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W.T. Swank and D.A. Crossley Jr.

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26. Acid Precipitation Effects on Forest Processes

B.L. Haines and W.T. Swank

Acid rain can displace essential elements from plant leaves (Wood and Bormann 19 and soil (Wiklander 1973/74), and it can inhibit element uptake by plants (Arnon (1942; Black 1968). These processes of leaching and inhibition of uptake have the pc tial to disrupt the cycling of mineral elements upon which forest production is p dependent. Quantification of the potential magnitude and consequence of this dis tion of mineral cycling is critical to the development of alternative management cies. A balance is needed between the cost of reducing emission of acid forming o› of sulfur and nitrogen into the atmosphere from the combustion of fossil fuels, an(value of forest production affected by acid rain.

Acid rain occurs in industrialized countries, including much of the eastern (Likens and Butler 1981; Brezonik et al. 1980) as well as in areas remote from in trial development (Galloway et al. 1982; Haines et al. 1983). The precipitatic Coweeta is acidic.

This paper summarizes and updates the review of Haines and Waide (1980) described results of experiments designed to determine potential effects of acid rai forest processes at Coweeta. Specifically, we describe the potential effects of acid on canopy processes, litter leaching, soil leaching, and element uptake by roots. I growth and the integration of above and below ground processes are explored in tion to the interacting stresses of acid rain, oxidants, and other environmental v bles. For reviews of acid rain studies on a global scale see Drablos and Tollan (19 Hutchinson and Havas (1980), Teasley (1984), D'Itri (1982), Morrison (1984), E (1984), and Linthurst and Altschuller (1984).

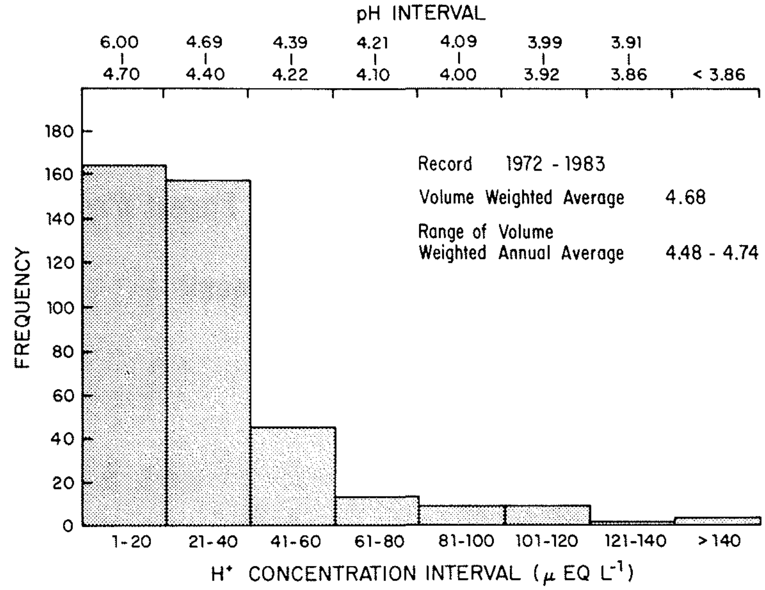

Figure 26.1. Frequency of H^+ concentrations for all periodic bulk precipitation collections f 1972–1983.

Acidity in Rain

The frequency distribution of H^+ concentrations in bulk precipitation collection shown in Figure 26.1. Over a 12-year period only 18 observations had pH values lo than 4.0. The highest pH value for an individual collection during the entire period 6.4 and the lowest was 3.1. The long term volume weighted pH of bulk precipitat is 4.6, with a range in annual values of 4.5 to 4.7.

As precipitation enters and moves through a forest ecosystem, water chemi undergoes substantial changes (Swank and Swank 1984). The average annual H^+ c centration in major hydrologic compartments of a mixed hardwood forest at Cowe shows H^+ depletion as water passes through successive ecosystem components (T 26.1). The forest canopy and uppermost 25 cm of soil are major sites of H^+ depleti By the time precipitation reaches the stream, H^+ concentrations are reduced from µeq L^{-1} to 0.2 µeq L^{-1}, which is equivalent to two pH units (4.8 to 6.7). These in data illustrate the potential buffering effects of the ecosystem to acid rain.

