This is to certify that the

thesis entitled

The Effects of Simulated Acid Precipitation on Regeneration and Soils in the Jack Pine-Grayling Sand Ecosystem

presented by

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has been accepted towards fulfillment of the requirements for

Master of Science degree in Forestry

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Major professor

Date May 10, 1983

THE EFFECTS OF SIMULATED ACID PRECIPITATION ON REGENERATION AND SOILS IN THE JACK PINE-GRAYLING SAND ECOSYSTEM

By

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A THESIS

Submitted to
Michigan State University
in partial fulfillment of the requirements
for the degree of

MASTER OF SCIENCE

Department of Forestry

1983

ABSTRACT

THE EFFECTS OF SIMULATED ACID PRECIPITATION
ON REGENERATION AND SOILS IN THE
JACK PINE-GRAYLING SAND ECOSYSTEM

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The occurrence of precipitation with an average pH of 4.5 in northern lower Michigan suggested a study of acid rain impact on the jack pine-Grayling sand ecosystem. A greenhouse experiment examined effects of simulated acid precipitation on jack pine regeneration and the Grayling sand growth medium. Treatments consisted of stock rain acidified to pH levels 4.7, 4.0, 3.0, 2.5, and 2.0. Soil acidification and depletion of exchangeable cations were restricted to pH 2.5 or below. Jack pine germination and survival were reduced at pH 2.5 or below. Seedling top weight increased, but root weight decreased, at pH 2.5. As rain pH decreased from 4.7 to 2.5, seedling nutrient concentrations increased, except phosphorus and magnesium which decreased. While pH levels approximating those of precipitation in northern lower Michigan did not adversely affect jack pine regeneration or Grayling soil properties during the eleven-week study, long term effects require further study.

ACKNOWLEDGMENTS

I would like to thank Dr. James B. Hart, who as my major professor provided advice, guidance, and support throughout the length of this study. I gratefully acknowledge Dr. Thomas M. Burton and Dr. Donald I. Dickmann for serving on my examination committee and for their review of this thesis. Thanks also go to Dr. Douglas G. Sprugel, who provided inspiration and advice during the initial stages of this study, and to Dr. James W. Hanover for providing the jack pine seed used in this study.

I am especially indebted to Dr. Phu Van Nguyen for his invaluable assistance during all phases of this research. His unfailing willingness to share his scientific and technical expertise was greatly appreciated.

I would also like to extend thanks to the following people for their willing contributions. To Bruce Birr, USFS, for his technical assistance in soil and plant analysis, and for his jovial good humor. To Roy Prentice, MSU Tree Research Center, for his help, advice, and interest during implementation and execution of the greenhouse study. To Robert Cheeney for assisting in setting up the greenhouse experiment, and for aid at various times of need. To Jeannine Freyman and Melissa VanBlargan for their assistance during the often tedious soil and plant analytical phase of this research. To Dave Cleland and Ven Bosman, USFS, for their assistance and cooperation in the location of the study site in the Mio Ranger District of the Huron-Manistee National Forest.

I would like to express my gratitude to my parents for their encouragement and assistance at all times, and for instilling in me the determination to carry out projects to completion. Finally, I thank my wife, Doreen, for her untiring encouragement, patience, and willing assistance throughout the duration of this labor.

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Chapter I

INTRODUCTION

Over the last thirty years, widespread increase in the acidity of precipitation has occurred in the Eastern United States, Canada, and Europe (Bormann, 1974; Cogbill and Likens, 1974; Oden, 1976). Annual precipitation acidity in the Northeastern United States currently averages around pH 4.0 with values as low as 2.1 recorded for individual precipitation events (Bormann, 1974; Likens and Bormann, 1974). While pure water should equilibrate with ambient levels of carbon dioxide to produce an acidity of approximately pH 5.6, the presence of naturally occurring sulfur compounds, gaseous and aerosal organic acids, and basic inorganic particles in the atmosphere suggest a range of natural rain pH from 5.0 to 8.0 (Likens and Bormann, 1974; Norton, 1977). The recent decrease in precipitation pH is considered to be largely the result of combustion of fossil fuels leading to increased emission of acid-forming sulfur and nitrogen oxides (Galloway et al., 1976; Likens, 1976; Likens et al., 1976; Likens et al., 1979).

