ACID RAIN: THRESHOLD OF LEAF DAMAGE IN EIGHT PLANT SPECIES FROM A SOUTHERN APPALACHIAN FOREST SUCCESSION

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(Received 17 March 1980; Revised 16 May 1980)

Abstract. Eight plant species were subjected to artifical acid rains of pH 2.5, 2.0, 1.5, 1.0 and 0.5 in order to determine the threshold for and symptoms of damage. The plants were *Erechtites, Robinia, Pinus, Quercus, Carya, Liriodendron, Acer* and *Cornus* from the Coweeta Hydrologic Laboratory near Franklin, North Carolina. Droplets of pH 2.0 produced brown necrotic spots on all species except *Pinus* while droplets of pH 1.0 produced necroses on leaves of all species examined. The size of necrotic spots increased with increasing acidity. Comparison of these results with the literature suggests that developing leaves are more easily damaged than are the mature leaves used in this study. The volume weighted average rainfall pH for Coweeta is 4.6 with observations ranging from 3.2 to 5.9. Results of this study suggest that a 10-fold increase in acidity from pH 3.2 to 2.2 in a single spring or summer storm could bring damage or death to mature leaves of dominant flowering plants in the Southern Appalachians.

1. Introduction

Acid rain is a growing concern of environmental scientists in Northern Europe (Brosset, 1973; Barret and Brodin, 1955), in the northeastern U.S. (Likens, 1976), in the southeastern U.S. (Haines, 1979) and in the western U.S. (Lewis and Grant, 1980) where it is suggested to result from the scavenging of oxides of N and S from the atmosphere by rain. These oxides are thought to be derived from the burning of fossil fuels (MacCracken, 1978; Likens, 1976). Hydrogen ions in acid rain are potentially disruptive of mineral element cycling because of their ability to displace mineral elements out of plant leaves (Kratky *et al.*, 1974; Wood and Bormann, 1974, 1975; Fairfax and Lepp, 1975) and out of soils (Wiklander, 1973-74) and to inhibit element uptake by plant roots (Black, 1968). Continued plant productivity on farms and in forests in part depends on stability of mineral element cycling. Simulated acid rain is also reported to disrupt photosynthesis in *Phaseolus* (Ferenbaugh, 1976) to disrupt reproduction in *Lycopersicon* (Kratky *et al.*, 1974) and to damage leaves in mosses, in *Pinus*, and in a variety of flowering plants (Sheridan and Rosenstreter, 1973; Wood and Bormann, 1974, 1975, 1977; Evans *et al.*, 1977; Evans and Curry, 1979).

During an earlier study of rates of element leaching from the leaves of herbs and tree seedlings subjected to artificial acid rains of pH 2.5, 3.5, 4.5, and 5.5, symptoms of acid rain damage were lacking (Haines and Chapman, unpublished). In order to

Water, Air, and Soil Pollution **14** (1980) 403–407. 0049–6979/80/0144–0403$00.75.

characterize symptoms of and to determine the threshold of acid rain damage for these plants, they were subjected to stronger artificial acid rain having pH values of 0.5, 1.0, 1.5, 2.0 and 2.5.

2. Materials and Methods

The plant species studied comprise a quasi-successional sequence in southern Appalachian deciduous forests. Plant and soil materials were obtained from logged and undisturbed forest watersheds at the Coweeta Hydrologic Laboratory near Franklin, North Carolina where University of Georgia and U.S. Forest Service personnel are studying the effects of disturbance on mineral element cycling. Species names are given in Table I. Most tree seedlings were dug up at Coweeta during the winter of 1976 and transplanted into 4 l plastic pots which had been filled with soil from the field site. Plants were maintained in a greenhouse in Athens, Georgia where they were watered with distilled water. During the winter of 1978 roots and shoots were trimmed back and the seedlings were replanted in fresh soil from the field site. Seedlings of the weed, *Erechtites heiracifolia* in the Compositeae, were from a waste site in Athens, Georgia. Seedlings of *Carya illinoensis* were obtained from commercial seed sources to use as a serrogate of *Carya glabra* which had insufficient numbers of seedlings at Coweeta.

