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HYDROGEN AND SULFATE ADDITIONS TO THE FOREST FLOOR AND THEIR EFFECTS ON SOIL AND LITTER ARTHROPODS

A Thesis

Presented for the

Master of Science

Degree

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ABSTRACT

Two- and ten-times the annual ambient inputs of both sulfate ($SO_4^=$) alone and hydrogen (H^+) plus sulfate (acid-sulfate) were applied at five week intervals to the forest floor of Walker Branch Watershed. Over a 14-month period, densities of litter macroarthropods averaged 19% lower in the high sulfate treatment compared to the control. Soil arthropod populations increased significantly in response to the low sulfate and to both acid-sulfate treatments. Fungivores and predators in the soil and litter exhibited responses similar to those observed in the total populations.

The treatments produced chronic and apparent acute effects on forest floor arthropods. Chronic effects on litter macroarthropod populations were observed in the high sulfate treatment. Treatment effects on litter populations were especially severe during late summer and early autumn, normally a time of environmental stress caused by low soil and litter moisture.

Graphical inspection revealed apparent acute treatment effects in June 1981 and January 1982 when arthropod sampling took place three to seven days after treatments were applied. In both months, the low sulfate treatment increased soil arthropod densities while both ten-times treatments decreased densities compared to the control.

The chronic effects of the high sulfate treatment probably resulted from the large potassium (K) additions to the forest floor ($438\ kg \cdot ha^{-1} \cdot yr^{-1}$). Potassium sulfate was used in the sulfate applications. The apparent acute effects of both ten-times treatments also probably resulted from concentrated additions of K to the forest

floor. The overall positive response of soil mesofauna to the high acid-sulfate and to both two-times treatments may be due to the fact that small additions of K fertilizers have a beneficial effect on forest floor arthropods (Hryniuk 1962, Cary et al. 1971). Soil arthropods were not adversely affected by the hydrogen ion additions probably because most of the H was buffered by the litter.

The treatments may have indirectly affected forest floor arthropods by influencing microfloral activity. Respiration measurements taken in the litter showed that evolution of carbon dioxide was 26% less in the high sulfate treatment than in the control.

Analysis of soil nutrients showed increased levels of K and SO_4 corresponding to the low and high times treatments. Soil pH, aluminum (Al), and available phosphorus (P) appeared unaffected by the treatments. Soil pH was unaffected by the acid-sulfate treatments because most of the additional H was neutralized by the forest floor. Analysis of litter leachate during a single treatment interval indicated that only 31% of the H applied in the high acid-sulfate treatment reached the mineral soil. Thus, even after 18 months of treatments, the forest floor litter still served as an excellent buffer against large increases in H inputs to the soil environment.

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CHAPTER I

INTRODUCTION

Acid rain is known to have a detrimental effect on many freshwater systems. Its effects on terrestrial systems are poorly known. Because forest ecosystems are characterized by efficient cycling and retention of nutrients (Reichle 1975, Witkamp and Ausmus 1976), it is important to study factors such as H and SO_4 deposition which could disrupt mineral cycling. Over the long term, such disruptions could have a severe impact on forest productivity.

The study reported below was conducted to determine the effects of neutral and acidic SO_4 deposition on soil and litter arthropods and the consequent effects on available P. The specific objectives were to pinpoint functional groups that are affected by increased acid deposition and to assess the impact on both direct (soil arthropods) and indirect (soil pH and Al) factors governing soil P. By analyzing the effects of H and SO_4 deposition on arthropod trophic structure, it becomes possible to apply the results obtained in this study to other ecosystems that are impacted by acid rain.

Soil invertebrates are an essential component in decomposition and elemental cycling processes in forest ecosystems (Edwards et al. 1970, Crossley 1977). These invertebrates play an integral role in the fragmentation of litter and may also be important in regulating rates of nutrient release in forest ecosystems (Satchell 1974, McBrayer 1977). Availability of P to plants appears to be strongly controlled by decomposer invertebrates (MaCauley 1975, McBrayer 1977, Seastedt and Crossley 1980).

The effects of acidic and nonacidic SO_4 on these essential organisms is poorly known. Several researchers have shown that soil invertebrates are adversely affected by additions of dilute sulfuric acid (H_2SO_4) to the forest floor (Lundkvist 1977, Baath et al. 1980, Lohm 1980). However, these results apply only to certain taxonomic groups or single species which makes it difficult to extrapolate such findings to other communities or ecosystems. Moreover, most studies have focused on the acidification effects of acid deposition. Anthropogenic inputs of nonacidic sulfate-sulfur (SO_4-S) to Walker Branch Watershed have been estimated to be at least 4.96 kg/ha/yr or 34% of the total input (Richter et al. 1982). Large additions of nonacidic SO_4-S, which are deposited as salts, may have a detrimental effect on soil organisms by disrupting osmotic potential (Marshall 1977).

Acid rain may indirectly affect nutrient cycling by influencing chemical reactions in the soil. In particular, soil pH, Al, and P may be affected by H additions. For example, the soil environment may become increasingly acidic as H ions accumulate. Increased H concentration releases Al into the soil solution which acidifies the soil even further (Black 1968). As soils become increasingly acidic, essential nutrients, such as P, are immobilized by Al in the soil solution (Lindsay and Moreno 1960). The indirect effects of H deposition on P availability are critical to evaluating the impact of acid rain on P regulation by decomposer arthropods.

CHAPTER II

REVIEW OF LITERATURE

I. THE ROLE OF DECOMPOSER INVERTEBRATES IN DECOMPOSITION AND NUTRIENT CYCLING

In recent years, soil invertebrates have been viewed as regulators of the decomposition process in forest ecosystems (Kitchell et al. 1979, Satchell 1974). They are important in both the physical breakdown (fragmentation) of litter and in regulating nutrient flux.

Fragmentation by the decomposer invertebrate community constitutes the first step in the decomposition process. Most soil invertebtates are morphologically adapted to feed on detrital resources using schlerotized mouthparts. The physical breakdown of litter and detritus results in an increase in exposed surface area so that it becomes more susceptible to attack by microorganisms (Jensen 1974). This mechanical fragmentation destroys plant cuticle, exposes cell contents, increases oxidation, and promotes leaching of soluble components (Witkamp and Ausmus 1976). It is estimated that soil invertebrates consume from 20% to 100% of annual litterfall (Webb 1977, Anderson and Healey 1970).

Litter and detritus undergo further decomposition in the digestive tract of soil invertebrates as internal symbionts feed on the fragmented materials. Several species of dung beetles, cockroaches, and termites rely upon symbiotic protozoa or bacteria for digestion of plant polysaccharides (Swift et al. 1979). Studies have shown that some termites and xylophagous beetles produce feces containing three times

less cellulose than the wood from which they fed, indicating significant reduction of cellulose by gut symbionts (Lee and Wood 1971).

The production of feces from fragmented litter is an important source of nutrients for other members of the decomposer community. Microbial populations thrive on fecal material, which contains nutrient concentrations similar to the concentrations found in litter (Webb 1977). Presumably, microbial decomposition is enhanced by the increased surface area of feces (Englemann 1961, Wallwork 1970).

Soil invertebrates indirectly promote decomposition by improving the environment for other decomposer organisms. Decomposer invertebrates burrow and create passages in the soil which promote soil structure and improve aeration and water movement (Kevan 1962). Soil arthropods enhance soil fertility by constantly mixing litter and soil mineral particles and by translocating organic matter and nutrients from one soil horizon to another (Crossley 1977). Earthworms and ants translocate considerable quantities of mineral soils upwards. Several researchers have noticed increases in nutrient concentrations associated with this upward movement. For example, Kitchell et al. (1979) found that exchangeable calcium (Ca) increased 40% and nitrate concentrations increased by 380%.

Soil invertebrates may increase the rate of decomposition by dispersing spores and bacteria. Most soil animals are equipped with bristles, scales, or spines, which help to spread such microorganisms. Soil arthropods provide the mobility that is necessary for innoculation of new habitats by microbes and fungal spores.

Several researchers have proposed that decomposer invertebrates regulate rates of organic matter mineralization, especially in ecosystems where high precipitation, seasonal plant uptake, and low soil cation exchange capacity can cause serious nutrient depletion by leaching (Satchell 1974, McBrayer 1977). Soil invertebrates can break down insoluble organic molecules rich in nitrogen and phosphorus and convert them into soluble inorganic forms. Amino nitrogen, a common component of plant protein, may be directly incorporated into the tissues as chitin or animal protein or converted into uric acid and released in feces (Swift et al. 1979).

Several researchers have demonstrated that soil invertebrates concentrate elements in their tissues above those found in leaf litter. Reichle (1971) measured nitrogen and phosphorus concentrations in saprovores exceeding that of litter by a factor of ten. He found that elemental concentration increased with an increase in trophic level. For example, sodium concentrations in soil saprovores and predators were 17 and 27 times greater respectively than litter concentrations. Experiments by McBrayer (1977) and MaCauley (1975) showed that decomposer invertebrates concentrate nitrogen and phosphorus within body tissues. The soil invertebrates community may concentrate up to 20 times as much P as enters the soil via litter and 1.5 times as much as enters from fungi and litter (McBrayer 1977). McKercher et al. (1979) found the Enchytraeids and larval Elateridae had large concentrations of P in their tissues. Analysis showed that over half of the P was present as inorganic orthophosphate. Inorganic phosphates are highly soluble and are available for immediate plant uptake upon the death of soil organisms (McKercher et al. 1979).

Decomposer invertebrates have been shown to concentrate other nutrients such as calcium in their tissues. The role of mites in the retention of Ca has been discussed by Crossley and Witkamp (1964), Wallwork (1975), and Lebrun (1979). The millipede Glomeris marginata is known to concentrate Ca in its exoskeleton (Gist and Crossley 1975, McBrayer et al. 1974).

II. FEEDING HABITS OF DECOMPOSER INVERTEBRATES

The feeding habits of decomposer invertebrates enable determination of trophic groups that are susceptible to acid deposition. In addition, trophic level delineation allows one to determine decomposer compartments where P flow may be disrupted. Table 1 summarizes the feeding habits of soil invertebrates.

Myriapoda

Myriapoda include the pauropods, symphylans, chilopods, and diplopods. Pauropods are extremely small, seldom more than 1 to 2 mm long, and are rarely found in appreciable numbers in the soil. Little is known of their feeding habits but Hüther (1959) observed Pauropus lanceolatus and Allopauropus gracilis feeding upon mycelia.

Symphylans are well distributed throughout the upper layers of the soil. However, they are unable to construct their own burrows and most make use of existing cracks and tunnels in the soil (Edwards 1955). Most symphylans are detritivores but some species (e.g., Scutigerella immaculata) will feed on young roots when soil conditions are unfavorable (Edwards 1955).

Table 1. Feeding habits of soil and litter arthropods.

Taxon	Trophic groups			
	Fungivore	Predator	Detritivore	Litter grazer
Oribatei	X			
Gamasina		X		
Uropodina				X
Prostigmata		X		
Entomobryidae	X			
Isotomidae			X	
Onychiuridae	X			
Poduridae			X	
Protura			X	
Diplura		X		
Symphyla			X	
Pauropoda	X			
Chilopoda		X		
Diplopoda				X
Aranea		X		
Pseudoscorpionida		X		
Coleoptera			X	
Diptera			X	
Thysanoptera	X			
Psocoptera	X			
Isoptera			X	
Hemiptera	X			

Sources: Baker and Wharton 1952, Borror et al. 1976, Hartenstein 1962, Hüther 1959, Kevan 1962, McBrayer et al. 1970, Raw 1967, Wallwork 1967, Wallwork 1970, Watson et al. 1976.

The Chilopoda are important predators in the forest floor especially in sheltered areas such as decaying wood and litter. Almost all centipedes are carnivores but some geophilomorphs will occasionally fed on plant litter. For example, Lithobius variegatus will switch from a predatory role to that of a litter grazer during winter months (Lewis 1965).

Among the myriapod taxa, millipedes have received the most attention. Diplopods feed primarily on litter but Wallwork (1967) observed Schizophyllum cabulosum and Tachypodoiulus niger feeding on living plant material. Millipedes contribute to the decomposition process by promoting the physical degradation of organic matter. In experiments with Glomeris marginata, van der Drift (1950) showed that these millipedes utilized only 6% by weight of the material they consumed, excreting the remainder. Gere (1956) experimented with G. hexasticha and obtained similar results. Gere also found that millipedes fed on freshly fallen litter consumed less and utilized more than those fed on decomposing litter.

Oribatei

Because of their numbers, oribatid mites are an important part of the decomposer food web. These mites often dominate in both numbers and biomass in organic and mineral soil horizons (McBrayer et al. 1970, Crossley and Bohnsack 1960). Many oribatids feed on fungi and bacteria and it has been suggested that they may control the growth of these organisms (Engelmann 1961). Using Cs^{137} tagging, McBrayer et al. (1970) concluded that the families Oribatulidae and Carobidae were

fungivores. Hartenstein (1962) studied the feeding habits of 20 species and found that about half of them preferred fungi whereas the others preferred decomposing plant material.

Other Oribatei feed on detritus and a few are predators. The families Cymbaeremeidae, Camasiidae, and Phthiracaridae are litter saprovores and the Palaeacaridae and Ephilohmanniidae are mineral soil detritivores (McBrayer et al. 1970). Rockett and Woodring (1966) observed Peralumna omniphagus feeding on nematodes. In contrast, Tadros (1979) was unable to induce any of 6 species of oribatids to feed on dead oribatei or insects.

Mesostigmata

Most Mesostigmata are considered predaceous, in part, based on morphology of the mouthparts. Indeed, many of the Gamasina feed on proturans, collembolans, and pauropods (Wallwork 1967). Predaceous gamasines have highly specialized mouthparts which serve to macerate the body tissues of the prey and to assist in the imbibition of body fluids. Other members in the Gamasina include a number of saprophagous forms, such as members of the genus Cilliba (Wallwork 1967).

The Uropodina primarily consume litter and dead plant remains (McBrayer et al. 1970) but they may take only bacteria and mould fungi (Kühnelt 1976). Some forms, such as Fuscouropeda marginata, are coprophagous (Kühnelt 1976).

Prostigmata

The Prostigmata, with their stylet-like mouthparts, are believed to be predaceous. The predatory nature of such families as Bdellidae,

Cheyletidae, Rhagidiidae, and Trombidiidae is well established (Baker and Wharton 1952). The Tydeidae have been shown to feed on eggs and small soil arthropods (Baker and Wharton 1952). Little is known, however, of the smaller soil dwelling prostigmatids. Some members of the Scutacaridae, Pyuemotidae, and Tarsonemidae are parasitic on larger arthropods and may occur in the soil by accident (Wallwork 1967). Many smaller Prostigmata are thought to subsist on fungi. At least some members of the Prostigmata are detritivores. For example, Bryobia sp. (Tetranychidae) feeds on litterfall (Kühnelt 1976).

Collembola

Collembola rank second only to the Acari in abundance in the soil environment. Most are considered fungivores or litter grazers, but a few are faculative predators. Wallwork (1976) noted Isotoma spp. feeding on rotifers and tardigrades. Identification of the feeding habits of larger Collembola has been attempted by gut analysis. Hale (1967) concluded that the larger forms fed primarily on soil fungi whereas the smaller species consumed humus. In fact, the feeding habits of Collembola may even vary within a single species. Tomocerus sp. collected from two woodland habitats showed gut contents consisting entirely of mycelia in one and detritus in the other (Hale 1967). Gilmore and Raffensperger (1970) observed Tomocerus sp. feeding on humus and fungal hyphae when litter was scarce. Studies using radionuclides indicate that at least some members of the Entomobryidae and Onychiuridae are fungivores (McBrayer 1970). McBrayer also found Isotomidae feeding on detritus in the mineral soil.

