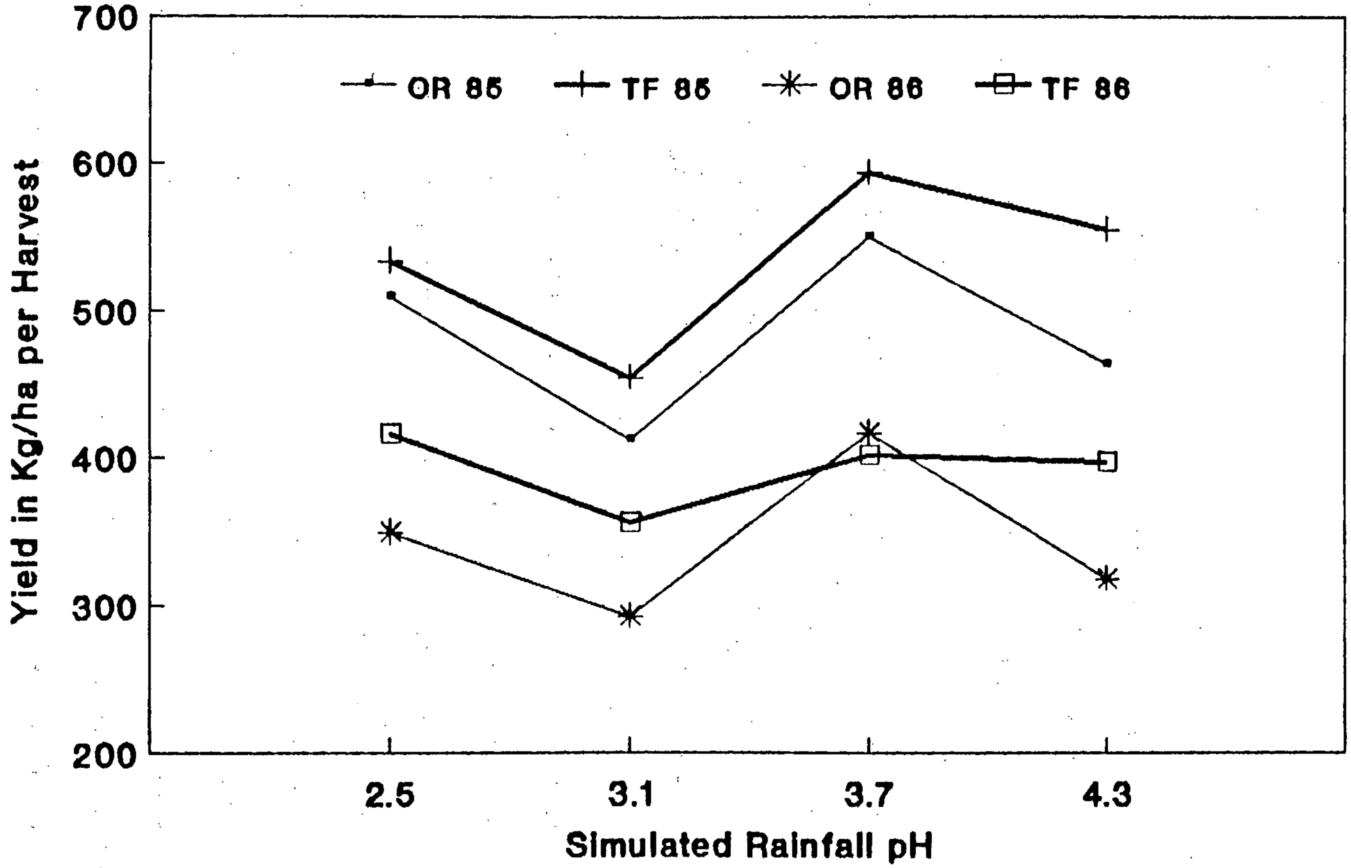

Figure 4-1. Dry matter yields of orchardgrass and tall fescue in 1985 and 1986 at four rainfall levels and averaged over all cultivars.