Forest Canopy

Potential responses of plant canopies were investigated in separate experiments uti ing various combinations of early secondary successional herb species, mature h wood forest species, and plantation pines occurring at Coweeta (Table 26.2).

Table 26.1. Average Annual H Ion Concentrations in Hydrologic Compartments for a Mixed Hardwood Forest at Coweeta (WS 7, Pretreatment)

Compartment	H^+ Concentration ($\mu eq\ L^{-1}$)
Precipitation	17.1
Throughfall	5.1
Litter water	4.6
Soil water (25 cm)	1.0
Stream water	0.2

From Swank and Swank (1984).

Rates of foliar leaching were quantified for species subjected to simulated acid r of pH 5.5, 4.5, 3.5, and 2.5. Simulated acid rains consisted of deionized water a salt and an acid component. The salt component contained the following amc of elements in mg/L: Ca 0.23, Na 0.17, K 0.08, Mg 0.05, NH_4-N 0.02, and P 0.007. These are similar to the average bulk rainfall element concentrations fou Coweeta. The acid component was made with reagent grade acids to produce the r ratios of SO_4:NO_3:Cl of 10:7:1 reported by Cogbill and Likens (1974) for New state acid rain. No attempt was made to simulate organic nitrogen, organic phosph

Table 26.2. List of Plant Species and Experiments Where Plant Processes Were Eval Following Application of Simulated Acid Rains

	Leaching[a]	Damage Threshold[b]	Gas Exchange[c]	Growth[c]	Le Wetta
Erechitites hieracifolia (L) Raf.	X	X			X
Erigeron canadensis L.	X				
Robinia pseudo-acacia L.	X	X	X	X	X
Quercus prinus L.	X	X			X
Carya illinoensis (Wang). K. Koch	X	X			
Liriodendron tulipifera L.	X	X	X	X	X
Acer rubrum L.	X	X			
Cornus florida L.	X	X			
Pinus strobus L.	X	X			
Liquidambar styraciflua L.			X	X	X
Platanus occidentalis L.			X	X	X

[a] Haines, Chapman, and Monk (1985).
[b] Haines, Stefani, and Hendrix (1980).
[c] Neufeld, Jernstedt, and Haines (1985).
[d] Haines, Jernstedt, and Neufeld (1985).

or organic acids found in natural rainwater. Significant differences were found am species, with the herbs *Erigeron* and *Erechtites* showing the highest rates of fo leaching. No significant differences were found among pH treatments (Haines et 1985).

How much below pH 3.5 would leaves need to be acidified to cause damage? Lea of eight species (Table 26.1) were subjected to droplets of simulated acid rain having values of 2.5, 2.0, 1.5, 1.0, and 0.5. Damage, quantified as diameters of necrotic sp at sites of droplet application, did not occur above pH 2.0 (Haines et al. 1980).

The effect of simulated acid rain on gas exchange was examined in four tree spe (Table 26.2).Groups of plants received simulated acid rain at pH 5.6, 4.0, 3.0, or for 20 minutes per day every third day for a total of 16 exposures. Decreases in photosynthesis occurred only at pH 2.0; *Liriodendron* showed the smallest reduct and *Platanus* the most. Photosynthetic rates in *Platanus* decreased after exposure to 2.0 mainly due to changes in mesophyll conductance (CO_2 fixation processes) (Neu et al. 1985).

Differences in leaf damage susceptibility were related to leaf wettability measure either water holding capacity or droplet contact angle (Haines et al. 1985). *Plata* the most susceptible tree examined had a relatively low contact angle and high w holding capacity, while *Liriodendron*, the least susceptible species, had a high con angle and low water holding capacity. *Liriodendron* leaves were glabrous, with cell the adaxial epidermis supporting granular surface wax deposit on the cuticle. Lea of *Platanus* were covered with branched trichomes on both surfaces, and epicutic waxes were absent from the adaxial surface. Thus, the wetter a leaf could become greater the damage by pH 2.0 acid rain.