III. EFFECTS OF ACID PRECIPITATION ON DECOMPOSER INVERTEBRATES

Most research concerning the influence of acid precipitation has focused on the Enchytraeidae (Oligochaeta), the Acari, and Collembola. Enchytraeids are an essential component of the soil faunal community in northern coniferous forests. Many researchers have noted a decline in enchytraeid populations after applications of dilute sulfuric acid solution. Baath et al. (1980) observed a sharp decrease in enchytraeids, particularly in populations of Cognettia sphagnetorum after treatment applications. Lohm (1980) and Lundkvist (1977) obtained similar results for this species. On the other hand, Abrahamsen et al. (1977) found no difference in total numbers of enchytraeids, nor any changes in populations of C. sphagnetorum. More recently, Abrahamsen et al. (1980) observed a small increase in C. sphagnetorum populations in soils acidified with solution of pH 4 and almost complete eradication of the species in soils acidified with pH 2.5 solution.

Investigators studying Collembola and Acari detected no differences in total numbers of these groups (Baath et al. 1980, Lohm 1980, Abrahamsen et al. 1980). However, there is some evidence that certain species are affected by increased acidity. Baath et al. (1980) and Abrahamsen et al. (1980) noted significant increases in populations of Tullbergia krausbaeri with increasing acidification. In addition, Abrahamsen et al. (1980) found an increase in total numbers of Collembola, which they attributed to the sharp rise in populations of Tullbergia sp.

For the Acari, Baath et al. (1980) and Lohm (1980) found no differences among total numbers of mites but did find decreased populations of Trachytes sp. and Oppio obsoleta. Abrahamsen et al. (1980) also found no change in total numbers of mites, the only significant effect of acidification being an increased abundance of the Brachychtoniidae. Hagvar and Abrahamsen (1980) appllied dilute sulfuric acid to sterilized soil samples and allowed them to be colonized by soil organisms. They noted an increase in total Acarina populations compared to untreated samples and attributed the increase to increased populations of Nothrus silvestis and Tectocepheus velatus (Oribatei).

IV. EFFECTS OF ACID PRECIPITATION ON SOILS AND VEGETATION

Acid precipitation may affect nutrient cycling not only by influencing soil fauna but also by direct effects on soil chemistry and vegetation. Effects on soils include decreased soil pH, mobilization of aluminum and trace metals, reduced phosphorus availability, and increased leaching of nutrients. Interpretation of the role of decomposer invertebrates in elemental cycling, particularly P flux, may be hindered by the direct effects of such acidity.

Experimental studies confirm that artificial acidic precipitation applied to soils with low buffering can cause a measurable decrease in soil pH. Abrahamsen et al. (1977) found that application of dilute H_2SO_4 reduced the pH of the O, A, and B horizons in a spruce podzol soil, in some cases by more than 0.5 units. They also noted a reduction in base saturation and attributed it to leaching of Ca and Mg. Tamm

(1976) observed similar declines in pH and base saturation after applying dilute H_2SO_4.

Increased solubilities of elements such as iron (Fe), manganese (Mn), and aluminum (Al) occur as a result of acidification of soils. Although Fe and Mn are essential plant micronutrients, elevated levels of these metals are detrimental to growth of some species (U.S.-Canada 1981). In particular, Al becomes toxic in high concentrations (Bohn et al. 1979, Black 1968). Al toxicity is a direct result of increased soil acidity. Clay minerals tend to become chemically unstable below pH 5, so that Al previously bound within the crystal lattice becomes exchangeable as clay mineral destruction occurs (Foy 1975). This process allows Al^{+3} ions to move into the soil solution where they hydrolyze, forming H+ ions, further increasing soil acidity. Much soil acidity is apparently directly attributable to exchangeable Al. In fact, exchangeable Al^{+3} is the predominant source of acidity between pH 4 and 5.5 because H^+ ions are unable to occupy exchange sites in significant numbers above pH 4 (Bohn et al. 1979).

Black (1968) and Foy (1975) found that Al^{+3} in the soil solution restricted the depth and degree of branching of plant roots. Wright and Donahue (1953) found high concentrations of Al in roots of plants suffering from stunted root development.

Under acid conditions, phosphorus mineralization is hindered by the increased solubility of aluminum (Black 1968). In acid solutions, Al^{+3} and Fe^{+3} react with phosphate to form precipitates with very low solubilities.

$$Al(OH)^{+2} + 3H+ \longrightarrow H+ + Al^{+3} + 2H_2O$$

$$Al^{+3} + PO_4^{-3} \longrightarrow AlPO_4$$

Immobilization by Al and other trace metals under acid conditions is one of the major pathways by which P is made insoluble for use by plants and microbes (Lindsey and Moreno 1960).

In acid soils, P may also be directly absorbed onto noncrystalline clay colloids. Yuan (1980) noted that P retention could be correlated with the Si/Al ratio of aluminosilicates. He found that P adsorption increased with increasing Al.

Several researchers have investigated the effects of simulated acid precipitation on nutrient leaching in the soil (Fisher et al. 1968, Lee and Weber 1980). Roberts et al. (1980) noted losses of exchangeable cations after applications of dilute sulfuric acid. The rate of loss decreased with depth. They also observed a buffering effect on the H+ ion in the F and H litter layers that increased in the mineral soil. In fact, the acidity of leachate from the mineral soil showed no difference between the control and treatment plots. Abrahamsen et al. (1977) found similar reductions in soil cation content in the O and A horizons following acidification.

Nutrient losses via leaching occur by (1) displacement of cations from colloid surfaces by H^+ and Al^{+3}, and (2) transport of exchanged cations through the soil solution in conjunction with soluble anions such as $SO_4^=$ (Johnson and Cole 1977).

Acid precipitation increases inputs of $SO_4^=$ and nitrate (NO_3^-) to the soil. Nitrate is rapidly leached from the soil but, because N is commonly deficient in many forest ecosystems, it is usually retained in

the plant-soil system (Likens et al. 1977, Abrahamsen et al. 1977). In contrast, $SO_4^=$ may be retained in the soil by hydrous Fe and Al in a reaction similar to the immobilization of P. Organic soils, which are low in Fe and Al, have little capacity to retain $SO_4^=$ but mineral soils have greater capacity, particularly in the Fe- and Al-rich B horizon. Soils that adsorb $SO_4^=$ often exhibit considerable resistance to base cation leaching (Johnson and Henderson 1979, Johnson 1980). These soils are usually highly weathered and have large concentrations of hydrous Fe and Al.

Acid precipitation also may directly affect forest productivity by causing damage to vegetation. Direct effects include reduced growth and seedling survival and damage to leaf tissues.

Experimental applications of dilute H_2SO_4 have resulted in losses of plant tissue of 30% in soybeans, corn, and potatoes (U.S.-Canada 1981). Wood and Bormann (1974) studied the effects of acid mist on the growth of Betula alleghaniensis (Britt) seedlings and found that foliar necrosis developed at pH 3. Similarly, necrosis was observed on the leaves of Phaseolus vulgaris (L.) at pH 4 (Lepp and Fairfax 1976). Experiments of Pinus strobus indicate that a pH of 2.3 or less causes necrosis of the needles (Wood and Bormann 1977).

The influence of acid precipitation on tree growth has been investigated using tree analysis, by application of dilute sulfuric acid, and by comparison of regions differing in the amount of anthropogenic acid inputs. Regional analysis of tree rings suggests a decline in forest growth in an area of Sweden subject to acidic inputs (Jonsson and Sundberg 1972). In contrast, Abrahamsen et al. (1977)

did not detect any effect on diameter growth in Norway. Studies in North America, likewise, have failed to show any decline in growth (Cogbill 1977).

Experiments involving applications of dilute sulfuric acid solution have met with mixed results. Wood and Bormann (1974) observed a reduction in plant growth after application of mist having a pH of 2.3. Germination of spruce seedlings was inhibited below pH 4 (Abrahamsen et al. 1977). On the other hand, Tamm (1977) found no effect on growth of pine trees after application of dilute H_2SO_4. Acid precipitation may even increase tree growth. Tveite and Abrahamsen (1980) treated Scots pine seedlings with acid rain of pH 3, 2.5, and 2 and noted more rapid growth than in untreated seedlings.

Acid precipitation may influence the susceptibility of plants to disease and plant pathogens. Shriner and Cowling (1980) postulated that acid rain increases senescence and weathering of tissues, thereby reducing resistance of the host plant. In addition, acid precipitation may increase vulnerability of vegetation to bacteria and pathogenic fungi by damaging leaf cuticle.

CHAPTER III

MATERIALS AND METHODS

Site Description

Study plots were established on a ridgetop on Walker Branch Watershed (WBW) located on the U.S. Department of Energy's Oak Ridge Reservation. The area lies in the Ridge and Valley physiographic province of eastern Tennessee. The climate is of the humid mesothermal type with moderate summer and winter temperatures. Mean annual temperature (1950 to 1980) was 14.1°C (NOAA 1980) and annual precipitation (1970 to 1980) averaged 143 cm (J. Jones, Pers. comm.).

The study plots have a southwest aspect and the soils are classified in the Fullerton series, a Typic Paleudult. The soils, with cherty silt loam surface layers, are located on slopes of 3 to 7% and are underlain by Knox dolomite. A detailed soil description is presented by Johnson et al. (1981). Vegetation at the site is characterized as a mixed oak forest. Chestnut oak (Quercus prinus), white oak (Q. alba), and northern red oak (Q. rubra) are the dominant species. Other species occurring less frequently incude tulip poplar (Liriodendron tulipifera), red maple (Acer rubrum), blackgum (Nyssa sylvatica), sourwood (Oxydendron arboreum), shortleaf pine (Pinus echinata), and dogwood (Cornus florida).

Treatments

Two replicates were established, each consisting of five 8 m x 8 m plots. Plots were randomly selected with each plot exposed to one of five treatments based on the estimated annual input of SO_4-S

(18 kg/ha/yr) to Walker Branch Watershed (Shriner and Henderson 1978). Treatments consisted of two-times annual sulfate (3.6 g SO_4-S/m^2/yr) (2S), ten-times annual sulfate (18 g SO_4-S/m^2/yr) (10S), two-times SO_4 and H (3.6 g SO_4-S/m^2/yr plus .112 g H/m^2/yr) (2H), ten-times SO_4 and H (18 g SO_4-S/m^2/yr plus .562 g H/m^2/yr) (10H), and a control (distilled water only) (C). Recent measurements of H inputs to Walker Branch (Richter et al. 1982) indicate that H contributes .6 keq/ha annually. The 2H and 10H applications supply an additional 1.12 and 5.62 keq/ha/yr, respectively. The H treatments, though not exact, adequately represent two- and ten-times the annual H inputs to Walker Branch.

Acidic and neutral sulfate compounds were used in the treatment applications in order to study the impact of both acidic and nonacidic sulfate deposition on forest floor arthropods. Sulfuric acid and elemental sulfur were not considered because these chemicals provide only acidic sulfate and thus, would not yield any useful information concerning nonacidic sulfate deposition. Neutral sulfate was applied as K_2SO_4 and acidic sulfate was applied as $KHSO_4$. Potassium salts were used for several reasons: (1) forest floor arthropods required only small amounts of K (as opposed to Na), (2) potassium is seldom a limiting nutrient in forest ecosystems and is often present in amounts exceeding the requirements for healthy forest development, and (3) potassium that is not taken up by vegetation is rapidly leached from the soil.

The salts were dissolved in 16 L of distilled water and applied to the forest floor with a plastic garden watering can. The annual amounts

described above were applied as ten equal treatments at approximately five-week intervals (Table 2).

Sampling

Soil and litter samples were taken at approximately monthly intervals between November 1980 and March 1982 (Table 2). Twenty soil samples per plot were collected each month using a steel soil corer with dimensions of 5 cm in diameter by 15 cm long. Eight litter samples per plot were taken using a 0.1 m^2 circular frame. All sampling points were selected by a randomization process. Samples were immediately transported to the laboratory and refrigerated until the organisms could be extracted.

Because the number of monthly invertebrate samples greatly exceeded the number of Tullgren funnels, all plots were not sampled on the same date. Usually, one replicate was sampled on a given date and the second replicate was sampled one week later. This procedure allowed inferences to be made concerning interactions between treatment, replicate, and month since replicates were sampled at varying time periods after treatment applications.

Sample Extraction and Identification

Soil and litter samples were extracted for 72 hours using modified Tullgren funnels (Tullgren 1918). Room temperature was maintained at 20°C during periods of extraction. Invertebrates were collected and stored in an aqueous solution of 70% ethanol and 5% glycerine. The extracted invertebrates were sorted to order, suborder, or family. For analyses, organisms were grouped into trophic levels: fungivore,

Table 2. Dates of treatment applications and arthropod sampling.

Month	Treatment	Sampling
November/December 1980		Nov. 13, 20/Dec. 12, 15
January 1981	Jan. 16	Jan. 26,28
February	Feb. 25	
March		Mar. 5, 9
April	Apr. 7	Apr. 14, 16, 28
May	May 12	May 21, 28
June	Jun. 22	Jun. 25/Jul. 2
July		Jul. 28/Aug. 4
August	Aug. 6	Aug. 24/Sept. 1
September	Sept. 10	Sept. 25/Oct. 2
October	Oct. 19	Oct. 26/Nov. 4
November		
December	Dec. 2	Dec. 9, 15
January 1982	Jan. 25	Jan. 25/Feb. 1
February	Feb. 24	
March		Feb. 24/Mar. 8

detritivore, litter grazer, or predator, based on the predominant feeding habit of the various taxa (Table 1).

All of the invertebrates collected belonged to the phylum Arthropoda with the exception of the Enchytraeidae and Lumbricidae (Annelida). The mites (Acarina) were the most widespread and common forest floor arthropods. They were broken down into the suborders: Prostigmata, Mesostigmata, and Cryptostigmata or Oribatei. The springtails (Collembola) were the second most abundant group of soil invertebrates. Five families were identified: Entomobryidae, Onychiuridae, Poduridae, Isotomidae, and Sminthiuridae.

Chemical Analyses

Soils were analyzed for pH, available phosphorus (P), and sulfate (SO_4) quarterly while aluminum (Al) and potassium (K) levels were measured at 6-month intervals. For each analysis, five samples per plot were obtained by combining 10 randomly selected invertebrate cores into groups of twos. Samples were ground and passed through a 2-mm sieve.

pH was measured with a 0.1 M solution of $CaCl_2$ in a soil: solution ratio of 1:2. Phosphorus analysis was performed using Bray P (#2) according to Black (1965) and analyzed on a Technicon Autoanalyzer. Water soluble SO_4 was measured after shaking a 20:1 distilled water:soil mixture for 30 minutes and filtering through Whatman #42 filter paper. The extract was analyzed on a Technicon Autoanalyzer using the methyl thymol blue procedure (EPA 1979). Potassium and Al extracts were made in a similar manner except that 1 N NH_4Cl was used in a 10:1 solution:soil ratio. Potassium and Al

were measured using an Atomic Absorption Flame Spectrophotometer. All analyses of extracts were carried out by the ORNL Analytic Chemistry Division.

Litter samples from the O_i and O_e horizons were analyzed for pH in June 1982. Five samples per horizon from each plot were collected from the 10H and control treatments. Litter pH was determined in a 1:10 litter:distilled water solution.

In April 1982, two tension-free lysimeters were placed in each plot of the 10H and control treatments. The lysimeters were placed at the interface of the litter and mineral soil to collect leachate from the litter. Samples were collected after each storm event and pH was measured.

CO_2 Measurements

Microbial and microfloral activity in the forest floor was estimated by measuring CO_2 evolution according to the method of Edwards (1982). Ten litter samples per plot were taken from the 10S and control treatments on two occasions in August 1982. Samples were collected from the O_e horizon, weighed to 1 g (moist weight), incubated for at least four days, and flushed with CO_2-free air. CO_2 evolution from each sample was measured three times over a 72-hour period.