Table 4-5, Effect of cultivar on nutrient concentration of orchardgrass forage in 1985

Harvest Date	Cultivar[+]	N	S	P	K	Ca	Mg
		$g\ kg^{-1}$					
April 10	Able	26.3	2.50	2.66a	23.8	2.43a	2.68a
	Hallmark	24.1	2.42	2.51b	22.2	1.98b	2.16b
	Potomac	25.3	2.29	2.54b	23.5	2.18b	2.47a
Sig. of F test[4]		NS	NS	**	NS	**	**
April 23	Able	29.8	2.50	3.16	29.9ab	3.41a	3.58
	Hallmark	28.6	2.57	3.21	26.7b	3.30ab	3.27
	Potomac	28.1	2.59	3.30	32.6a	3.17b	3.45
Sig. of F test		NS	NS	NS	*	*	NS
May 15	Able	20.8a	2.71	2.69	24.0	2.88	3.30a
	Hallmark	18.3b	2.56	2.70	22.8	2.51	2.92b
	Potomac	19.2ab	2.66	2.77	23.0	2.62	3.14ab
Sig. of F test		*	NS	NS	NS	NS	**
June 11	Able	21.3	3.27	2.93	23.9	4.56	5.24
	Hallmark	20.5	3.08	2.87	22.8	4.55	5.20
	Potomac	20.6	3.05	3.01	22.9	4.34	5.32
Sig. of F test		NS	NS	NS	NS	NS	NS
July 10	Able	16.9	3.29	2.89	24.0a	3.45	5.41
	Hallmark	15.4	3.20	2.97	21.9ab	3.42	4.99
	Potomac	15.8	3.19	3.05	21.0b	3.34	5.56
Sig. of F test		NS	NS	NS	*	NS	NS
Aug. 15	Able	17.0	2.66	2.90	20.9	2.98	2.66b
	Hallmark	16.7	2.71	2.96	20.0	3.02	2.72ab
	Potomac	16.5	2.59	3.07	21.0	3.04	2.87a
Sig. of F test		NS	NS	NS	NS	NS	*
Nov. 12	Able	17.6	2.84	3.09	22.2	3.41	2.35
	Hallmark	18.0	2.98	3.07	22.4	3.33	2.42
	Potomac	18.0	2.71	3.02	23.4	3.42	2.57
Sig. of F test		NS	NS	NS	NS	NS	NS

[+] Data averaged over rainfall pHs (4.3, 3.7, 3.1, 2.5). Rainfall pH x cultivar interactions were not significant at the 5 percent level, except for Mg on April 23 and P on May 15.

[4] The effect of cultivar is not significant (NS) or is significant at the 1 (**) or 5 (*) percent level. Where significant, mean separation is by Waller-Duncan t test, k-ratio = 100.

In 1986, S was increased in orchardgrass forage on half the harvest dates as rainfall pH decreased (Table 4-6). As noted above in Appendix Tables 7 and 8, there was more S received from the lower pH treatments. There was only one date with a significant effect of rainfall pH on other elements (on Mg in the first harvest). In tall fescue, there was only a significant effect on S and Ca in the third harvest and P in the sixth (Table 4-7). The only orchardgrass cultivar effects in 1986 were higher N in the first harvest for Able and higher S and Ca in the second and third harvests, respectively, for Hallmark (Table 4-8).

More cultivar effects were observed for fescue than for orchardgrass in 1986. In the first harvest, Forager was generally lower in nutrients than the other cultivars while the reverse occurred in the seconh harvest (Table 4-9). Forage K and Ca differed by cultivars in four harvests, while S was different in three harvests and N, P, and Mg were different in two harvests. Significant interactions of rainfall pH x cultivar occurred very infrequently.

The seasonal trends of nutrients in the different harvests of orchardgrass and fescue had two main patterns in 1986 but were less distinct in 1985 when there was no September N application (Tables 4-10, 4-11, 4-12). The S, P, Ca, and Mg concentrations increased from spring to summer, while N and K decreased from spring through summer and then increased after the September N application.

Repeated measures analysis indicated a very strong influence of harvest date on nutrient concentrations (Tables 4-10, 4-11, 4-12) and a lesser effect of rainfall pH and cultivar in the second year. In general, orchardgrass P and Ca concentrations tended to be highest and N lowest for pH 3.1 simulated rainfall in 1985, and, in 1986, P tended to be highest and N lowest for pH

Table 4-8. Effect of cultivar on nutrient concentrations in orchardgrass forage at different harvest dates in 1986