The acid rain solutions consisted of deionized water plus a salt and an acid component. The salt portion simulated average element content of rainfall at Coweeta

TABLE I

Diameters, mean ± SD in mm, of necrotic spots on leaves subjected to five levels of rain acidity

Plant species and life form	pH of droplets applied				
	0.5	1.0	1.5	2.0	2.5
Erechtites hieracifolia (L) Raf. Herbaceous weed ($n = 6$)	10.5 ± 1.3	7.3 ± 1.5	4.2 ± 0.75	3.2 ± 4.0	0 ± 0
Pinus strobus L. Tree ($n = 8$)	*	*	*	*	*
Robinia pseudo-acacia L. Shrub to tree ($n = 6$)	8.5 ± 1.0	5.75 ± 2.6	5.2 ± 0.5	2.0 ± 0.2	0 ± 0
Quercus prinus L. Tree ($n = 8$)	10.6 ± 1.0	5.6 ± 0.5	2.4 ± 1.1	0.3 ± 0.4	0 ± 0
Carya illinoensis (Wang.) K. Kalt Tree ($n = 8$)	11.6 ± 1.6	8.6 ± 1.2	4.1 ± 1.5	2.8 ± 1.8	0.25 ± 0.5
Liriodendron tulipifera L. Tree ($n = 8$)	10.5 ± 1.8	8.0 ± 1.5	4.0 ± 1.7	1.6 ± 1.68	0.1 ± 0.4
Acer rubrum L. Tree ($n = 8$)	10.1 ± 1.4	7.1 ± 1.7	3.6 ± 1.1	1.2 ± 0.7	0
Cornus florida L. Shrub-small tree ($n = 8$)	10.7 ± 1.4	7.5 ± 0.5	4.1 ± 0.6	0.8 ± 1.0	0

* Spot diameters not measured on needles, see text for description of damage.

(Swank and Henderson, 1976) with the followings amount in mg l^{-1}: Ca 0.23; Na 0.17; K 0.08; Mg 0.05; NH_4–N 0.02; and PO_4–P 0.007. The acid portion was made with reagent grade acids to produce the weight ratio of $SO_4:NO_3:Cl$ of 10:7:1 reported by Cogbill and Likens (1974) for New York State acid rain. The salt solutions were amended with the acids to the desired pH value.

Plants which had earlier been subjected to artificial acid rains of pH 5.5 were utilized. Each species was again represented by two plants. On each plant, a healthy leaf was selected. Two rows of five circles were drawn on the leaf with a felt tipped pen. Circles were about 5 mm in diameter. One row of circles was assigned pH treatments of 0.5 to 2.5 while circles in the other row were assigned treatments in the reverse order. This should cancel out possible differences in acid rain susceptibility of leaf bases and leaf tips.

Acid solutions were applied in two trials. In trial A, 0.013 ml droplets of acid were applied between 4 and 5 pm and results recorded after 60 h. In trial B, 0.01 ml droplets were applied between 4 and 8 pm and were recorded after 48 h. In both trials, because of problems in localizing drops on the needles of *Pinus strobus* the needles were dipped into the acid solutions.

Leaves were first evaluated for presence or absence of necrotic spots within the defined circles and next for size of necrotic spots.

3. Results and Discussions

For all species the application of droplets having pH values between 0.5 and 1.5 produced necrotic spots (Table I). Damage was rarely observed where solutions of pH 2.5 were applied. This re-confirms the findings of no damage at pH 2.5 in the earlier study of Haines and Chapman (unpublished). In the present study, damage at pH 2.5 was caused by scratches from the pipette tip in three cases. At pH 2.0 *Quercus* and *Cornus* appeared to be slightly more resistant to damage than the other species because necrotic spots were less frequent and were smaller than in other species. At pH 1.5 through pH 0.5 all the angiosperm species were damaged with sizes of spots increasing with increasing acidity. This suggests that the leaf has some buffering capacity which is progressively taxed by greater acidity. Needles of *Pinus strobus* exhibited damage at pH values between 1.0 and 0.5. Damage was confined to the younger needles and was evidenced by browning and collapse.