The presence throughout the Northeastern United States of rainfall that is significantly more acidic than normal suggests the possibility of regional impacts on the ecologic structure, function, and productivity of forest ecosystems distant from the sources of pollutant emission (Armentano and Loucks, 1980). Specific life forms, life stages, or life processes of forest vegetation may be differentially susceptible to inputs of injurious substances in precipitation (Galloway et al., 1978). Germination, flowering, fertilization, and breaking of dormancy are all potentially sensitive stages (Likens, 1976). Different soil types may also have differing susceptibilities to the input of acid precipitation (Malmer, 1976).

The average precipitation pH in northern lower Michigan is between 4.4 and 4.6, well below the theoretical lower pH level of natural rainfall (Semonin et al., 1981). This acid rain impinges on the infertile Grayling sand soils, which are occupied by jack pine (*Pinus banksiana*) forests throughout northern lower Michigan. Based on total buffering capacity and management, the Grayling and similar soils in northern lower Michigan are considered to be potentially sensitive to acidic inputs in precipitation (Altshuller and McBean, 1980). The combination of chronically acidic precipitation and vulnerable soils suggests that the jack pine ecosystem may be susceptible to adverse effects related to acid precipitation.

The regeneration phase of jack pine is perhaps the critical stage both in the life cycle of the species and to the overall ecosystem integrity. Because jack pine is important in this region as a pulpwood species and as nesting habitat for the endangered Kirtland's warbler, much research has been devoted to devising a workable silvicultural system for successful regeneration of jack pine stands (Abrams and Dickmann, 1982). Periodic wildfires also initiate natural regeneration of the species.

Jack pine seeds, deposited on poorly buffered mineral soil seedbeds following fire or logging, are highly dependent on rainfall for the moisture needed during germination and establishment. Acidic precipitation, falling on newly dispersed seeds, germinating seeds, or young seedlings, has the potential to drastically affect the successful completion of the jack pine regeneration cycle. Acid precipitation impinging on the Grayling soils may also modify soil properties important to the establishment of jack pine seedlings. Alteration in regeneration success induced by precipitation acidity would have implications for future management of jack pine on Grayling soils in northern lower Michigan.

The objective of this study was to determine in a greenhouse the impact of simulated acid precipitation on the early stages of jack pine regeneration. Germination, seedling establishment, and subsequent seedling growth and nutrient status were examined over one growing season. In conjunction, the effects of simulated acid precipitation on the chemical properties of the Grayling sand growth medium were determined. The focus of this study was therefore the relationship between the acid precipitation, seedling, and soil components of the jack pine-Grayling sand ecosystem.

Chapter II

LITERATURE REVIEW: EFFECTS OF ACID PRECIPITATION ON REGENERATION OF FOREST TREES

Regeneration is a crucial stage at which individual trees are vulnerable to adverse environmental conditions. Acid precipitation represents an additional environmental stress on the early life stages of forest trees. This review examines the influence of precipitation acidity on regeneration of forest trees from the aspects of germination, foliar injury, nutrient assimilation, and growth and productivity.

GERMINATION

Seed germination is potentially the most sensitive stage during the life of an individual tree that could be affected by acid precipitation. A resting, viable seed must absorb water before it is able to begin the digestive, translocatory, respiratory, and assimilatory processes necessary for embryo growth and seed germination (Schopmeyer, 1974). Any one of these processes could be affected by impingement of acid precipitation on the seed or its germinating medium.