Statistical Analyses

The data were analyzed on an IBM computer using the procedures of the Statistical Analysis Systems (SAS 1979). Univariate statistics were calculated on logarithmic and square root transformations to

determine whether invertebrate populations were normally distributed. In most cases, the logarithmic transformation improved the normality and reduced heterogeneity of variance. Analysis of variance was used on log transformed data in a three-way design with treatment as a fixed factor and replicate and month as random factors. Means were separated using Duncan's Multiple Range Test. All tests of significance were made at an alpha level of $p = 0.05$.

CHAPTER IV

RESULTS AND DISCUSSION

I. INVERTEBRATE POPULATIONS

Arthropod densities in the control treatment were analyzed to determine whether the populations at Walker Branch Watershed were representative of the soils and topography of the eastern Tennessee region. Arthropod densities in the current study were compared to two other studies in eastern Tennessee, on the Cumberland plateau (Larkin 1981) and at a second site on the Oak Ridge Reservation (McBrayer et al. 1974). The following comparison attempts to look at similarities and differences in trophic composition and in estimates of arthropod populations in the three studies. For this reason, values used in the comparison are calculated from untransformed data.

Soil and litter arthropods were sampled between November 1980 and March 1982. In 1981, the mean annual arthropod density in the control plots was 52,600 organisms/m^2 (Table 3). July had the lowest number of organisms (27,000) while the arthropod population peaked (90,600) in December 1981. Mites (Acarina) were the most abundant organisms (37,500), constituting 71% of the total arthropod population. Within the Acarina, oribatid mites were dominant (29,200), contributing 56% to the total population. Collembola were the second most abundant group of soil organisms averaging 7,300 organisms/m^2 (14%).

Decomposer invertebrates often follow a bimodal annual population density cycle in temperate deciduous forest ecosystems (McBrayer et al. 1974). The annual pattern consists of a major peak in late fall or

Table 3. Mean monthly soil arthropod densities (number/m^2) in the control treatment with one standard error in parentheses. Multiply values by 10^3 to obtain actual densities.

Date	Replicate 1		Replicate 2		Mean	
December 1980	54.7	(9.8)	89.6	(16.4)	72.2	(9.9)
January 1981	64.4	(16.7)	65.3	(11.0)	64.9	(9.8)
March	55.9	(9.2)	49.9	(10.1)	52.9	(6.8)
April	31.6	(4.9)	35.2	(7.0)	33.4	(4.2)
May	32.2	(6.8)	26.2	(4.4)	29.2	(4.0)
June	24.7	(4.4)	33.0	(5.0)	28.8	(3.4)
July	6.5	(2.2)	47.5	(10.0)	27.0	(6.0)
August	44.3	(7.6)	66.5	(12.0)	55.4	(7.2)
September	58.9	(11.1)	62.9	(8.7)	62.5	(6.9)
October	75.8	(12.0)	78.6	(8.7)	77.2	(7.0)
December	85.1	(16.6)	96.1	(7.4)	90.6	(11.0)
January 1982	79.4	(7.7)	91.9	(14.6)	85.5	(5.3)
February	61.8	(9.6)	72.5	(7.3)	67.2	(6.8)
Mean (Jan. 81-Dec. 81)	47.6	(3.5)	56.0	(3.3)	51.8	(2.4)

early winter, a lesser peak in the spring, and a summer low. Soil arthropod populations reach their greatest density in late autumn at a time when litterfall is the greatest and eggs laid in late summer begin to hatch (Wallwork 1967).

Numerous studies involving decomposer invertebrates have been carried out in eastern Tennessee (Crossley and Bohnsack 1960, Edwards et al. 1969, McBrayer et al. 1970, Kelly 1973, McBrayer et al. 1974, Larkin 1981). Two of these studies involved extensive sampling over a 12 month period. McBrayer et al. (1974) studied energy flow and nutrient cycling in decomposer invertebrates in a Liriodendron sinkhole on the Oak Ridge Reservation. Larkin (1981) compared soil invertebrate populations from two watersheds on the Cumberland plateau. Figure 1 compares soil arthropod populations from the Liriodendron sinkhole, the Camp Branch Watershed on the Cumberland plateau, and the current study on Walker Branch Watershed.

In all three studies, soil arthropod populations reached their peak during November-December while densities were lowest during June-August. The Liriodendron sinkhole had the greatest density of decomposer invertebrates with 78% and 102% more invertebrates than Walker Branch and Camp Branch, respectively.

The large difference in anthropod density between the Liriodendron sinkhole and the other two sites can be attributed to the contrasting soil and forest floor environments of the study areas. The Liriodendron site is located in a natural depression and is underlain by the Emory soil series (Fluventic Umbric Dystrochrept), a slightly acid (pH $\simeq$ 5.9), deep (>6 m), well drained alluvial soil with

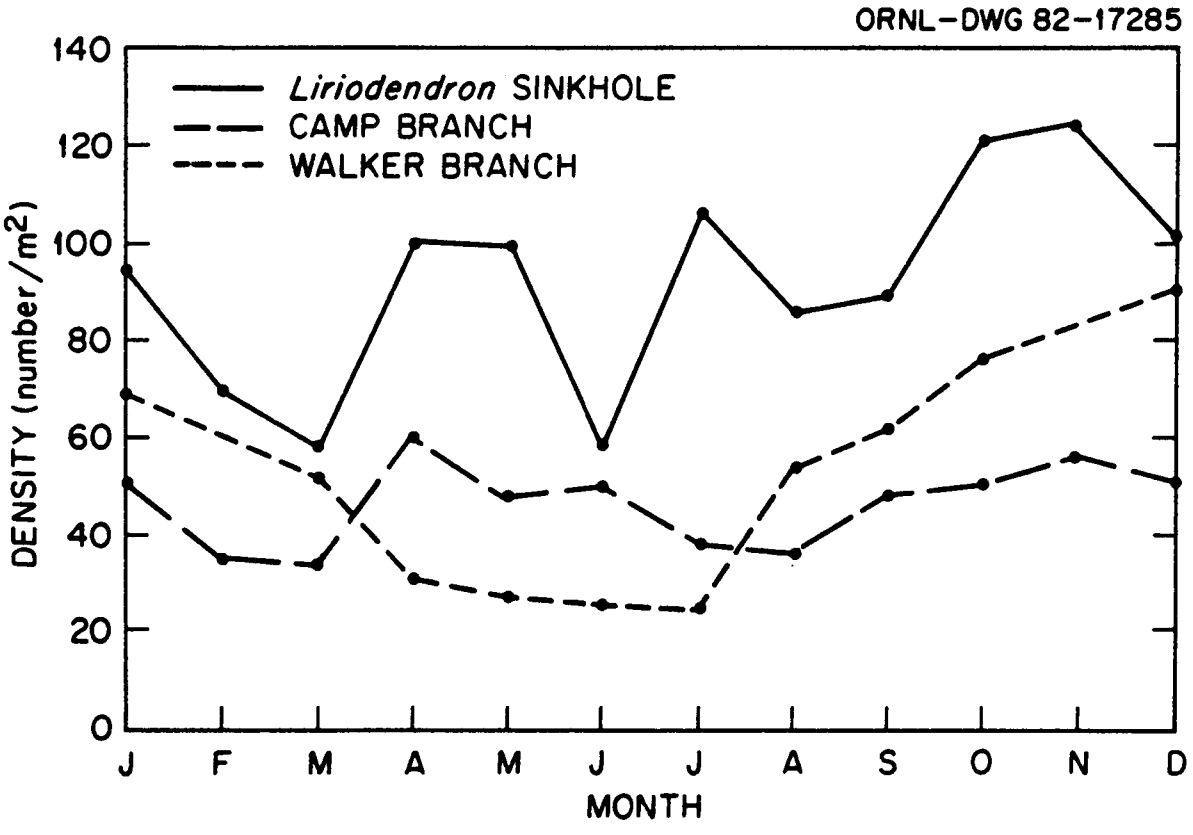


Figure 1. Mean monthly soil arthropod densities at Camp Branch, Walker Branch, and the Liriodendron sinkhole. Multiply values by 10^3 to obtain actual densities.

moderately high organic matter content (3.4% in top 20 cm) (Reichle et al. 1973, Richardson et al. 1973). In contrast, the Walker Branch and Camp Branch sites are located on moderately deep to deep ridgetop soils that are more acidic (pH ≃ 4.6-4.8), lower in organic matter (2.4% at WBW), and have lower CEC (Peters et al. 1970, Kelly 1980).

The low soil arthropod densities at Walker Branch and Camp Branch can be attributed to the droughtiness and the quality of organic matter on the ridgetop soils. The forests at Camp Branch and Walker Branch are dominated by oaks which have a high leaf lignin content (Cromack and Monk 1975). In contrast, the lignin content of the leaves of tulip

poplar, which dominate the sinkhole site, is much lower (Cromack and Monk 1975). Hence, decomposer arthropod populations in the Liriodendron sinkhole are larger, in part, because of increased palatability of the litter substrate. In addition, forest floor arthropods may have a preference for tulip poplar litter because their nutrient content is higher than that of oak litter (Johnson et al. 1982). The relatively high soil acidity at these sites probably has no direct effect upon soil arthropod density since studies have shown that many decomposer invertebrates actually prefer acid soil conditions (Abrahamsen et al. 1980, Hagvar and Abramsen 1980, Hagvar and Kjondal 1981).

The spring increase in soil arthropod populations that is characteristic of many temperate deciduous forest ecosystems was present in the Liriodendron sinkhole and Camp Branch studies but was absent from the current study. This absence may have resulted from a severe drought which affected much of the southeast from June 1980 through the spring of 1981. Precipitation at Walker Branch during 1980 was 98.8 cm compared to the 1970-1980 mean of 143 cm.

Mites (Acarina) were the most abundant soil arthropods on all of the study sites, contributing 71%, 72%, and 66% to the total populations at Walker Branch, Camp Branch, and the Liriodendron sinkhole, respectively. Collembola populations were more variable, contributing 14%, 19%, and 24% to Walker Branch, Camp Branch, and the Liriodendron sites.

Litter inhabiting macroarthropods at the Liriodendron and Walker Branch sites were markedly different. Macroarthropod densities were 1500% greater at the Liriodendron site with dipteran larvae accounting

for most of the difference. The large litter arthropod population at the Liriodendron sinkhole is probably a result of higher levels of soil moisture and a forest floor (primarily tulip poplar litter) which is high in nutrients and is easily decomposed. In addition, part of the large difference between the two sites can be attributed to the 1981-82 drought that occurred during the current study. Fungivore populations at the two sites also differed significantly with fungivores contributing up to 80% of the total population at Walker Branch compared to 60% at the Liriodendron site.

The Camp Branch and Walker Branch studies were conducted on well drained upland soils and both studies showed similar soil arthropod densities. On the other hand, the Liriodendron study was conducted in a limestone sinkhole. This type of environment is not uncommon in the eastern Tennessee region but it represents only a small percentage of the land in this area. Soil arthropod densities were much higher at the sinkhole site than at Camp Branch and Walker Branch. Hence, soil arthropod densities at Camp Branch and Walker Branch are probably more representative of the region than those in the Liriodendron study.

II. TREATMENT EFFECTS

Significant treatment effects were observed in both the litter and the soil. In general, the two-times treatments had a beneficial effect upon arthropod populations while the 10S treatment reduced population densities compared to the control. Litter arthropods were unaffected by the acid treatments. Detailed soil and litter arthropod density data are given in Appendix A.

Pretreatment soil and litter arthropod samples were taken from all plots in November and December 1980. Analysis of total litter populations and number of taxonomic groups in the litter revealed no difference between treatments. On the other hand, soil arthropods appeared to show significant pretreatment differences (Table 4). Detailed statistical analysis, using ANOVA in an unbalanced design, revealed that most of the variance was due to time of sampling and an insignificant amount ($p < 0.05$) was a result of treatments. These results are not surprising since decomposer arthropods are affected by environmental factors (precipitation, temperature, litterfall) which result in continuous population fluctuations. The absence of pretreatment differences in the soil are further substantiated by the fact that soil arthropod densities in the first three post-treatment months showed no significant difference between the five treatments.

Litter Macrofauna

Litter arthropod populations showed significant ($p \leq 0.05$) treatment effects, the 10S treatment having much lower densities (19%) than the 2S and control (Table 5). With the exception of fungivores, litter arthropods were unaffected by the acid treatments. Also, the number of taxonomic groups in the litter was not affected by the treatments. Monthly means and 95% confidence intervals for litter arthropods and for major trophic groups are presented in Appendix Tables A-1 through A-5.

Chronic effects of both the 2S and 10S treatments were apparent during the summer and early autumn (Figure 2) at a time when litter organisms are most susceptible to drought. The 10S treatment had

Table 4. Mean pretreatment soil arthropod densities (number/m^2) with 95% confidence intervals in parentheses.

Sampling date	Treatment/Replicate	Density		
November 13	$10H_1$	(23,236)	33,000	(45,454)
November 20	$10S_2$	(27,372)	33,700	(40,145)
November 13	$10S_1$	(25,653)	36,500	(50,493)
November 20	$2H_2$	(29,488)	38,000	(47,716)
December 12	C_1	(28,951)	43,400	(63,318)
December 15	$10H_2$	(22,868)	46,300	(91,216)
December 12	$2S_1$	(40,593)	52,100	(65,577)
December 15	C_2	(26,985)	58,100	(122,381)
December 12	$2H_1$	(47,177)	65,800	(90,372)
December 15	$2S_2$	(52,755)	70,900	(93,948)

Table 5. Means (number/m^2) and results of Duncan's Multiple Range Test for litter macrofauna.

Treatment	Mean	Duncan grouping
2S	242	A
C	237	A
10H	216	A, B
2H	209	A, B
10S	192	B

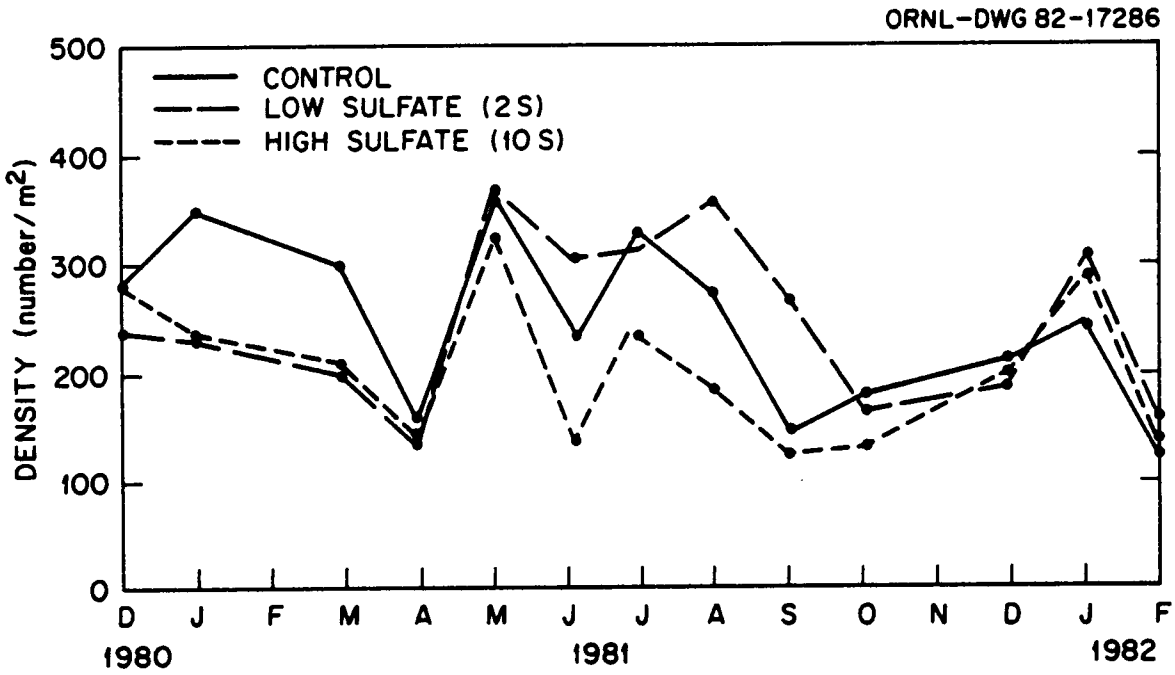


Figure 2. Mean monthly litter macrofauna densities in the low and high sulfate and control treatments.

significantly lower numbers (163 organisms • m^{-2} • month) than the control (252 organisms • m^{-2} • month) beginning in June and continuing through September 1981. Densities in the 2S (312 organisms • m^{-2} • month) were much higher than the control during the same period. The persistent effects of the sulfate treatments occurred in both replicates.