Harvest Date	Cultivar[+]	N	S	P	K	Ca	Mg
		---------------------- g kg^{-1}	------------------				
April 22	Able	24.6a	2.87	2.87	25.6	3.12	2.14
	Hallmark	21.8b	2.80	2.86	24.5	3.18	2.11
	Potomac	22.5b	2.79	2.78	24.1	2.74	2.08
	Sig. of F test[♠]	**	NS	NS	NS	NS	NS
May 27	Able	14.8	3.22 b	3.86	23.2	4.40	3.25
	Hallmark	14.9	3.44 a	3.96	21.0	4.34	3.16
	Potomac	15.0	3.00 b	3.67	22.1	4.28	3.14
	Sig. of F test	NS	**	NS	NS	NS	NS
July 8	Able	15.1	3.32	4.65	20.2	4.46b	3.83
	Hallmark	15.0	3.39	5.08	19.1	4.88a	3.95
	Potomac	14.7	3.21	4.60	19.3	4.64b	3.93
	Sig. of F test	NS	NS	NS	NS	**	NS
Sept. 24	Able	42.4	2.54	3.27	26.0	4.74	4.04
	Hallmark	41.5	2.61	3.29	24.5	4.74	3.76
	Potomac	43.8	2.55	3.30	25.3	4.86	4.17
	Sig. of F test	NS	NS	NS	NS	NS	NS
Oct. 22	Able	22.0	2.77	2.70	15.7	5.30	3.58
	Hallmark	23.1	2.95	2.67	16.3	5.36	3.72
	Potomac	24.0	2.87	2.92	14.4	5.16	3.78
	Sig. of F test	NS	NS	NS	NS	NS	NS
Nov. 21	Able	27.3	3.16	2.93	22.7	3.92	2.88
	Hallmark	28.4	3.24	3.16	22.7	3.86	2.86
	Potomac	25.5	3.17	3.21	22.0	3.84	3.01
	Sig. of F test	NS	NS	NS	NS	NS	NS

[+] Data averaged over rainfall pHs (4.3, 3.7, 3.1, 2.5). The rainfall pH x cultivar interactions were not significant at the 5 percent level except for S on May 27, P on Sept. 24, and P, K, and Mg on Nov.21.

[♠] The effect of cultivar is not significant (NS) or is significant at the 1 percent (**) level; mean separation by Waller-Duncan t test, k-ratio = 100.

Table 4-9. Effect of cultivar on nutrient concentrations in tall fescue forage at different harvest dates in 1986

Harvest Date	Cultivar[+]	N	S	P	K	Ca	Mg
		g kg^{-1}					
April 22	Forager	19.1b	2.27b	2.87	20.0b	2.46b	2.03b
	Kenhy	21.1a	2.80a	2.76	23.4a	2.54ab	2.19ab
	Kentucky 31	20.9a	2.66a	2.76	23.8a	2.92a	2.26a
	Sig. of F test[4]	*	**	NS	*	*	*
May 27	Forager	15.3	2.85a	3.59a	18.5b	4.28a	3.26a
	Kenhy	14.1	2.70a	3.04b	21.7a	3.82ab	3.00ab
	Kentucky 31	14.2	2.46b	2.97b	20.2ab	3.56b	2.73b
	Sig. of F test	NS	**	*	*	*	*
July 8	Forager	15.0	3.19b	4.32	17.6b	5.16a	4.12
	Kenhy	14.1	3.47a	4.58	20.1a	4.74b	4.14
	Kentucky 31	14.0	3.24ab	4.25	18.0b	5.04ab	4.10
	Sig. of F test	NS	*	NS	*	*	NS
Sept. 24	Forager	41.2	2.66	3.16	24.3b	4.52	3.73
	Kenhy	41.1	2.68	3.09	25.1b	4.56	3.92
	Kentucky 31	40.4	2.82	3.37	29.1a	4.68	4.14
	Sig. of F test	NS	NS	NS	*	NS	NS
Oct. 22	Forager	20.6	2.69	2.89a	15.0	4.98	3.57
	Kenhy	19.1	2.78	2.68b	14.7	4.86	3.42
	Kentucky 31	18.8	2.66	2.97a	16.6	4.64	3.55
	Sig. of F test	NS	NS	*	NS	NS	NS
Nov. 21	Forager	23.5ab	2.97	3.00	22.2	3.42a	3.06
	Kenhy	24.0a	2.98	3.12	23.3	3.10b	2.84
	Kentucky 31	21.5b	2.85	3.12	21.8	3.06b	2.98
	Sig. of F test	*	NS	NS	NS	*	NS

+ Data averaged over rainfall pHs (4.3, 3.7, 3.1, 2.5). The rainfall pH x cultivar interactions were not significant at the 5 percent level except' for Ca on Oct. 22 and Mg on Nov. 21.