Litter

Leaf litter was removed from 31 cm diameter circles on the forest floor of mature h wood forest WS 2 and subjected to simulated acid rain of 5.5, 4.5, 3.5, or 2.5. Leacl of NH_4-N, K, Ca, Mg, and PO_4-P increased with increasing rainfall acidity. Howe solution NO_3 concentrations were depleted by passing through litter with grea depletion occurring at the lowest pH (Haines 1981). Nitrate may have been inco rated into microbial biomass.

If the volume weighted annual average rainfall pH were to decrease by an orde magnitude from the present 4.7 to 3.7, the annual rates of element leaching from l would probably increase. Elements leached during the growing season migh immobilized by microbial populations, adsorbed to exchange sites in soil, taken u plant roots, or leached out of the system. Elements leached from litter during the wi when tree roots and microbial processes are less active might be lost via deep leacl to streams or ground water.

Soils

Soils obtained from the white pine (*Pinus strobus*) plantation WS 1 and hardwood 7 were leached with artificial solution having a salt component and a simulated rain component. The salt component was made to mimic the composition of w

collected from beneath the litter with zero tension lysimeters (Best and Monk 19
Best unpublished observations, Haines et al. 1982). When the study was designed, magnitude of acid rain induced leaching of salts from leaves and from leaf litter v not known. Therefore, salt strengths of 10× and 100× were also formulated so a bracket a wide range of salt leaching rates. These salt solutions were then acidifie pH values of 5.5, 4.5, and 3.5 with mixtures of SO_4:NO_3:Cl of a 10:7:1 ratio sim to that reported for New York state acid rainfall (Cogbill and Likens 1974). With io strengths of 1×, 10×, and 100× at 3 pH levels, there were nine treatment comb tions to which composite soils from each watershed were subjected. Composite samples representing a hypothetical core 10 cm³ in volume were leached with 216 of simulated soil solutions for 20 hr on a shaker, centrifuged, and the superı decanted for analysis. This was repeated 10 times to simulate the potential leacl over a 10 year period (Haines and Waide 1981).

Generally, the patterns of soil element enrichment and loss were the same in b pine and hardwood soil systems. Most elements showed a cumulative net loss at all levels with a 1× salt solution. At 10×, Ca, Mg, and P showed adsorption to s instead of loss. At 100×, K, Na, Ca, Mg, and P generally showed adsorption to the while Al, Mn, and Fe generally showed a net loss from soil into solutions. In experiment both pH and ionic strength were changed by factors of 10. A change in strength by a factor of 10 had a greater effect than a tenfold change in the acid cont Data from this experiment need further analyses and interpretation, particularly v regard to buffering capacity as defined by base saturation, etc.

Roots

Rates of Ca uptake by excised *Liriodendron* roots were determined for artificial solutions that had been acidified to pH values of 5.0, 4.0, and 3.0. The excised r were incubated in a gradient of synthetic soil solutions ranging from 0.2 to 10 times 2.4 mg Ca/L found in soil solution draining from the litter layer of a hardwood fo at Coweeta. By the use of ^{45}Ca tracer, the relation of the Ca uptake rate to Ca concen tion was determined (Figure 26.2). The rates of element uptake by roots at pH 5.0 at pH 4.0 at a concentration of 5 mg Ca/L (near the Michaelis-Menten half satura constants for both pH 4.0 and 5.0 treatments), were 0.15 and 0.12 mg Ca/g dry we root/30 min. In contrast, roots exposed to pH 3.0 solutions at 5 mg Ca/L had upt rates on the order of 0.01 mg Ca/g dry weight root/30 min or about 10 times less t roots incubated at pH values of 5.0 and 4.0. If soil solutions were acidified to pH : Ca uptake and possibly the uptake of other elements would be decreased. These res are from a single experiment on a single species and substantially more experime tion is needed before firm conclusions are reached. The effects of pH altered alumir speciation on element uptake by roots also need to be evaluated.