Litter fungivores were affected in a manner similar to total macroarthropod populations. Densities in the 10S were significantly lower than the control (Table 6). Notably, fungivore densities in both acid treatments were also significantly lower than the control. Fungivore populations in the 2H and in both ten-times treatments were significantly lower during the summer. Densities in these three

Table 6. Means (number/m^2) and results of Duncan's Multiple Range Test for litter fungivores.

Treatment	Mean	Duncan grouping
C	74	A
2S	67	A
2H	55	B
10H	54	B
10S	51	B

treatments averaged 46% to 49% lower than densities in the control between June and October 1981.

Litter predators were affected in much the same way as total litter populations. Predator densities in the 10S were significantly lower than densities in the 2S (Table 7). However, densities in the control were not significantly different from either sulfate treatment. As in the total litter population, predator densities in the 10S were depressed throughout the summer and early autumn, possibly indicating a long-term effect.

There were no statistically significant differences in litter detritivore densities among the five treatments. But, as in the case of fungivores, populations were lowest in the ten-times treatments. Litter detritivores were unaffected by the treatments, probably because many of these organisms (e.g., dipteran and coleopteran larvae) spend only a portion of their life cycle in the litter. Colonization of the

Table 7. Means (number/m^2) and results of Duncan's Multiple Range Test for litter predators.

Treatment	Mean	Duncan grouping
2S	45	A
C	43	A, B
10H	41	A, B
2H	39	A, B
10S	38	B

litter by detritivores is a constant process as the adults lay eggs in the forest floor. Hence, litter detritivores are less dependent on a favorable forest floor environment than are other trophic groups which spend their entire life in the soil and litter.

Macrofaunal litter grazers are represented by the Diplopoda which were affected differently than other trophic groups. The 10S treatment had significantly higher populations of millipedes than the two-times treatments. Densities in the control were not significantly different from any of the treatments. It is not clear why litter grazers responded differently to the treatments than the other trophic groups.

Soil Mesofauna

Soil arthropod populations also showed significant treatment effects. The 2S, 2H, and 10H were much higher than the control and 10S treatments (Table 8). However, the chronic treatment effects that

Table 8. Means (number/m^2) and results of Duncan's Multiple Range Test for soil mesofauna.

Treatment	Mean	Duncan grouping
2S	42,900	A
2H	41,500	A
10H	40,000	A
C	35,900	B
10S	35,100	B

were observed during the summer and early autumn in the litter were not present in the soil (Figure 3). Monthly means and confidence intervals for soil arthropod numbers and for major trophic groups are presented in Appendix Tables A-6 through A-10.

Graphical inspection suggested that short-term treatment effects were present in replicate one when arthropod sampling took place soon after a treatment application. In June 1981, arthropod samples were collected from replicate one three days after treatments were applied. Arthropod densities in both ten-times treatments declined sharply between May and June in replicate one (Figure 4). At the same time, both two-times treatments showed increased densities compared to the control. Arthropod populations were sampled again in late July, 33 days after treatment applications, and densities in replicate one increased in both ten-times treatments while populations decreased in the 2S, 2H, and control. On the other hand, replicate two was sampled 10 days

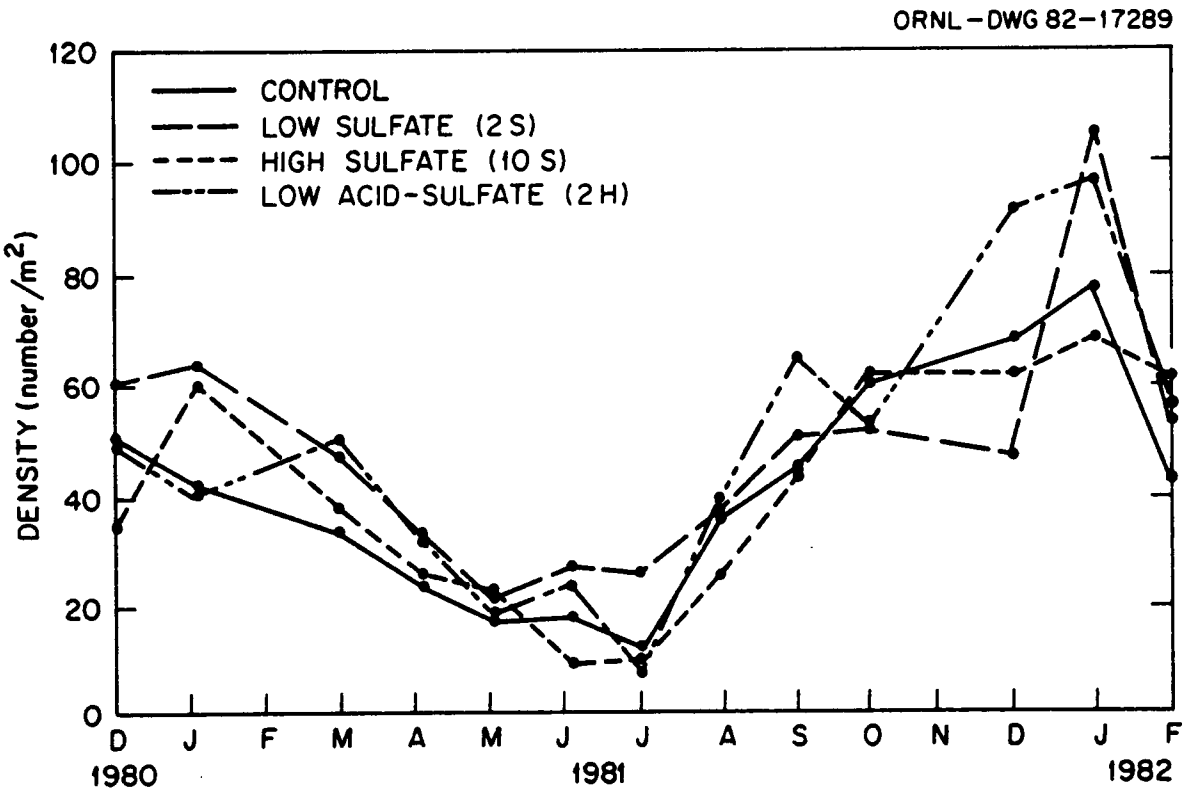


Figure 3. Mean monthly soil mesofauna densities in the low and high sulfate, low acid-sulfate, and control treatments. Multiply values by 10^3 to obtain actual densities.

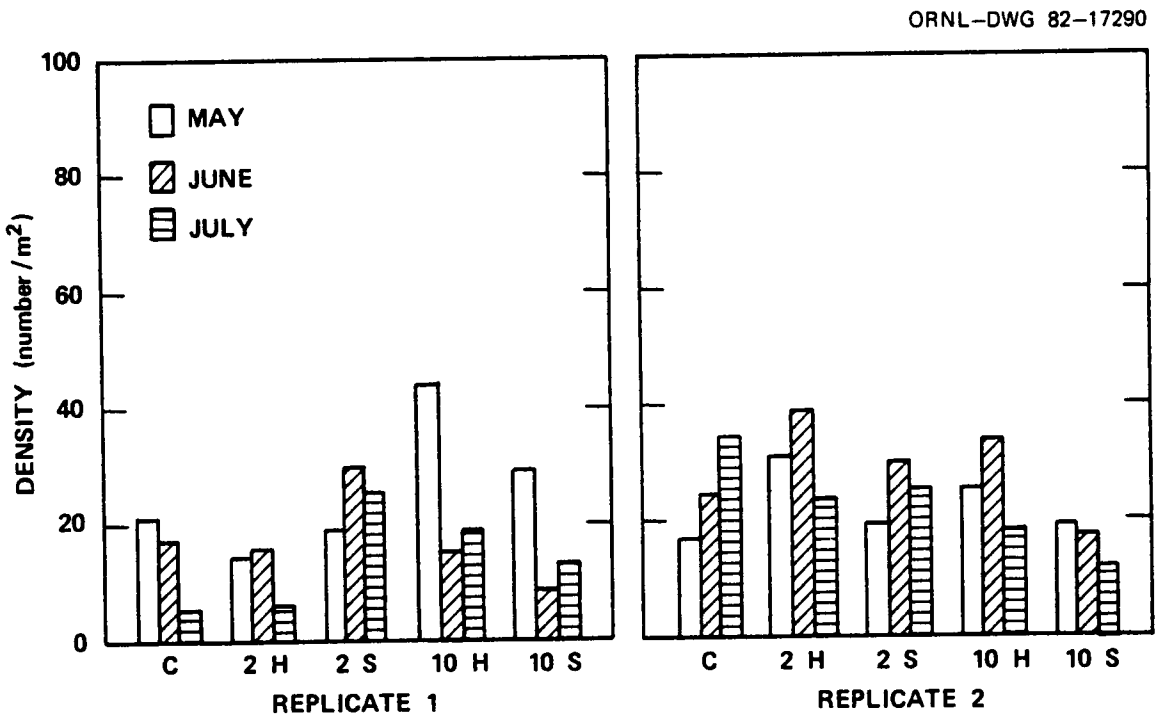


Figure 4. Mean soil mesofauna densities in the five treatments in May, June, and July. Multiply values by 10^3 to obtain actual densities.

after treatments were applied in June and arthropod populations were unaffected (Figure 4). These findings suggest that the soil mesofauna may be susceptible to acute effects caused by the treatment applications.

It appears that short-term treatment effects were also present in January 1982 when replicate two was sampled seven days after treatment applications. During this time, arthropod populations in replicate two declined in both ten-times treatments while densities in the control increased (Figure 5). In January, replicate one was sampled 55 days after treatment applications, and densities increased in all of the treatments (Figure 5).

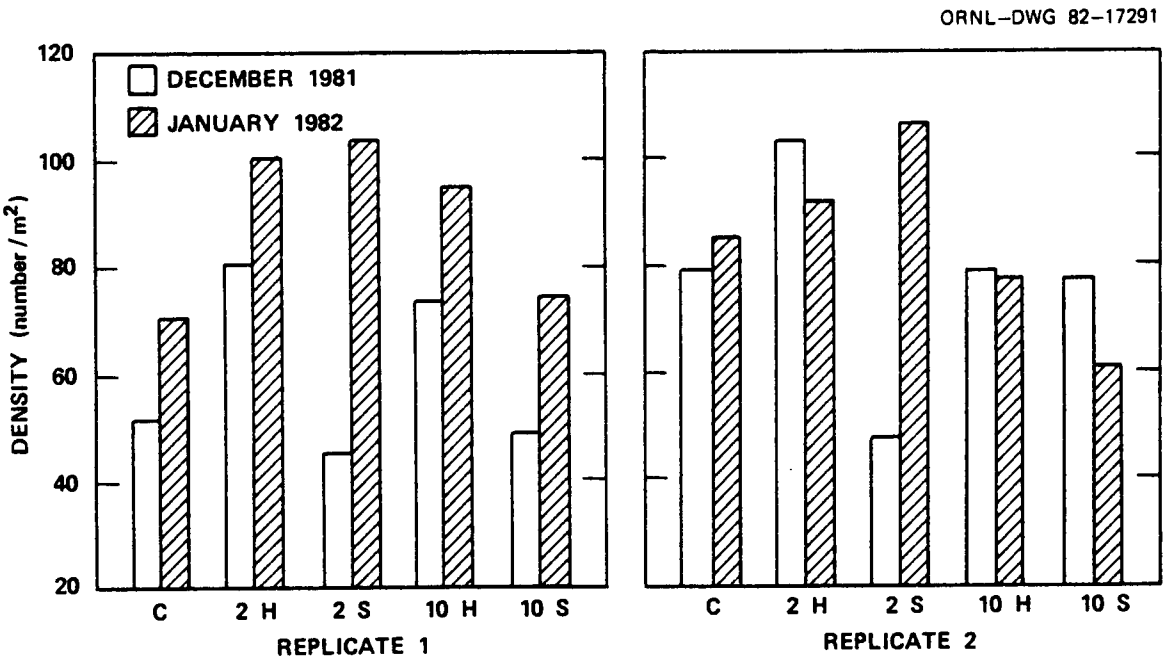


Figure 5. Mean soil mesofauna densities in the five treatments in December 1981 and January 1982. Multiply values by 10^3 to obtain actual densities.

It is not possible to ascertain whether these apparent effects resulted from treatment applications or were caused by environmental factors such as precipitation, temperature, soil moisture, or other soil properties. However, inspection of weather records in June and January revealed no significant difference in the amount of precipitation that occurred two weeks before replicate sampling took place. In conclusion, this study is unable to quantitatively analyze for acute treatment effects because the statistical design of the experiment was not constructed to answer such questions.

Soil fungivores constitute 80% of the total soil population and, thus, account for most of the treatment effects observed in the soil mesofauna. Overall, densities in both two-times treatments were

significantly greater than in the 10S and control (Table 9). Once again, graphical inspection revealed that acute effects were present in June and January and were identical to the effects observed in the total populations.

Soil predators were affected in a manner similar to fungivores (Table 10). The two-times treatments had a positive effect upon predator populations compared to the control and the 10S. Again, acute effects appeared to be present in replicate two during January when predator populations increased 73% in the 2S treatment. Replicate two, which was sampled seven days after treatment application, also had decreased predator densities in both ten-times treatments compared to the control. Once again, it is not clear whether these acute effects are a result of treatments or are due to other factors.

Soil detritivores were affected in the same manner as fungivores and predators. Populations in the 2S treatment were significantly

Table 9. Means (number/m^2) and results of Duncan's Multiple Range Test for soil fungivores.

Treatment	Mean	Duncan grouping
2S	28,900	A
2H	28,100	A
10H	27,400	A, B
C	24,400	B, C
10S	23,800	C

Table 10. Means (number/m^2) and results of Duncan's Multiple Range Test for soil predators.

Treatment	Mean	Duncan grouping
2S	7,800	A
2H	7,600	A, B
10H	6,800	B, C
C	6,100	C, D
10S	5,900	D

higher than the 10S and control (Table 11). Once again short-term treatment effects appeared to be present in June and January.

Detritivore densities, during June, showed treatment effects similar to those observed in the total soil populations as densities decreased sharply in both ten-times treatments in replicate one. However, July detrivore populations were affected somewhat differently as densities in both ten-times treatments in replicate one more than doubled, approaching May population levels (Figure 6). At the same time, densities in the control plot decreased sharply. Soil fungivores and predators did not show such a strong recovery in the ten-times treatments during July. These results suggest that soil detritivores may be able to recover more rapidly from the effects of the ten-times treatments than other trophic groups. Short-term effects were also present in January as treatments affected detritivores in the same way as total soil populations.

Table 11. Means (number/m^2) and results of Duncan's Multiple Range Test for soil detritivores.