◆ The effect of cultivar is not significant (NS) or is significant at the 5 percent (*) or 1 percent (**) level; mean separation by Waller-Duncan t test, k-ratio = 100.

Table 4-12. Repeated measures analysis of nutrient concentrations in fescue cultivars at different harvest dates and simulated rainfall pH in 1986

Harvest Date	N	S	P	K	Ca	Mg
	---------------------------g kg^{-1}---------------------------					
April 22	20.4 c[+]	2.57 d	2.80 d	22.4 b	1.33 e	2.16 d
May 27	14.6 d	2.67 cd	3.20 b	20.2 c	1.95 c	3.00 c
July 8	14.4 d	3.30 a	4.39 a	18.6 d	2.50 a	4.13 a
Sept. 24	40.9 a	2.72 c	3.21 b	26.2 a	2.30 b	3.93 a
Oct. 22	19.6 c	2.71 c	2.86 cd	15.5 e	2.41 ab	3.52 b
Nov. 21	23.0 b	2.93 b	3.08 bc	22.4 b	1.60 d	2.97 c
<u>Rainfall pH</u>						
4.3	22.6	2.72	3.38	21.6	1.96	3.15
3.7	22.3	2.74	3.17	22.4	1.89	3.28
3.1	21.4	2.71	3.13	19.0	2.16	3.46
2.5	22.3	3.04	3.36	20.9	2.02	3.24
	NS[♠]	Q**	Q**	C**	C*	NS
<u>Cultivar</u>						
Forager	22.5	2.76 b	3.32	19.7 b	2.07	3.30
Kenhy	22.2	2.90 a	3.22	21.6 a	1.96	3.24
Kentucky 31	21.7	2.78 ab	3.24	21.6 a	2.00	3.30
	NS		NS		NS	NS

[+] Mean separation by Waller-Duncan t test, k-ratio = 100.

[♠] Polynomial regression is not significant (NS) or is significant at the 1 percent (**) or 5(*) percent level and is quadratic (Q) or cubic (C).

least brown tissue on the August date. There was no visible injury to the grass foliage from simulated rainfall in the second year.

Soil pH declined slightly during the experiment (Table 4-16) as did the P, Ca, and Mg soil test values. The K values declined more markedly during the experiment.

Since the total rainfall (ambient plus simulated) was above normal in

Table 4-13. Greenness estimate and Munsell color value and chroma for forage exposed to simulated acid rain from two harvest dates in 1985

Effect	Greenness Score+ Fescue	Greenness Score+ Orchardgrass	Munsell Color♠ Value Fescue	Munsell Color♠ Value Orchardgrass	Munsell Color♠ Chroma Fescue	Munsell Color♠ Chroma Orchardgrass
June 11						
Rainfall pH						
4.3	1.92	1.83	4.00	4.83	4.33	5.33
3.7	2.17	2.17	4.33	5.17	4.67	5.33
3.1	2.00	1.50	4.00	4.33	4.33	4.67
2.5	2.17	1.67	4.17	4.67	4.33	5.67
Sig. of F test"	NS	NS	NS	NS	NS	NS
Cultivar						
Forager	1.50 b[s]	Able 2.00	Forager 4.00 b	Able 4.44	Forager 4.00	Able 5.75
Kenhy	2.00 b	Hall. 1.75	Kenhy 4.50 a	Hall. 4.88	Kenhy 5.25	Hall. 5.50
Ky 31	2.69 a	Potomac 1.63	Ky 31 3.88 b	Potomac 4.50	Ky 31 4.00	Potomac 4.50
Sig. of F test	**	NS	*	NS	NS	NS
July 10						
Rainfall pH						
4.3	1.92	1.75	5.83	6.83 a	6.50	4.50 b
3.7	2.17	1.96	5.83	6.67 ab	7.17	5.33 a
3.1	2.00	1.71	6.00	6.50 b	6.83	4.50 b
2.5	1.91	1.58	5.91	6.42 b	6.73	5.00 ab
Sig. of F test	NS	NS	NS	*	NS	*
Cultivar						
Forager	1.78 b	Able 1.63	Forager 5.94 b	Able 6.69	Forager 6.13 b	Able 5.63 a
Kenhy	1.44 c	Hall. 2.00	Kenhy 6.38 c	Hall. 6.50	Kenhy 7.38 a	Hall. 4.38 b
Ky 31	2.83 a	Potomac 1.63	Ky 31 5.33 c	Potomac 6.63	Ky 31 6.93 a	Potomac 4.50 b
Sig. of F test	**	NS	**	NS	**	**

+ Greenness of tissue, 1=light green, 3=dark green.