The results of this study suggest that the threshold for damage in *Pinus strobus* is at a pH value 1.0 to 0.5 while the threshold for the other species lies between pH 2.5 and 2.0. At pH values more acid than this threshold the leaf tissue is simply killed. A graduated response from slight damage to dead was not found.

The species are listed in Table I roughly in successional order with the early successional plants at the top and the climax forest species towards the bottom. No successional trends in susceptibility to acid rain damage are discernible.

Results from the present study are partly at variance with results of others studied. In the present study artificial rain was applied to fully expanded, mature leaves.

In four earlier studies, seedlings presumably having actively expanding leaves were used. In some of these studies the threshold for damage was as high as pH 3.0 (Wood and Bormann, 1974, 1975) and changes in leaf morphology and size were observed (Wood and Bormann, 1977; Ferenbaugh, 1976). Injury to the adaxial leaf surfaces appeared near trichomes and stomata when Evans *et al.* (1977) exposed seedlings of *Phaseolus vulgaris* to artificial acid rain. The frequency of lesions was related to the degree of leaf expansion. The more expanded leaves had higher densities of lesions, but they also had a greater cumulative exposure to acid rain. Lesion development first involved collapse of epidermal cells followed by collapse of spongy mesophyll cells.

Comparison of results from the present study with results from the literature suggests that developing leaves may be more susceptible to acid rain damage than are mature leaves. The rainfall acidity at the time of leaf expansion thus may be an important determinant of the amount of damage to photosynthetic organs in the forest. For Hubbard Brook, New Hampshire, the weighted monthly mean [Σ(conc) (vol)/Σvol] rainfall H^+ concentration from 1965 to 1974 showed a marked seasonal trend. H increased steadily from a February low value of 46 μ eq l^{-1} (pH 4.3) to a July peak of 102 μ eq l^{-1} (pH 3.9), thereby overlapping the period of leaf expansion. After July the acidity decreased once again to the February level (Hornbeck *et al.*, 1977). For a given volume weighted rainfall acidity, less damage to plant leaves might occur if the maximum H^+ input occurred during the late summer and fall.

With knowledge of damage thresholds and of present day rainfall chemistry we can ask how much more acid would be required before damage to mature leaves might be seen in the field? In the present study, the threshold for damage to mature leaves lies between pH 2.5 and 2.0 for flowering plants and between 1.0 and 0.5 for *Pinus strobus*. The volume weighted H^+ for Hubbard Brook was 89 μ eq l^{-1} (Cogbill and Likens, 1974). This corresponds to pH 4.05. The volume weighted average H^+ for Coweeta Hydrological Laboratory, Franklin, North Carolina, the source of most of the plants used in the present study is 25 μ eq l^{-1} which corresponds to pH 4.6 (Swank and Douglass, 1975). Observations at Coweeta ranged from pH 3.2 to 5.9. Because the pH scale is logarithmic with a decrease in 1 pH unit corresponding to a 10-fold increase in the H^+ concentration, it is apparent that a 100-fold increase in the volume weighted H^+ at Hubbard Brook from 4.0 to 2.0 would bring mature leaves of the flowering plants past the threshold of damage. A 100-fold increase in H^+ at Coweeta would change the pH from 4.6 to 2.6 which is close to the threshold of damage. In the earlier study by Haines and Chapman (unpublished) the same plant species were treated with rainfall of pH 2.5 for 10 periods of 1 h each with no effects. However, in the present study one-time exposures to droplets of pH 2.0 produced necrosis on leaves of flowering plants and drops of pH 1.0 produced necrosis in *Pinus*. Thus it is the extremely acid storm which is likely to be the critical determinant of forest canopy response to acid rain. With the lowest pH value reported for Coweeta being pH 3.2, merely a 10-fold increase in acidity to pH 2.2 in a single spring or summer storm seems likely to bring damage or death to mature leaves of flowering plants at Coweeta.

Acknowledgment

Research partially supported by U.S. EPA Grant R 80530510 and NSF Grants DEB 7619930, DEB 7705324A01 and DEB 7904537 to the University of Georgia. We thank W. J. Brown, K. Tankersley, and U. Thomason for technical assistance.

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