Treatment	Mean	Duncan grouping
2S	5,500	A
10H	5,200	A, B
2H	5,100	A, B
10S	4,800	B
C	4,700	B

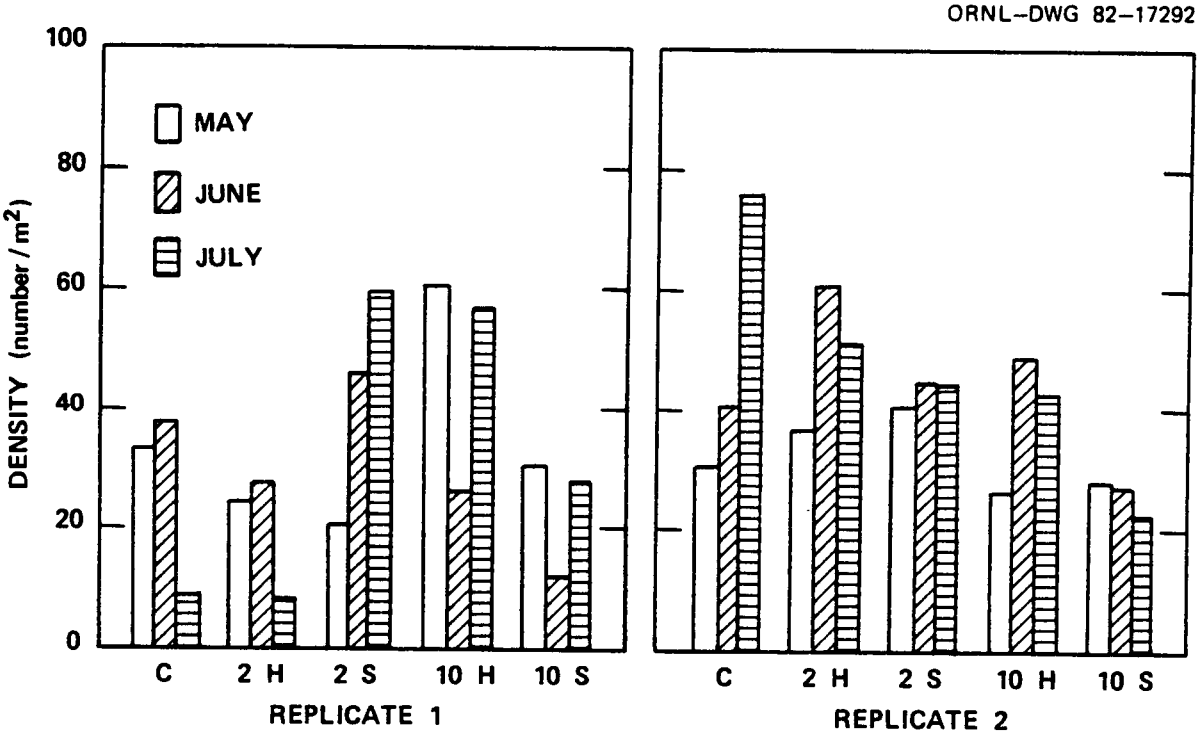


Figure 6. Mean soil detritivore densities in the five treatments in May, June and July. Multiply values by 10^2 to obtain actual densities.

Soil litter grazers are represented by the Uropodina. Uropodine mites were adversely affected by the ten-times treatments (Table 12). However, acute affects of the ten-times treatments were not observed in either June or January.

Increased soil arthropod densities in the 2S, 2H, and 10H treatments may be a result of a beneficial effect of small additions of K fertilizers. The 2H, 2S, and 10H treatments contained 10%, 20%, and 50% of the quanitity of K in the 10S treatment. Soil arthropod densities in the 10S were not significantly different from the control. Short-term positive effects of the two-times treatments were noted in June and January, when samples were taken three and seven days, respectively, after treatments were applied. Short term beneficial treatment effects were observed in the 2S in the litter and both the 2S and the 2H in the soil.

Table 12. Means (number/m^2) and results of Duncan's Multiple Range Test for soil litter grazers.

Treatment	Mean	Duncan grouping
2H	700	A
C	670	A, B
2S	660	B
10H	630	B
10S	620	B

Several researchers have shown that soil arthropod populations increase in response to additions of mineral fertilizers (Tischler 1955, Edwards and Lofty 1969, Artemjeva and Gatilova 1975). Edwards and Lofty (1969) found that applications of NPK fertilizer increased populations of both Collembola and Acarina in cultivated soils. Artemjeva and Gatilova (1975) obtained similar results for Collembola, Gamasina, and Prostigmata under several different cultivation schemes. Franz (1953) observed small increases in Collembola and Acarina in grassland soils.

Decomposer invertebrates in forest soils show fertilizer effects similar to those observed in agricultural and grassland soils. Mayer-Krapoll (1963) observed increases of 175%, 240%, and 440% in Collembola, myriapod, and mite populations in an oak forest after NPK applications. The same author obtained similar results in the forest floor of a beech forest. Litter inhabiting insects such as the Thysanoptera, Coleoptera, and Diptera were affected by fertilizer additions much the same as the soil mesofauna. Mayer-Krapoll (1963) found that insect populations in oak and beech forests, excluding Collembola, were 225% and 1000% more numerous in fertilized plots than in control plots. Hryniuk (1962) observed a 125% increase in insect populations in arable land treated with NPK.

Several researchers have studied the effects of specific fertilizer constituents, notably K, on the soil fauna community (Hryniuk 1962, Cary et al. 1971). Five years after applying 448 kg/ha K as KCl to a pine forest, total microarthropod populations increased with the Mesostigmata, Cryptostigmata, and Prostigmata increasing by

25%, 12%, and 3.5% respectively (Cary et al. 1971). During the same period, Cary et al. observed a 5% decrease in Collembola compared to the control. Hryniuk (1962) compared invertebrate populations in plots treated with NK, PK, NP, and NPK and found that plots treated with NK and PK fertilizers had greater arthropod densities than either the NP or NPK plots. Hryniuk observed Acarina populations in the NK, PK, and NP treatments that were 119%, 135%, and 76% compared to the control. Collembola and other forest floor insects were affected similarly.

Litter arthropods were adversely affected by the 10S treatment. In addition, apparent acute effects of the ten-times treatments were observed in soil arthropod populations in June and January. This study (see soil nutrients, p. 35) and others have shown that large doses of fertilizers may have a negative effect on soil fauna (Artemjeva and Gatilova 1975, Marshall 1977). Kühnelt (1961) suggested that species density and composition decrease with increasing salt concentration and that fertilizer additions may be responsible for the "shock effect" or immediate reduction in populations following applications. This phenomenon has been observed by several researchers including Hryniuk (1966) and Huhta et al. (1967).

The response of soil and litter arthropods to the treatments may have resulted from direct or from indirect effects. Direct effects include changes in osmotic potential and soil pH. The treatments could indirectly affect decomposer arthropods by regulating microflora, which are the primary food for many forest floor arthropods. Generally, small additions of fertilizers have a positive effect on microfloral populations which, in turn, stimulates the soil fauna populations

(Marshall 1977, Heungens and van Daele 1981). However, large doses of fertilizers may adversely affect microflora (McCormick and Wolf 1980) and have a negative impact on soil and litter arthropods.

As an index of microfloral activity, CO_2 evolution was measured in O_2 litter samples taken from the 10S and control treatments. Significant treatment differences were observed. CO_2 evolution in the control (62.3 $\mu g \cdot hr^{-1} \cdot g^{-1}$ dry wt) was 34% greater than in the 10S (46.4 $\mu g \cdot hr^{-1} \cdot g^{-1}$ dry wt) treatment. Johnson and Guenzi (1963) and Laura (1974) studied the effects of neutral salts on soil respiration and obtained similar results. These findings suggest that the negative effects of the 10S in the litter and the overall positive effects of the 2S, 2H, and 10H in the soil were a result of treatments affecting microfloral populations.

Soil Nutrients

Treatment applications had little or no effect on measured soil nutrient parameters except through accumulation of K and SO_4. Soil K and SO_4 levels increased during the sampling period in accordance with the two- and ten-times treatments. Soil pH and exchangeable Al were not significantly affected by the treatment applications. Available P was also unaffected by the treatments. Monthly means and standard errors for soil nutrients are presented in tables B-1 through B-5.

Soil K levels were significantly higher in both the sulfate and the acid-sulfate treatments than in the control. Potassium concentrations in the five treatments were ranked in the following order: 10S > 10H > 2S > 2H > C. These findings reflect the chemical composition of the treatments as the SO_4 additions provide

two times as much K, using K_2SO_4, as the corresponding acid-sulfate additions, which utilize $KHSO_4$. Except for the control, K levels in all treatments increased during the sampling period. Soil K in the 10S treatment was significantly higher than in any of the other treatments (Figure 7). These results support the argument that the high salt concentration, particularly K, is responsible for the significantly lower litter arthropod densities in the 10S and for the acute effects of both ten-times treatments on soil arthropods.

Soil SO_4 also increased in accordance with the treatments. The ten-times treatments had the highest SO_4-S concentrations while the

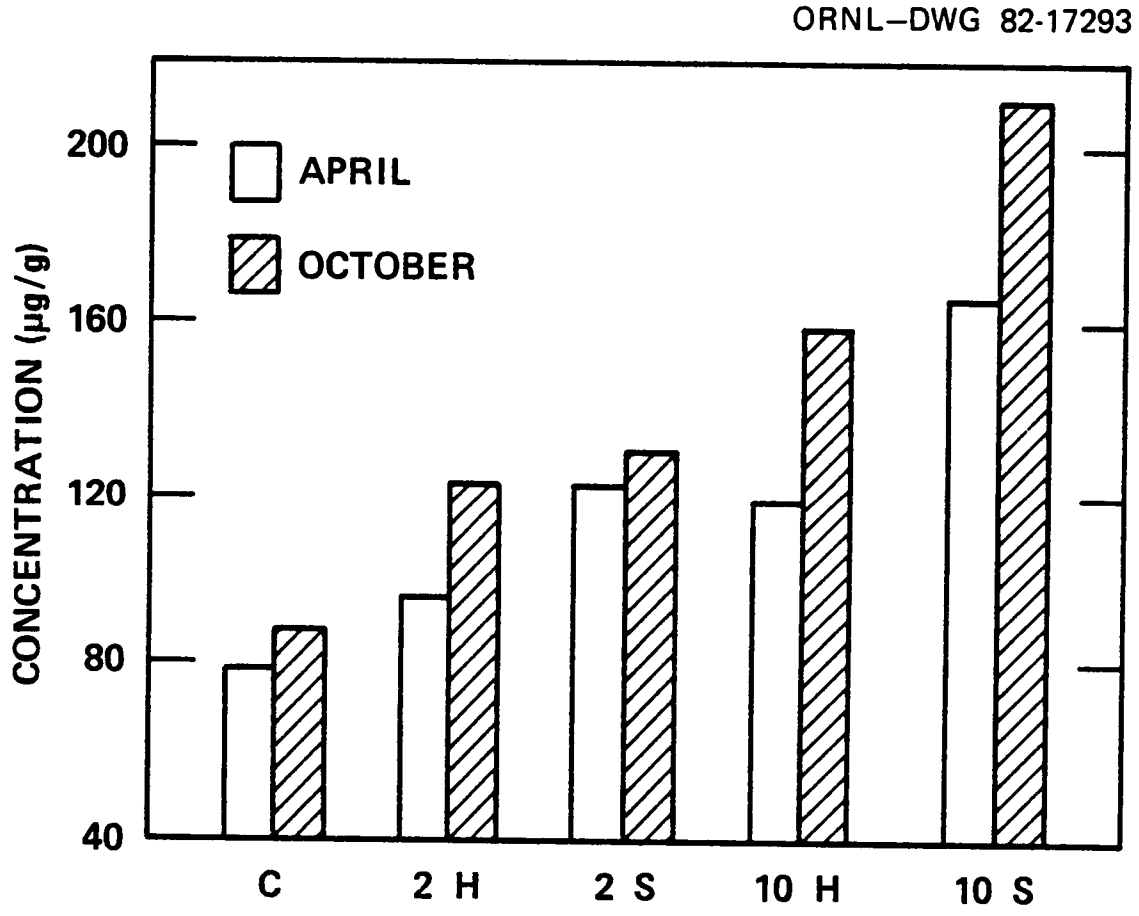


Figure 7. Soil potassium concentrations in the five treatments in April and October.

control exhibited the lowest level (Figure 8). Both the two- and ten-times treatments had increased SO_4 levels beginning in April and continuing through the study period. Sulfate levels in the control remained about the same during the study. Soil SO_4 concentrations were greatest in both replicates of the 10H treatment. These results are not surprising since $KHSO_4$ is retained in the soil to a greater extent than K_2SO_4 (Mehlich 1981).

Two important measures of soil acidity, pH and exchangeable Al, were not significantly affected by the treatments. Interpretation of these data was made difficult because of pretreatment plot differences. In particular, the 10H plot in replicate one was less acidic than the other plots. Soil pH averaged 4.6 in this plot compared to a pH of

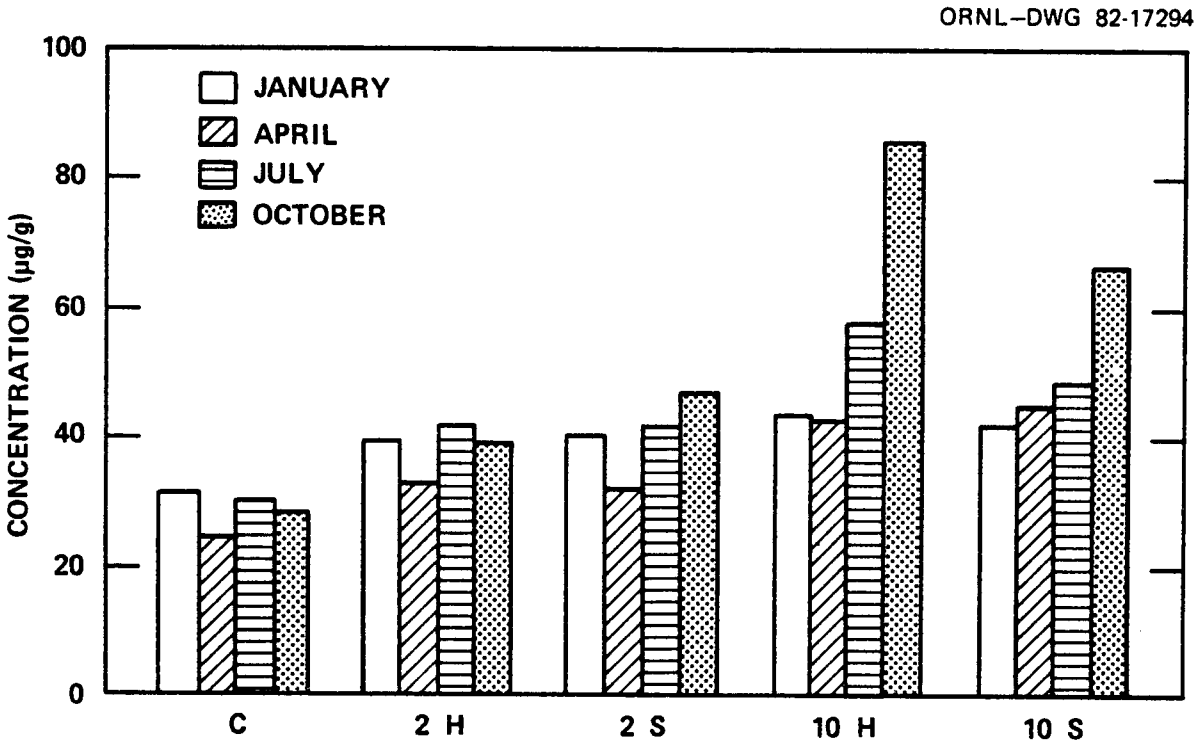


Figure 8. Quarterly soil sulfate concentrations in the five treatments.

about 4.0 in the other plots. The lower acidity observed in the 10H (replicate one) plot can be attributed to the proximity (2 m) of this plot to a road gravelled with dolomitic limestone. Hence, alkaline dust and leachate from the road may have contaminated this particular plot. All other plots are located farther away from the road (5-20 m) and apparently had not been affected by the limestone gravel.