♠ Hue in 5.0 GY, lighter as value increases, more yellow as chroma increases.

Effects are not significant (NS) or are significant at the 1 (**) percent or 5 (*) percent level.

Mean separation by Waller-Duncan t test, k-ratio = 100.

occurrence of acid rain events in nature, where variation in rainfall chemistry can be highly variable in time. The added nutrients and water may have offset detrimental effects of H, and the soil may have buffered this effect. Since the amount of N supplied in the pH 2.5 treatment is much larger than that supplied in ambient precipitation or other pH treatments (Appendix Tables 7, 8, 9), this N may have offset the effects of H from this treatment. This relatively short, two-year period of exposure with species that are comprised of heterozygous cultivars may not have been sufficient to cause serious visible or measurable yield losses in perennial grasses. The occurrence of measurable differences in forage nutrients, however, may

Table 4-16. Effect of simulated rainfall pH on soil test values at 0-7.5 cm depth on three sampling dates

Rainfall pH	Soil pH	P	K	Ca	Mg
		------ $g\ kg^{-1}$ ------			
		October 30, 1985			
4.3	6.0	14	53	983	183
3.7	6.0	13	84	1013	187
3.1	6.2	15	65	788	190
2.5	6.0	15	61	1076	166
		September 9, 1986			
4.3	5.9	15	27	726	148
3.7	5.9	14	40	688	152
3.1	6.0	15	17	788	138
2.5	5.8	15	19	784	132
1987					
4.3	5.9	12	20	807	133
3.7	5.8	11	46	718	148
3.1	5.8	13	20	825	127
2.5	5.6	13	20	760	106

indicate potential effects on quality with prolonged exposure to acid rain.

Although there is no clear cut effect of rainfall pH on plant response, the data strongly indicate a differential effect of pH 3.1 on overall plant responses. The pieces of such evidence are as follows, although not all are significant differences: (1) From repeated measures analysis of forage nutrients, orchardgrass at pH 3.1 had highest P and Ca and lowest N in 1985 and highest P and lowest N in 1986; fescue at pH 3.1 had highest Ca and Mg and lowest N, P, and K in 1986; and (2) from repeated measures analysis, yields were lowest at pH 3.1 in both 1985 and 1986. Also, these responses agree with the conclusion of field germination studies where pH 3.1 differed from other simulated rainfall pH treatments (Haun et al. 1988).

SUMMARY

Three cultivars each of orchardgrass and tall fescue were subjected to four pH levels (4.3, 3.7, 3.1, 2.5) of simulated acid precipitation for two growing seasons. Ambient precipitation was not excluded. Total precipitation during these two calendar years averaged 976 mm of ambient plus 402 mm of simulated precipitation per year. Mole ratios of nitrate to sulfate were similar in simulated and ambient rainfall. Forage yields were not affected by rainfall pH on individual harvest dates. Cultivar differences in yield mainly reflected differences in maturity. Forage was analyzed for the following elements: N, S, P, K, Ca, and Mg. The principal effect of rainfall pH on forage nutrients for any one harvest date was an increase in S concentration as the pH was lowered. Orchardgrass forage was affected in more harvests than tall fescue. On thirteen harvest dates over two years, only one other element on one date in orchardgrass and two others on two dates in tall

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Table 3. Dry matter yield of orchardgrass in 1986 as affected **by** simulated rainfall pH and cultivar

	April 22	May 27	July 8	Sept. 24	Oct. 22	Nov. 21	Total
	kg ha^{-1}						
Simulated Rainfall pH							
4.3	300	210	280	460	580	130	1,960
3.7	460	270	360	460	690	170	2,410
3.1	290	240	240	630	590	120	2,110
2.5	350	270	290	480	680	150	2,220
	NS	NS	NS	NS	NS	NS	NS
Cultivar							
Able	300 b†	250	310	480	690	150	2,180
Hallmark	370 a	240	290	520	640	140	2,200
Potomac	370 a	250	280	510	600	140	2,150
		NS	NS	NS	NS	NS	NS

%ere ANOVA is significant at the 5 percent level, mean separation is **by** Waller-Duncan t test, k-ratio=100. Rainfall pH x cultivar interactions were not significant at the 5 percent level.