Growth

The effect of simulated acid rain on growth was examined in the same plants for wl gas exchange was examined (Table 26.2). Height growth decreased only at pH 2. *Platanus* and *Robinia*. Height of *Platanus* at pH 2.0 was 73% that subjected to pH

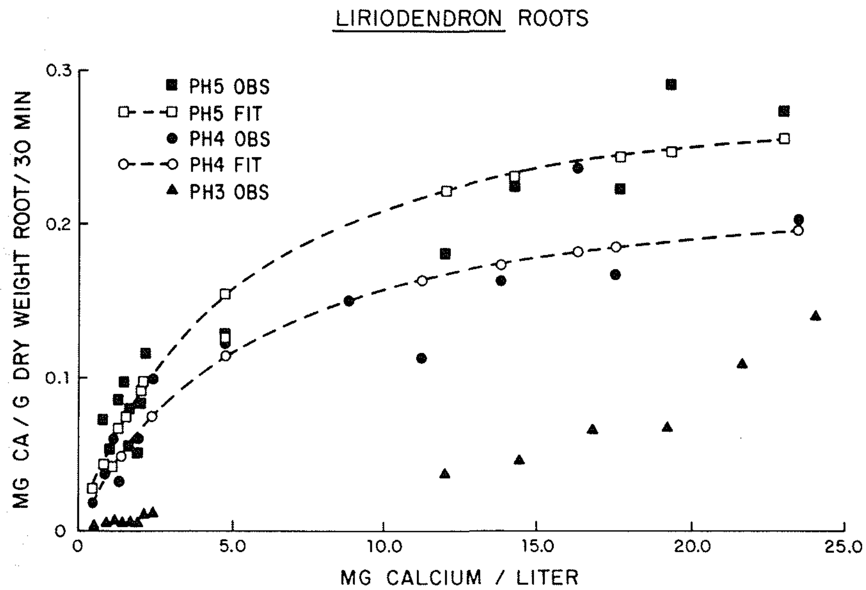

Figure 26.2. Rate of absorption of Ca by *Liriodendron tulipifera* (tulip poplar tree) roots in of Ca/gram dry weight of root/30 min as function of concentration of Ca in solution and of s tion pH. Dashed lines are least squares best fit to Michaelis model by program of Cleland (19 Inhibition of Ca uptake at pH 3 precluded fitting data to model.

while height of *Robinia* at pH 2.0 was 50% that subjected to pH 3.0. At pH 2.0, t biomass was significantly decreased in *Platanus* to 68% and in *Liquidambar* to 67% plants subjected to pH 3.0 simulated rain. Stem and root weights decreased the m (Neufeld et al. 1985) possibly because of decreased carbon uptake due to leaf dama

Potential Effects of Chronic Acid Deposition

The approximate threshold values of acid rain effects at Coweeta (Table 26.3) are ba on short-term experiments. These results suggest that solutions of pH 3.5 will prom element leaching from leaf litter and from soils, but will not affect plant can processes. However, these experiments did not address the potential effects of lo term or chronic exposure of the system to rain with pH values of 3.5 and higher. Pot tially acid rain sensitive processes which we have not investigated are pollen germi tion, root–microbe–soil interactions, leaf weathering, and sulfur and alumin transformations.

Discussion

Plant biomass accumulation and reproductive investment integrate both above below ground plant–environmental interactions. Essential interactions include (1) net acquisition of solar radiation at rates avoiding increased respiration or damag

Table 26.3. Approximate Threshold pH Levels for Effects of Simulated Acid Rain on Terres
Process at Coweeta

Compartment	Mineral Element Leaching[a,b]	Threshold for Damage[c]	Mineral Element Uptake[b]	Photosynthesis[d]	Gr
Canopy–Leaves	none at 5.5–2.5	2.0–1.5	–	2.0	
Litter	2.5	–	–	–	
Soil	3.5	–	–	–	
Roots	–	–	3.0	–	
Whole plant	–	–	–	–	2

[a]Haines, Chapman and Monk (1985).
[b]Haines (1981).
[c]Haines, Stefani, and Hendrix (1980).
[d]Neufeld, Jernstedt, and Haines (1985).