Individual treatments and plots were analyzed in order to factor out the pretreatment plot differences. By comparing the magnitude of change in pH in all plots during the study period, it became evident that soil pH was unaffected by treatments. Soil pH declined in all treatments during the study (Figure 9) but the magnitude of decrease was similar for all treatments. Although not statistically significant, the magnitude of decrease in the 10H plot in replicate one was the

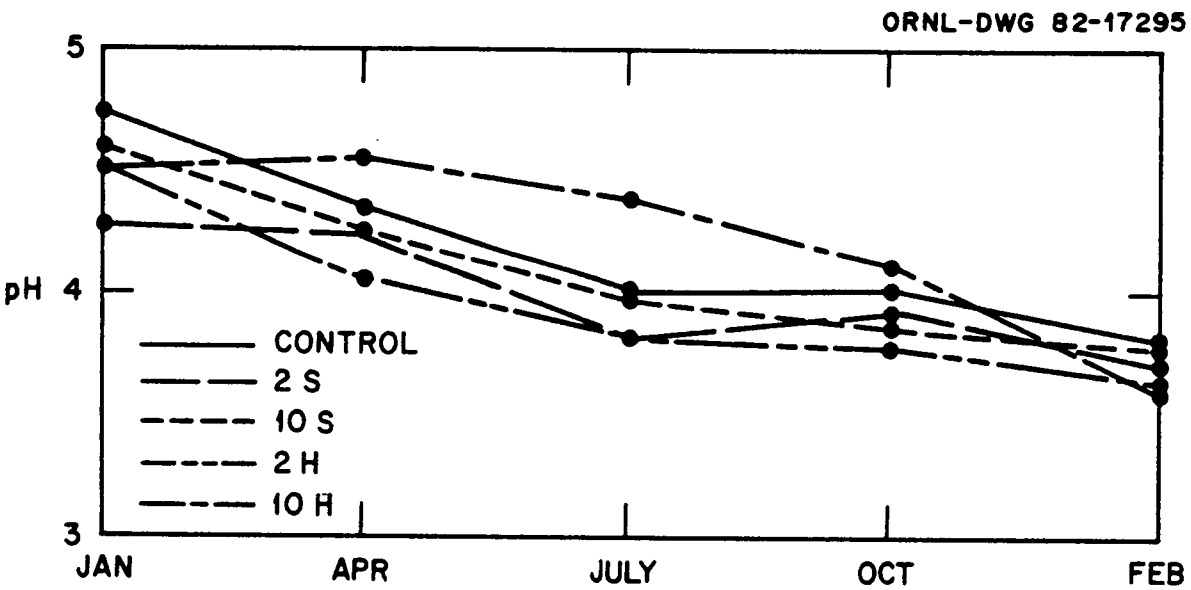


Figure 9. Quarterly soil pH values in the five treatments.

largest at 1.42 units. It is not clear whether this decrease was a result of the treatment or whether it was due to soil variability.

Like pH, the effects of treatments on soil Al were determined by comparing the magnitude of change in individual plots and treatments. The analysis revealed that soil Al was not significantly affected by the treatment applications. However, both the 10H and 2S treatments had large increases in exchangeable Al between April and October (Figure 10). Once again, it is not clear whether the increase was a result of treatments or of sampling error.

The reason that the acid-sulfate treatments did not affect soil pH and Al is because most of the H additions may never reach the mineral soil. Instead, the H is buffered by the forest floor litter layer. Analysis of O_i litter pH in the 10H and control treatments revealed a significant difference as pH in the 10H averaged 3.7 while the control pH was 4.5. Measurements of pH in O_e litter also showed significant treatment differences but the magnitude of difference was half that found in the O_i litter. O_e pH was 4.9 in the 10H and 5.3 in the control.

pH measurements of leachate collected from lysimeters in the 10H and control plots further support the argument that H ions are strongly retained by the forest floor. Leachate pH during the treatment interval July 1, 1982, to August 10, 1982, was significantly different with the 10H having a pH of 4.67 and the control with pH 6.15. Measurements of leachate acidity in the 10H treatment showed that only 17.68 of the 56.2 meq/m^2 of H applied during that interval reached the mineral soil. Seventy-six percent of the total leachate acidity collected

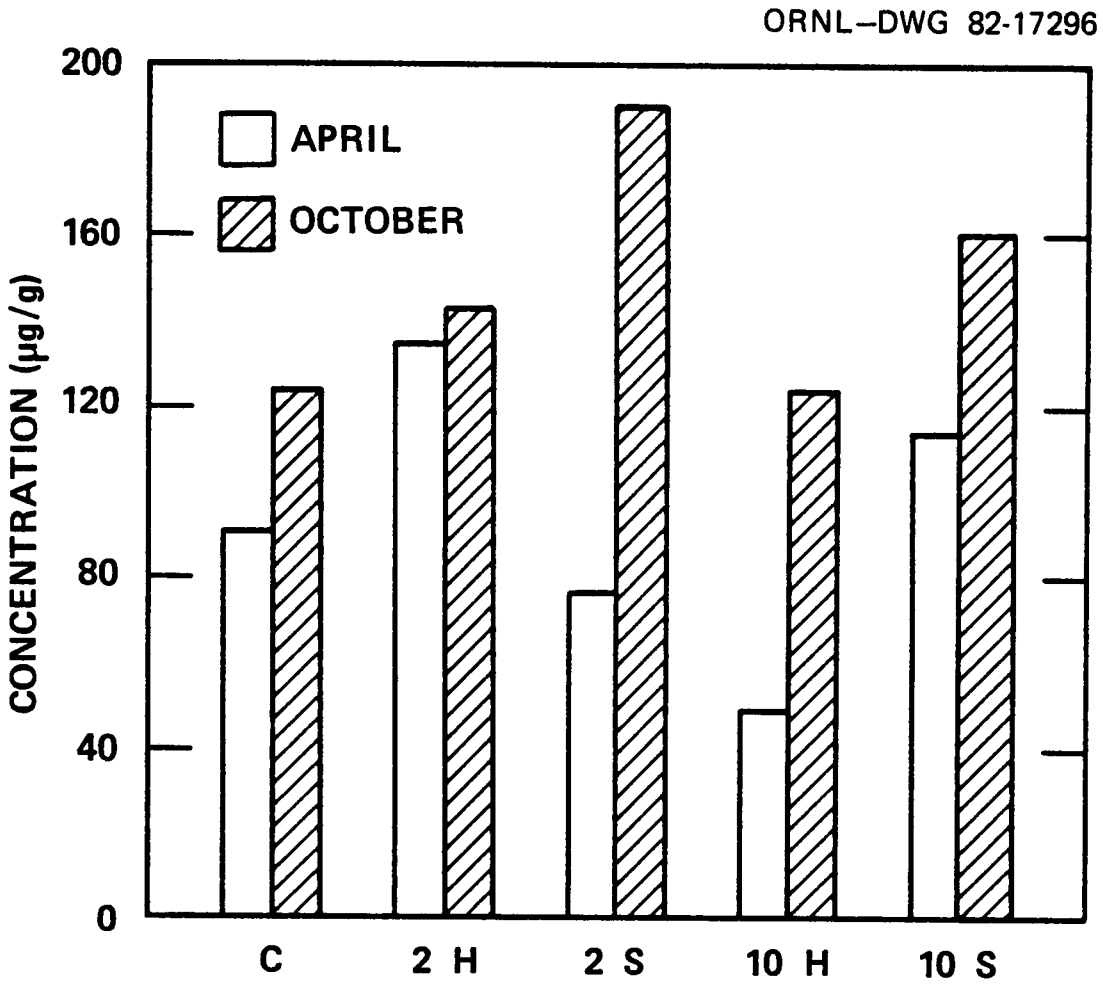


Figure 10. Soil aluminum concentrations in the five treatments in April and October.

during the five-week period came from the first rain event that occurred after the July 1 treatment (Figure 11). It appears that the forest floor provides an excellent buffer against increased H inputs since, even after 18 months of treatments, 69% of the H addition in July was retained by the litter. In fact, leachate acidity during July was probably higher than normal as rainfall for the period was 24.36 cm or about 200% of the July average. These results are consistent with

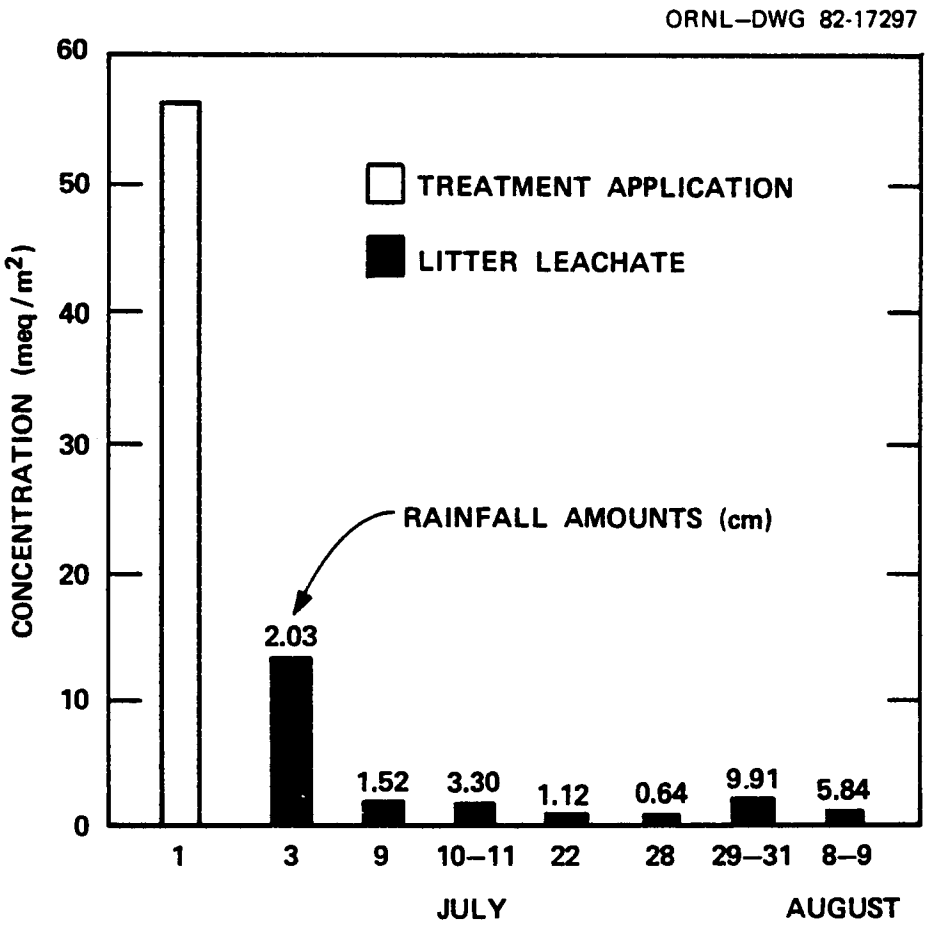


Figure 11. Hydrogen ion concentration in the treatment application and the litter leachate in the high acid-sulfate (10H) plots during the July/August treatment interval.

other studies which show the forest floor acts to buffer anthropogenic and natural H inputs (Plice 1934, Richter et al. 1982).

Available P in the soil was unaffected by the treatment applications. In addition, P concentration could not be correlated with changes in soil arthropod densities in the five treatments. Perhaps the effect of treatments on soil arthropod populations was not large enough to observe any change in available P.

Several researchers have shown that, in acid soils, P availability decreases with decreasing pH (Lindsay and Moreno 1960, Bohn et al. 1979), but, in this particular study, there was no positive correlation between pH and available P. In fact, the treatment with the highest pH (10H) had the lowest P values (Figure 12).

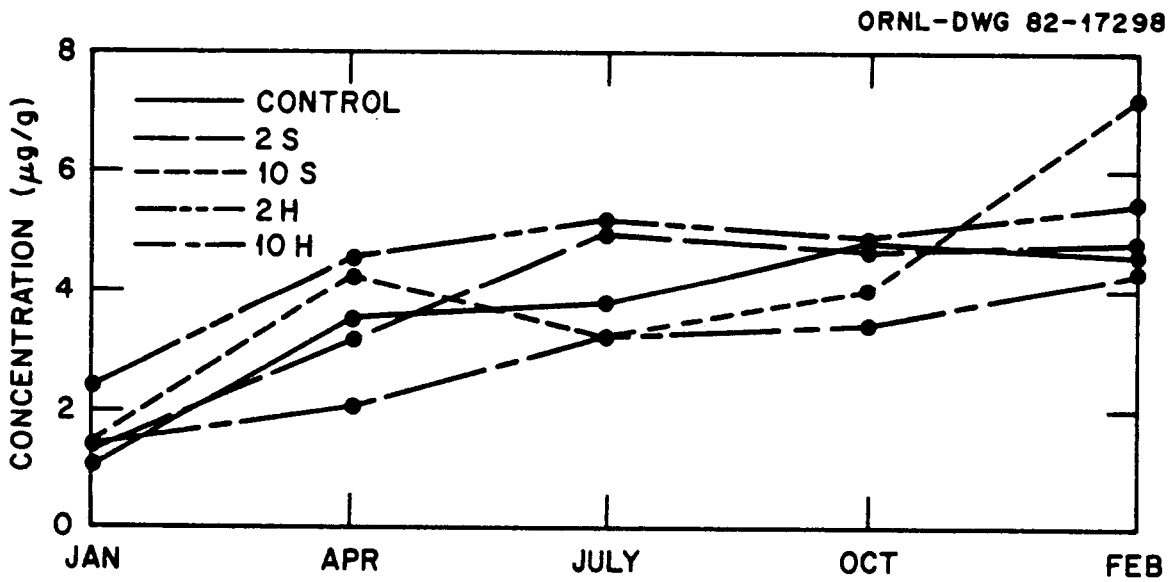


Figure 12. Quarterly soil phosphorus concentrations in the five treatments.

CHAPTER V

SUMMARY AND CONCLUSIONS

Acidic and neutral SO_4 solutions were applied to the forest floor to study the effects of increased acid deposition on decomposer arthropods and on decomposer regulation of P in the forest floor. Treatments consisted of ambient (no applications), two-times, and ten-times the annual inputs of SO_4 and H plus SO_4 to plots on Walker Branch Watershed. Arthropods were sampled monthly in the litter and soil. Soils were analyzed for available P and pH, Al, SO_4, and K.

Litter macroarthropods were affected by the SO_4 treatments, particularly the 10S where total densities (192 organisms/m^2) were significantly less (19%) than the control (237 organisms/m^2). The 2S treatment had slightly higher densities (242 organisms/m^2) than the control. Litter fungivores showed more pronounced treatment effects than total litter populations as densities in the 10S and both acid-sulfate treatments were significantly lower than the control. Litter predators were affected in the same manner as the total macroarthropod populations. Litter detritivores were unaffected by the treatments.

Long-term effects of the SO_4 additions were observed in the litter arthropod populations. Between June and October 1981, litter macroarthropod densities in the 10S treatment were significantly lower (35%) (163 organisms$\cdot m^{-2} \cdot$month) than the control (252 organisms $\cdot m^{-2} \cdot$ month). During the same period, macroarthropods in the 2S treatment were 19% higher (312 organisms $\cdot m^{-2} \cdot$ month) higher than

densities in the control. These long-term effects were most pronounced during late summer and autumn as soils, particularly on ridgetops, dry out. The combination of low precipitation and high evapotranspiration during this period could have a stressful effect on litter arthropods by drying out the litter.