Table 4. Dry matter yield of tall fescue in 1986 as affected by simulated rainfall pH and cultivar

	April 22	May 27	July 8	Sept. 24	Oct. 22	Nov. 21	Total
	-----------------------------			kg ha^{-1}			-----------------------------
Simulated Rainfall pH							
4.3	520	280	240	490	680	210	2,420
3.7	470	280	240	550	710	210	2,460
3.1	490	270	230	390	620	180	2,180
2.5	490	270	270	570	800	220	2,620
	NS	NS	NS	NS	NS	NS	NS
Cultivar							
Forager	640 a[+]	230 c	240	530	690	190	2,520 a
Kenhy	420 b	280 b	260	470	690	210	2,330 ab
Kentucky 31	420 b	320 a	240	500	730	210	2,420 b
			NS	NS	NS	NS	

[+]Where ANOVA is significant at the 5 percent level, mean separation is by Waller-Duncan t test, k-ratio=100. Rainfall pH x cultivar interactions were not significant at the 5 percent level except on May 27.

Table 7. **Wet deposition of elements in ambient precipitation from September 1984 through December 1986**

Year	Calendar Quarter	Precipitation	H	NO_3-N	SO_4-S	Cl	Ca	Mg	K
		mm			kg ha^{-1}				
84	4	288	0.100	1.25	3.32	1.74	2.53	0.28	0.57
85	1	232	0.125	1.04	1.04	1.15	1.39	0.23	0.18
85	2	189	0.165	0.74	2.36	0.87	1.05	0.09	0.18
85	3	272	0.248	0.84	2.70	0.87	0.44	0.05	0.06
85	4	280	0.150	0.47	1.80	0.70	0.37	0.06	0.12
84-85	**Overall**	**1261**	0.788	4.34	**11.22**	5.33	5.78	0.71	**1.11**
86	1	205	0.179	0.78	2.17	1.38	0.74	0.08	1.60
86	2	160	0.143	0.94	2.00	0.45	0.45	0.06	0.21
86	3	274	0.143	1.00	2.55	1.07	0.99	0.11	0.19
86	4	337	0.208	0.80	2.27	1.43	0.40	0.08	0.66
86	**Overall**	**976**	0.673	3.52	**8.99**	4.33	2.58	0.33	0.68

Table 8. Deposition of elements in simulated rainfall from September 1984 through December 1986

Simulated Rainfall Treatment	H	NO_3-N	SO_4-S
	1984-85+		
	---- kg ha^{-1} ----		
4.3	0.3	1.9	4.7
3.7	1.0	4.4	10.5
3.1	3.3	14.8	36.2
2.5	10.4	58.7	139.6
	1986♦		
4.3	0.3	0.7	2.2
3.7	1.0	2.9	8.9
3.1	3.4	12.1	31.1
2.5	9.7	53.0	122.7

+Total simulated rainfall applied in 1984-85, 414 mm, mean application, 4.1 ± 1.7 mm per event; other ions (kg ha^{-1}): Cl, 2.9; Ca, 2.0; Mg, 0.3; K, 0.6.

♦Total simulated rainfall applied in 1986, 427 mm; mean application, 6.3 ± 1.67 mm per event; other ions (kg ha^{-1}): Cl, 4.2; Ca, 1.4; Mg, 0.2; K, 0.5.

Table 9. Ambient dry deposition of elements from April 1986 through March 1987

Year	Calendar Quarter	H	NO_3-N	SO_4-S	Cl	Ca	Mg	K
		---- kg ha^{-1} ----						
86	2	0.001	0.36	0.48	0.42	0.90	0.09	0.41
86	3	0.018	0.26	0.47	0.40	0.80	0.07	0.27
86	4	0.003	0.37	0.90	0.75	0.67	0.08	0.30
87	1	0.006	0.44	0.78	0.64	0.81	0.09	0.31