leaves by overheating; (2) the net acquisition of CO_2 through stomata to the mesoj of leaves with minimum loss of water by the reverse pathway; (3) the net acquisitic essential mineral elements while avoiding accumulation of some elements at toxic centrations; and (4) the net acquisition of water from soil in excess of water loss via transpiration. These four acquisition processes may be disrupted by other proce which may be arbitrarily classified as physically and biologically mediated. S physically mediated processes are variations in rainfall, fire, air temperature, the v pressure deficit of the air, and soil water potential. Some biologically med processes include plant competition for solar energy, CO_2, essential elements, water; nutrient availability as controlled by litter decomposition, biological nitr fixation, microbial nutrient uptake, and nutrient uptake by plants; loss of plant pa parasites, pathogens, and to herbivores; and damage from acid rain, ozone, sulfur ide, and nitrogen oxides resulting from human modification of biogeochemical cyc

Acid rain is but one of many potentially interacting factors which can influenc net acquisition of energy, CO_2, minerals, and water. Determining the quantitative tribution of a single mediating factor to increased or decreased plant biomass acc lation or reproductive capacity is extremely difficult for in situ forest ecosyst Indeed, is quantification of acid rain effects upon tree growth at Coweeta a rea objective? Experimental work summarized in Table 26.3 suggests that the threshol damage to some ecosystem processes is between pH 2.0 to 3.0, while acid ra Coweeta ranges from 3.1 to 6.4 with a volume weighted average of 4.6. If ra acidity were to increase from the lowest recorded 3.1 by a factor of four to 2.5, n urable change would probably occur. We also recognize the difficulties in extrapol laboratory findings to in situ conditions; one must regard short-term, controlled st as a guideline to expected responses. We cannot unequivocally discount the long- effects of a moderately acid precipitation regimen on forest productivity at this si study is currently in progress to examine trends in tree growth at Coweeta in rel to natural and anthropogenic factors. Such research is appropriate, since long- stream chemistry trends for control watersheds indicate that hardwood ecosyste Coweeta may be in the initial phases of response to atmospheric input of airt chemicals (Chapter 4).

Potential negative effects of gaseous air pollutants are more immediate. The SO_4 NO_3 in acid rain are generally thought to be derived from SO_x and NO_x liberated to atmosphere in the burning of fossil fuels. Although the volume weighted rainfall pl Coweeta of 4.68 is more than 100 times higher than the threshold for leaf damage, postulate that the ambient concentrations of SO_x, NO_x, and/or O_3 at Coweeta may high enough to have direct effects on net plant metabolism.

Ambient levels of atmospheric pollutants have been demonstrated, via use of o topped chambers, to decrease yields of crops in England and the USA and to decre growth of successional plants in the Blue Ridge Mountains of N.W. Virginia by 3(50% (see review by Bormann 1982). In open topped chamber experiments, pl: received the same solar radiation, rain (or acid rain), insects, drought stress, etc., some chambers received air which was filtered to remove pollutants. Decreased gro of plants in ambient air compared with growth of plants in filtered air is interprete the effect of air pollutants on plant growth.

Extensive browning of current year foliage, particularly on dominant codominant white pine, was observed on Coweeta WS 17 during the relatively wet su mer of 1984 without evidence of insect damage or disease. The threshold for acid damage to white pine at Coweeta is about pH 1.5 (Haines et al. 1980) and during summer period, pH of bulk precipitation was not abnormally low. Examination foliage showed evidence of photooxidant damage (C. Berry, personal communicat: and at least three major oxidant events were observed between June and Septem A long-term data base on biogeochemical cycling and productivity in the planta provides an outstanding opportunity to document some of the effects of a major oxic event on ecosystem processes.

A greater resistance of plants to present day levels of acid rain than to levels of p tooxidants is not surprising. Plants have evolved with rain in their environment millenia. They have developed protective cuticles and waxes which minimize t water loss and mineral element leaching. Elevated concentrations of gases such as SO_2, and NO_x are relatively new to plants in evolutionary time, but these gases dif: through stomata into the plant leaf by the same pathway as CO_2. Resistance to th toxic gases may have evolved only in floras in regions of volcanic activity.

Our present knowledge about the relative importance of acid rain vs. oxidant imp on forest productivity at Coweeta is incomplete. Current research is addressing crit questions on this subject. These efforts will continue to be a major component of long-term research program at Coweeta.