Soil arthropods were affected by both the sulfate and acid-sulfate treatments. Overall, soil mesofauna densities in the 2S (42,800 organisms/m^2), 2H (41,500 organisms/m^2), and 10H (40,000 organisms/m^2) were significantly higher than the control (35,900 organisms/m^2). Densities in the control and 10S were not significantly different. Soil fungivores, predators, and detritivores were affected in the same manner as the total populations. The chronic treatment effects that were present in the litter did not occur in the soil.

Inspection of the data suggests that acute treatment effects were present when arthropod samples were collected soon (3-7 days) after a treatment application. Potential acute treatment effects were observed in replicate one, in June and in replicate two, in January. During June, the two-times treatments in replicate one had a positive effect upon soil arthropods as populations increased 54% in the 2S and 7% in the 2H compared to a 22% decline in the control. At the same time, soil arthropod populations in replicate one decreased 66% and 70% in the 10H and 10S plots. The treatment effects observed in replicate one during June were not present in replicate two which was sampled ten days after treatment applications. Acute effects of the ten-times treatments were noted during January in replicate two but the effects were not as pronounced as in June. Soil fungivores, predators, and

detritivores experienced apparent acute treatment effects similar to the effects observed in the total soil population.

This study is unable to quantitatively analyze for acute treatment effects because of the statistical design of the experiment. Thus, it is impossible to determine whether these observed acute effects were a result of the treatments or were caused by natural variability.

Several researchers have shown that small additions of K fertilizers increase populations of forest floor arthropods (Hryniuk 1962, Cary et al. 1971). Indeed, the 2S treatment had the greatest densities of the five treatments in both the litter and the soil. The acid-sulfate treatments, which contained only half of the K found in the corresponding SO_4 treatments, also had a positive effect on soil mesofauna. Litter macrofauna were unaffected by the acid-sulfate treatments. In the litter, the positive effects of K may have been offset by acidification of the litter environment caused by the H additions.

On the other hand, it has been shown that large additions of K fertilizers may produce a "shock effect" on forest floor invertebrates (Artemjeva and Gatilova 1975, Marshall 1977). Litter macrofauna populations in the 10S were significantly lower than the control, indicating a chronic effect of the large K applications. Soil mesofauna did not suffer chronic effects of the 10S treatments, possibly because of dilution of the K_2SO_4 by the litter. Acute effects of both ten-times treatments were observed in the soil while litter populations were adversely affected in the short-term by the 10S treatment only.

The effects of treatments on forest floor arthropods may have been caused by changes in microfloral populations. Litter respiration measurements in the control and 10S treatments revealed that CO_2 evolution was significantly lower (26%) in the 10S. These results indicate that the treatments indirectly affect forest floor arthropods by regulating microbial and fungal activity.

With the exception of K and SO_4, soil nutrient parameters were not clearly affected by the treatments. Soil K and SO_4 levels were in accordance with the quantity and chemical composition of the treatments. Soil K concentrations were greatest in the 10S treatment and decreased in the following order: 10H > 2S > 2H > C. These results support the argument that large doses of K have a negative effect on soil and litter arthropods since litter macrofauna densities were significantly less in the 10S treatment than in the control. Like K, SO_4 levels were highest in the ten-times treatments but there appeared to be no effect of SO_4 on soil or litter arthropods.

Because of the large buffering capacity of the forest floor litter, the treatment applications had no significant effect on soil pH and Al. Even after 18 months of treatments, only 31% of the H additions from a single 10H treatment application reached the mineral soil.

Available P, also, was unaffected by the treatment applications. Phosphorus was unaffected, possibly because the treatments did not affect soil arthropod densities to the extent where changes in soil nutrient levels could be observed. Perhaps, long term changes in soil arthropod densities must occur before there are any observable effects on soil nutrients.

Increased anthropogenic inputs of H had little or no effect on soil acidification processes on the study plots at Walker Branch Watershed. The large buffering capacity of the forest floor litter, which is renewed every fall, adsorbed most of the H so that very little reached the mineral soil. The H that did reach the soil was probably buffered by organic matter in the upper horizons. In addition, deciduous forest canopies have been shown to buffer atmospheric H inputs (Hoffman et al. 1980, Richter et al. 1982) so that the H that does reach the forest floor is of much lower concentration than the acid treatments that were applied. Because of the natural buffering capacity of deciduous forest ecosystems, the effects of increased H additions to these systems will have little, if any, adverse effect on forest floor arthropods.

On the other hand, the effects of increased additions of nonacidic SO_4 could have a severe impact on decomposer arthropods by affecting the osmotic potential of forest floor organisms. These compounds are much less reactive than acidic SO_4 and, hence, are only slightly buffered by the canopy and forest floor.

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APPENDICES

APPENDIX A

FOREST FLOOR ARTHROPOD DATA

Table A-1. Mean monthly litter macroarthropod densities (number/m^2) in the five treatments with 95% confidence intervals in parentheses. Values are backtransformed from natural logarithms of the raw data.

Date	Treatment				
	Control	2H	10H	2S	10S
December 1980	(200) 271 (364)	(235) 338 (476)	(170) 244 (347)	(177) 231 (302)	(205) 271 (357)
January 1981	(250) 340 (459)	(182) 217 (256)	(234) 331 (466)	(157) 226 (323)	(131) 230 (396)
March	(233) 281 (354)	(119) 161 (217)	(160) 215 (288)	(166) 210 (264)	(123) 200 (319)
April	(113) 156 (215)	(74) 142 (266)	(120) 199 (327)	(96) 144 (215)	(99) 150 (224)
May	(253) 356 (497)	(188) 245 (318)	(121) 211 (364)	(248) 359 (519)	(208) 301 (433)
June	(137) 238 (406)	(99) 176 (308)	(181) 312 (534)	(172) 294 (498)	(68) 119 (203)
July	(187) 318 (536)	(157) 251 (399)	(162) 254 (397)	(174) 301 (515)	(116) 212 (380)
August	(175) 268 (408)	(132) 263 (513)	(62) 99 (154)	(234) 357 (542)	(113) 170 (251)
September	(98) 143 (206)	(119) 210 (363)	(92) 158 (268)	(175) 257 (376)	(60) 112 (202)
October	(116) 164 (229)	(79) 127 (200)	(129) 183 (260)	(82) 153 (281)	(77) 122 (191)
December	(153) 210 (289)	(135) 215 (338)	(157) 213 (288)	(133) 184 (253)	(151) 198 (258)
January 1982	(178) 241 (324)	(180) 250 (347)	(151) 207 (282)	(180) 294 (475)	(156) 283 (507)
February	(79) 119 (178)	(61) 108 (187)	(109) 157 (223)	(99) 185 (211)	(79) 125 (193)

Table A-2. Mean monthly litter fungivore densities (number/m^2) in the five treatments with 95% confidence intervals in parentheses. Values are backtransformed from natural logarithms of the raw data.

Date	Treatment				
	Control	2H	10H	2S	10S
December 1980	(42) 72 (121)	(35) 74 (148)	(26) 41 (62)	(22) 45 (83)	(54) 75 (103)
January 1981	(61) 89 (128)	(25) 41 (64)	(18) 33 (56)	(15) 33 (66)	(28) 57 (108)
March	(53) 89 (146)	(18) 37 (67)	(31) 58 (102)	(33) 62 (111)	(12) 33 (74)
April	(53) 76 (109)	(22) 41 (71)	(30) 42 (57)	(16) 32 (58)	(29) 51 (83)
May	(28) 41 (58)	(15) 22 (31)	(18) 33 (56)	(24) 44 (74)	(22) 38 (62)
June	(57) 90 (139)	(18) 36 (65)	(38) 59 (89)	(33) 75 (157)	(14) 27 (48)
July	(26) 50 (88)	(30) 45 (69)	(16) 29 (49)	(37) 70 (125)	(18) 38 (71)
August	(51) 93 (154)	(9) 27 (63)	(8) 19 (39)	(32) 79 (180)	(21) 43 (79)
September	(36) 64 (109)	(30) 63 (127)	(26) 48 (85)	(80) 128 (203)	(17) 31 (52)
October	(34) 59 (97)	(22) 44 (81)	(39) 66 (108)	(25) 62 (136)	(17) 36 (68)
December	(23) 44 (79)	(18) 50 (119)	(29) 49 (77)	(21) 42 (75)	(14) 29 (52)
January 1982	(41) 71 (117)	(55) 97 (167)	(45) 67 (97)	(27) 68 (154)	(35) 70 (133)
February	(16) 30 (53)	(18) 39 (75)	(30) 56 (97)	(35) 53 (78)	(17) 32 (54)

Table A-3. Mean monthly litter predator densities (number/m^2) in the five treatments with 95% confidence intervals in parentheses. Values are backtransformed from natural logarithms of the raw data.

Date	Treatment				
	Control	2H	10H	2S	10S
December 1980	(24) 49 (92)	(53) 85 (133)	(28) 52 (93)	(48) 65 (87)	(32) 55 (92)
January 1981	(41) 69 (113)	(51) 63 (78)	(47) 64 (86)	(40) 66 (106)	(35) 56 (89)
March	(38) 53 (73)	(24) 34 (47)	(25) 35 (48)	(28) 40 (56)	(22) 32 (46)
April	(12) 20 (30)	(8) 20 (41)	(5) 12 (23)	(7) 15 (27)	(4) 12 (22)
May	(25) 40 (62)	(20) 31 (47)	(18) 32 (53)	(26) 38 (53)	(20) 33 (53)
June	(15) 29 (50)	(9) 22 (44)	(17) 32 (55)	(23) 39 (64)	(12) 22 (34)
July	(22) 36 (56)	(19) 32 (49)	(8) 19 (37)	(17) 34 (62)	(5) 14 (30)
August	(18) 36 (66)	(8) 16 (30)	(4) 10 (20)	(23) 43 (75)	(8) 20 (41)
September	(6) 13 (22)	(14) 31 (59)	(14) 27 (47)	(17) 33 (59)	(12) 26 (48)
October	(21) 35 (54)	(9) 21 (42)	(17) 35 (67)	(8) 17 (33)	(8) 15 (27)
December	(19) 36 (63)	(11) 23 (42)	(29) 46 (71)	(10) 20 (36)	(18) 39 (75)
January 1982	(23) 37 (55)	(16) 30 (52)	(33) 50 (75)	(30) 48 (76)	(30) 47 (73)
February	(3) 13 (29)	(4) 10 (19)	(12) 25 (47)	(9) 20 (39)	(12) 20 (32)

Table A-4. Mean monthly litter detritivore densities (number/m^2) in the five treatments with 95% confidence intervals in parentheses. Values are backtransformed from natural logarithms of the raw data.

Date	Treatment				
	Control	2H	10H	2S	10S
December 1980	(30) 48 (75)	(24) 53 (106)	(29) 51 (84)	(39) 54 (75)	(28) 55 (99)
January 1981	(47) 57 (70)	(30) 49 (78)	(62) 81 (106)	(60) 85 (117)	(36) 64 (108)
March	(39) 56 (77)	(35) 48 (64)	(36) 49 (66)	(16) 29 (47)	(33) 45 (61)
April	(7) 13 (21)	(14) 27 (47)	(10) 20 (33)	(14) 24 (37)	(9) 118 (31)
May	(98) 161 (260)	(51) 83 (133)	(48) 79 (125)	(69) 107 (62)	(72) 114 (179)
June	(30) 50 (80)	(26) 39 (56)	(31) 42 (57)	(41) 55 (73)	(19) 29 (43)
July	(34) 82 (183)	(50) 64 (83)	(58) 75 (97)	(25) 44 (73)	(30) 53 (90)
August	(29) 45 (67)	(29) 51 (85)	(22) 36 (57)	(41) 56 (74)	(33) 47 (67)
September	(17) 31 (51)	(31) 43 (59)	(13) 25 (44)	(30) 44 (61)	(15) 26 (43)
October	(17) 28 (42)	(7) 17 (34)	(19) 29 (43)	(19) 36 (61)	(20) 32 (50)
December	(43) 67 (102)	(54) 76 (104)	(46) 64 (87)	(52) 76 (109)	(48) 70 (99)
January 1982	(51) 77 (114)	(50) 72 (103)	(48) 67 (93)	(62) 94 (140)	(77) 128 (211)
February	(21) 36 (59)	(13) 29 (57)	(15) 29 (51)	(17) 34 (62)	(21) 33 (51)

Table A-5. Mean monthly litter grazer (Diplopoda) densities (number/10 m^2) in the five treatments with 95% confidence intervals in parentheses. Values are backtransformed from natural logarithms of the raw data.

Date	Treatment				
	Control	2H	10H	2S	10S
December 1980	(0) 0 (0)	(0) 9 (24)	(0) 14 (32)	(0) 9 (24)	(18) 72 (149)
January 1981	(0) 9 (24)	(0) 4 (15)	(5) 34 (71)	(0) 0 (0)	(0) 4 (15)
March	(0) 4 (15)	(0) 17 (40)	(0) 9 (24)	(0) 7 (24)	(0) 4 (15)
April	(0) 0 (0)	(0) 0 (0)	(0) 0 (0)	(0) 0 (0)	(0) 0 (0)
May	(0) 14 (32)	(0) 4 (15)	(0) 4 (15)	(0) 4 (15)	(0) 12 (32)
June	(5) 36 (78)	(0) 9 (24)	(0) 14 (32)	(0) 17 (40)	(0) 4 (15)
July	(30) 62 (102)	(0) 17 (40)	(0) 14 (32)	(0) 0 (0)	(14) 46 (87)
August	(9) 45 (93)	(0) 22 (48)	(4) 24 (48)	(0) 42 (124)	(0) 12 (32)
September	(0) 4 (15)	(0) 14 (39)	(0) 0 (0)	(0) 9 (24)	(0) 19 (47)
October	(0) 16 (45)	(0) 9 (24)	(0) 4 (15)	(0) 4 (15)	(0) 19 (47)
December	(0) 4 (15)	(0) 0 (0)	(8) 39 (78)	(0) 9 (24)	(0) 17 (40)
January 1982	(0) 9 (24)	(0) 0 (0)	(0) 0 (0)	(0) 14 (32)	(0) 24 (55)
February	(4) 24 (48)	(0) 12 (32)	(0) 0 (0)	(0) 12 (32)	(0) 31 (70)

Table A-6. Mean monthly soil arthropod densities (number/m^2) in the five treatments with 95% confidence intervals in parentheses. Values are backtransformed from natural logarithms of the raw data.

Date	Treatment														
	Control			2H			10H			2S			10S		
December 1980	(33,259)	49,696	(74,135)	(39,986)	49,530	(61,324)	(26,797)	38,604	(55,517)	(50,158)	60,292	(72,453)	(28,800)	34,560	(41,452)
January 1981	(29,238)	43,755	(65,357)	(24,182)	40,437	(67,394)	(28,196)	41,461	(60,856)	(40,846)	62,422	(95,255)	(46,055)	60,925	(80,543)
March	(20,972)	32,085	(48,948)	(39,840)	52,908	(70,211)	(31,584)	45,422	(65,228)	(31,320)	47,625	(72,284)	(26,274)	37,746	(54,131)
April	(17,153)	23,580	(32,346)	(22,743)	31,624	(43,896)	(20,564)	28,810	(40,283)	(23,916)	33,184	(45,969)	(19,388)	27,235	(38,177)
May	(12,899)	18,804	(27,310)	(14,525)	20,807	(29,712)	(26,552)	33,615	(42,521)	(17,081)	22,758	(30,267)	(15,975)	23,157	(33,467)
June	(13,382)	19,374	(27,951)	(16,970)	23,989	(33,825)	(15,842)	22,206	(31,046)	(21,242)	27,373	(35,232)	(8,250)	11,781	(16,736)
July	(7,281)	11,631	(18,411)	(7,011)	11,395	(18,336)	(13,031)	18,565	(26,360)	(18,620)	26,586	(37,874)	(6,997)	11,323	(18,143)
August	(29,990)	39,647	(52,360)	(31,192)	42,991	(59,181)	(18,372)	24,182	(31,779)	(27,380)	39,787	(57,714)	(22,353)	28,894	(37,306)
September	(31,865)	44,063	(60,857)	(50,630)	64,721	(82,696)	(34,214)	46,483	(63,088)	(33,660)	50,474	(75,564)	(35,794)	43,286	(52,324)
October	(43,315)	59,429	(81,467)	(36,502)	52,943	(76,688)	(49,434)	59,589	(71,809)	(40,818)	52,917	(68,559)	(49,350)	61,131	(75,696)
December	(46,535)	65,099	(90,987)	(67,744)	92,339	(125,799)	(62,242)	76,318	(93,552)	(27,068)	47,111	(81,721)	(40,922)	61,506	(92,317)
January 1982	(67,377)	78,210	(90,770)	(82,717)	96,197	(111,861)	(73,048)	85,375	(99,769)	(92,678)	105,367	(119,784)	(48,966)	68,089	(94,601)
February	(27,885)	43,794	(68,618)	(42,521)	56,834	(75,910)	(45,484)	61,992	(84,224)	(36,450)	54,195	(80,462)	(48,929)	59,444	(72,194)

Table A-7. Mean monthly soil fungivore densities (number/m^2) in the five treatments with 95% confidence intervals in parentheses. Values are backtransformed from natural logarithms of the raw data.

Date	Treatment				
	Control	2H	10H	2S	10S
December 1980	(21,912) 32,109 (46,942)	(26,345) 33,277 (41,998)	(17,661) 24,759 (34,630)	(31,689) 38,171 (45,959)	(17,194) 21,421 (26,657)
January 1981	(20,033) 30,232 (45,496)	(17,928) 29,090 (47,011)	(20,891) 30,359 (44,016)	(30,619) 46,163 (69,468)	(32,502) 42,636 (55,882)
March	(14,737) 22,248 (33,459)	(28,781) 38,575 (51,644)	(22,768) 32,662 (46,763)	(23,328) 35,288 (53,247)	(18,949) 27,083 (38,618)
April	(11,747) 16,201 (22,274)	(16,343) 22,379 (30,577)	(14,419) 20,167 (28,128)	(15,042) 20,799 (28,688)	(12,647) 18,318 (26,434)
May	(8,653) 12,484 (17,918)	(8,541) 12,467 (18,094)	(16,050) 20,583 (26,357)	(11,218) 14,925 (19,802)	(11,571) 16,732 (24,099)
June	(8,886) 12,611 (17,814)	(10,988) 15,417 (21,552)	(10,421) 14,345 (19,677)	(13,291) 17,118 (22,006)	(5,687) 8,053 (11,324)
July	(4,955) 7,738 (11,940)	(4,515) 7,005 (10,731)	(7,417) 10,458 (14,666)	(10,536) 15,132 (21,641)	(4,282) 6,641 (10,160)
August	(19,709) 26,008 (34,270)	(19,041) 25,923 (35,229)	(9,562) 13,795 (19,808)	(17,519) 25,219 (36,207)	(14,000) 18,430 (24,213)
September	(21,529) 29,517 (40,400)	(28,876) 36,482 (46,058)	(21,446) 28,762 (38,517)	(23,337) 34,355 (50,462)	(20,721) 25,445 (31,221)
October	(30,214) 41,133 (55,933)	(24,248) 34,342 (48,550)	(32,852) 39,764 (48,110)	(22,524) 30,285 (40,663)	(31,591) 39,481 (49,310)
December	(32,356) 45,474 (63,827)	(46,830) 63,362 (85,666)	(43,703) 53,776 (66,145)	(19,695) 33,414 (56,448)	(28,751) 42,000 (61,249)
January 1982	(49,409) 57,506 (66,917)	(58,850) 68,193 (79,007)	(51,483) 61,050 (72,377)	(62,490) 71,548 (81,908)	(35,572) 48,969 (67,340)
February	(20,568) 31,550 (48,255)	(29,155) 38,977 (52,052)	(32,876) 44,470 (60,090)	(25,046) 36,798 (53,956)	(31,142) 38,075 (46,527)

Table A-8. Mean monthly soil predator densities (number/m^2) in the five treatments with 95% confidence intervals in parentheses. Values are backtransformed from natural logarithms of the raw data.

Date	Treatment														
	Control			2H			10H			2S			10S		
December 1980	(8,061)	11,953	(17,612)	(7,250)	9,418	(12,191)	(3,992)	5,769	(8,247)	(10,161)	12,572	(15,972)	(3,832)	4,934	(6,316)
January 1981	(6,035)	8,311	(11,377)	(5,542)	8,744	(13,640)	(4,745)	6,788	(9,626)	(6,891)	9,906	(14,148)	(6,317)	9,102	(13,022)
March	(3,869)	5,547	(7,870)	(5,537)	7,837	(11,011)	(4,965)	6,802	(9,255)	(5,148)	7,509	(10,856)	(4,597)	6,469	(9,028)
April	(2,387)	3,316	(4,543)	(3,337)	4,911	(7,130)	(2,429)	3,731	(5,611)	(3,876)	5,343	(7,301)	(2,611)	3,753	(5,313)
May	(1,945)	2,833	(4,042)	(2,009)	2,984	(4,336)	(3,787)	4,864	(6,211)	(2,933)	3,946	(5,257)	(1,508)	2,357	(3,564)
June	(1,804)	2,645	(3,791)	(1,943)	3,015	(4,555)	(1,881)	2,740	(3,907)	(2,872)	4,009	(5,529)	(1,041)	1,544	(2,211)
July	(1,136)	1,883	(2,967)	(1,002)	1,745	(2,854)	(1,801)	2,681	(3,896)	(2,871)	4,047	(5,631)	(1,593)	2,367	(3,425)
August	(4,133)	5,705	(7,808)	(5,714)	8,004	(11,137)	(2,757)	3,719	(4,963)	(4,304)	6,117	(8,604)	(2,830)	3,680	(4,748)
September	(4,773)	6,505	(8,804)	(9,957)	14,184	(20,117)	(6,678)	8,825	(11,613)	(6,281)	8,832	(12,343)	(4,514)	5,948	(7,790)
October	(7,271)	9,550	(12,496)	(7,630)	10,867	(15,390)	(8,293)	10,777	(13,961)	(7,954)	10,288	(13,264)	(8,409)	10,470	(13,006)
December	(8,549)	11,522	(15,471)	(11,486)	14,969	(19,462)	(9,913)	12,783	(16,442)	(6,391)	9,820	(14,954)	(8,105)	11,401	(15,959)
January 1982	(10,756)	12,833	(15,294)	(14,221)	17,243	(20,886)	(10,973)	13,204	(15,869)	(15,418)	17,878	(20,717)	(7,969)	10,951	(14,990)
February	(5,440)	7,759	(10,979)	(6,638)	8,489	(10,819)	(7,460)	9,823	(12,886)	(6,354)	8,827	(12,191)	(7,134)	9,142	(11,677)

Table A-9. Mean monthly soil detritivore densities (number/m^2) in the five treatments with 95% confidence intervals in parentheses. Values are backtransformed from natural logarithms of the raw data.

Date	Treatment				
	Control	2H	10H	2S	10S
December 1980	(2,895) 3,974 (5,394)	(3,265) 4,223 (5,424)	(3,709) 5,043 (6,799)	(3,805) 4,872 (6,203)	(3,668) 5,087 (6,988)
January 1981	(1,943) 2,879 (4,172)	(1,979) 3,015 (4,482)	(2,430) 3,327 (4,498)	(3,725) 5,071 (6,844)	(2,750) 3,726 (4,993)
March	(1,680) 2,329 (3,171)	(2,947) 3,971 (5,299)	(3,369) 4,529 (6,037)	(1,866) 2,672 (3,752)	(2,511) 3,357 (4,440)
April	(2,490) 3,249 (4,200)	(1,863) 2,610 (3,593)	(2,142) 2,979 (4,081)	(2,346) 3,205 (4,322)	(2,097) 2,927 (4,022)
May	(1,949) 2,755 (3,825)	(1,758) 2,557 (3,637)	(2,543) 3,520 (4,809)	(1,841) 2,590 (3,578)	(1,652) 2,442 (3,522)
June	(2,391) 3,464 (4,932)	(2,337) 3,582 (5,372)	(2,104) 3,082 (4,426)	(2,939) 4,115 (5,692)	(849) 1,402 (2,179)
July	(1,163) 2,056 (3,426)	(893) 1,597 (2,654)	(3,340) 4,588 (6,241)	(3,041) 4,674 (7,059)	(1,298) 2,014 (3,014)
August	(4,036) 5,720 (8,029)	(4,568) 6,022 (7,893)	(1,662) 2,447 (3,516)	(5,397) 7,528 (10,428)	(3,157) 4,483 (6,290)
September	(4,745) 6,560 (9,003)	(6,076) 8,202 (11,015)	(4,732) 6,411 (8,628)	(4,215) 6,024 (8,526)	(5,732) 7,504 (9,780)
October	(5,305) 7,138 (9,549)	(4,174) 6,001 (8,540)	(4,719) 6,040 (7,694)	(4,270) 5,746 (7,677)	(5,246) 6,922 (9,085)
December	(4,926) 6,289 (7,993)	(6,552) 8,772 (11,690)	(6,146) 7,691 (9,595)	(3,110) 4,586 (6,664)	(5,875) 8,253 (11,572)
January 1982	(5,212) 6,467 (7,997)	(6,445) 8,112 (10,179)	(7,086) 8,528 (10,245)	(8,621) 10,869 (13,671)	(5,302) 7,038 (9,291)
February	(3,944) 5,475 (7,533)	(5,152) 6,434 (8,007)	(4,938) 6,362 (8,158)	(5,360) 7,353 (10,024)	(6,891) 8,459 (10,361)

Table A-10. Mean monthly soil litter grazer (Uropodina) densities (number/m^2) in the five treatments with 95% confidence intervals in parentheses. Values are backtransformed from natural logarithms of the raw data.

Date	Treatment				
	Control	2H	10H	2S	10S
December 1980	(0) 0 (0)	(0) 0 (0)	(0) 0 (0)	(0) 0 (0)	(0) 0 (0)
January 1981	(50) 139 (243)	(39) 155 (294)	(37) 144 (272)	(94) 261 (475)	(43) 144 (263)
March	(0) 14 (44)	(0) 38 (86)	(64) 179 (317)	(0) 81 (56)	(0) 38 (99)
April	(0) 25 (81)	(0) 0 (0)	(0) 0 (0)	(0) 0 (0)	(0) 56 (147)
May	(0) 21 (66)	(0) 40 (109)	(0) 67 (155)	(9) 77 (155)	(0) 48 (137)
June	(19) 98 (189)	(154) 373 (665)	(47) 161 (299)	(83) 200 (341)	(0) 57 (126)
July	(88) 248 (452)	(11) 94 (191)	(86) 242 (439)	(126) 301 (523)	(69) 181 (313)
August	(140) 322 (555)	(310) 543 (843)	(78) 199 (345)	(89) 238 (426)	(63) 190 (345)
September	(145) 305 (504)	(232) 435 (693)	(105) 239 (402)	(103) 235 (394)	(40) 128 (231)
October	(257) 430 (641)	(80) 172 (277)	(38) 109 (189)	(10) 82 (165)	(104) 203 (317)
December	(158) 335 (560)	(193) 341 (521)	(13) 67 (127)	(39) 111 (191)	(6) 52 (101)
January 1982	(0) 29 (72)	(51) 132 (226)	(0) 23 (59)	(120) 251 (410)	(32) 112 (204)
February	(0) 42 (96)	(61) 174 (309)	(0) 37 (84)	(14) 82 (158)	(25) 112 (214)

APPENDIX B

SOIL CHEMISTRY DATA

Table B-1. Mean monthly soil potassium concentrations (µg/g) in the five treatments with one standard error in parentheses.

Treatment	Date		$\bar{x}$
	April	October	
Control	79.1 (7.37)	87.7 (10.51)	83.4 (6.33)
2H	93.9 (12.53)	122.2 (7.74)	108.1 (7.87)
10H	128.7 (8.89)	159.2 (15.78)	144.0 (9.48)
2S	123.8 (14.18)	128.8 (9.25)	126.3 (8.26)
10S	166.0 (13.91)	213.6 (20.35)	189.8 (13.18)

Table B-2. Mean monthly soil sulfate-sulfur concentrations (µg/g) in the five treatments with one standard error in parentheses.

Treatment	Date				$\bar{x}$
	January	April	July	October	
Control	31.5 (1.18)	24.2 (2.04)	30.4 (3.41)	28.4 (1.19)	28.6 (1.13)
2H	39.0 (1.33)	33.1 (3.96)	40.6 (2.06)	38.9 (1.63)	37.9 (1.27)
10H	42.9 (2.13)	41.8 (4.28)	57.8 (5.82)	85.0 (8.06)	56.9 (3.84)
2S	40.4 (3.64)	31.3 (2.28)	42.0 (2.57)	46.2 (5.95)	40.0 (2.06)
10S	40.5 (2.29)	43.0 (3.12)	48.0 (3.74)	65.9 (5.82)	49.4 (2.48)

Table B-3. Mean monthly soil pH values in the five treatments with one standard error in parentheses.

Treatment	Date					$\bar{x}$
	January 1981	April	July	October	February 1982	
Control	4.7 (0.05)	4.4 (0.06)	4.0 (0.04)	4.0 (0.06)	3.8 (0.05)	4.2 (0.05)
2H	4.5 (0.12)	4.1 (0.11)	3.8 (0.04)	3.9 (0.05)	3.7 (0.08)	4.0 (0.06)
10H	4.5 (0.15)	4.5 (0.17)	4.4 (0.25)	4.1 (0.16)	3.6 (0.04)	4.2 (0.09)
2S	4.3 (0.12)	4.2 (0.06)	3.8 (0.03)	3.8 (0.06)	3.6 (0.09)	3.9 (0.05)
10S	4.6 (0.10)	4.3 (0.10)	4.0 (0.05)	3.9 (0.08)	3.8 (0.03)	4.1 (0.05)

Table B-4. Mean monthly soil aluminum concentrations (µg/g) in the five treatments with one standard error in parentheses.

Treatment	Date		$\bar{x}$
	April	October	
Control	92.7 (9.04)	125.5 (15.65)	109.1 (9.57)
2H	136.2 (26.45)	141.0 (12.18)	138.6 (14.18)
10H	48.6 (16.22)	121.7 (31.79)	85.1 (19.29)
2S	77.1 (11.01)	186.0 (20.05)	131.6 (16.73)
10S	115.7 (20.64)	159.2 (22.02)	137.5 (15.51)

Table B-5. Mean monthly soil phosphorus concentrations (µg/g) in the five treatments with one standard error in parentheses.

Treatment	Date					$\bar{x}$
	January 1981	April	July	October	February 1982	
Control	1.1 (0.16)	3.5 (0.30)	3.9 (0.50)	4.8 (0.59)	4.8 (0.44)	3.6 (0.27)
2H	2.3 (0.51)	4.5 (0.74)	5.1 (0.29)	4.9 (0.54)	5.4 (0.47)	4.4 (0.28)
10H	1.5 (0.19)	2.0 (0.41)	3.2 (0.42)	3.5 (0.43)	4.2 (0.51)	2.9 (0.22)
2S	1.3 (0.25)	3.1 (0.27)	5.0 (0.32)	4.7 (0.57)	4.8 (0.47)	3.8 (0.26)
10S	1.4 (0.27)	4.2 (0.71)	3.2 (0.49)	4.0 (0.32)	7.2 (0.75)	4.0 (0.36)

VITA

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