Research in Norway demonstrated that germination and early seedling growth of forest tree species were affected by treatment of the germinating medium with simulated acid precipitation (Abrahamsen et al., 1975). They studied the germination and establishment of Norway spruce (*Picea abies*) and scotch pine (*Pinus sylvestris*) on mineral soil artificially acidified by leaching with dilute sulfuric acid solutions. While scotch pine exhibited no negative effects at soil pH levels of 4.0 to 4.6, significant effects of soil pH on both germination and establishment of spruce were reported. Eighty percent of the spruce seeds did not develop normal seedlings at soil pH 3.8, with germination and establishment also being reduced at soil pH levels below 4.2.

Irrigation of five species of forest tree seeds in various media with acidified solutions also affected germination and establishment in a study in New York (Roman and Raynal, 1980). The five species were irrigated in plastic trays with dilute sulfuric acid solutions. Seed germination of white pine (*Pinus strobus*) was promoted by pH levels of 2.4 and 3.0; sugar maple (*Acer saccharum*) seed germination was not influenced by reaction of the medium; while red maple (*Acer rubrum*) and yellow birch (*Betula allegheniensis*) displayed decreased germination at pH 3 as compared to the control of pH 5.6. Eastern hemlock (*Tsuga canadensis*) germination was reduced only at pH 2.4.

Seeds of eleven woody species were germinated at simulated precipitation pH levels 3, 3.5, 4, and 5.6 in a study by Lee and Weber (1979). Simulated rain consisted of a stock solution containing Ca++, NH4+, Na+, K+, Mg++, NO3-,

SO_4^{--}, and Cl^- acidified with sulfuric acid. Seeds were planted in a mixture of clay loam, sand, and gravel. Simulated rain at pH levels of 4, 3.5, and 3 inhibited germination of staghorn sumac (Rhus typhina) but stimulated germination of eastern white pine, eastern red cedar (Juniperus virginiana) and yellow birch as compared to a control of pH 5.6. No significant effects on the germination of Douglas fir (Pseudotsuga menziesii), flowering dogwood (Cornus florida), red alder (Alnus rubra), shagbark hickory (Carya ovata), sugar maple, American beech (Fagus grandifolia), or tulip poplar (Liriodendron tulipifera) were noted.

Effects of buffered solutions on seed germination and early seedling growth of four coniferous species were studied by Abougendia and Redmann (1979). Citric acid-potassium hydrogen phosphate buffers at pH 2.2 and 3, with a distilled water control of pH 6.5, were applied to seeds placed on filter papers in glass petri dishes. Germination of lodgepole pine (Pinus contorta) at the pH 2.2 and 3 levels was higher than that at the distilled water reference pH of 6.5. Germination of white spruce (Picea glauca) and jack pine at the pH 2.2 level was equal to germination at the reference, while that of black spruce (Picea mariana) was significantly lower. Germination of both spruces at pH 3 was not significantly different from that of the reference. Jack pine germination at pH 3 showed a small but significant increase over the reference.

The effect of acid treatment on germination varied according to degree of acidity, type of substrate, chemical composition of germinating solution, and species. Germination of most species was not affected within the range of pH values tested. The tolerance of jack pine seed to extreme acidity during germination is of importance in the present study. The increase in germination at pH 3 suggests that acid precipitation may result in an increased germination success for jack pine seed.

The nature of the medium in which the seeds were germinated influenced the effect of acidity. Yellow birch seed germination was decreased by the unbuffered sulfuric acid solution treatments in plastic culture trays, but increased in a buffered medium of soil material treated with simulated precipitation. In the jack pine-Grayling sand ecosystem, the interaction of acid precipitation with the soil may modify the direct effect of precipitation acidity on jack pine germination.

DIRECT FOLIAR INJURY

The successfully germinated seed and developing jack pine seedling are also exposed to effects of acid precipitation. One mechanism suggested that would affect these early life stages is direct foliar injury from mineral acids in precipitation. Acid precipitation-induced foliar injury, by reducing photosynthetic capability, creating courts for pathogen invasion, and increasing nutrient loss, potentially decreases the vigor of developing jack pine seedlings.

Wood and Bormann (1974) treated yellow birch with an aqueous mist of distilled water adjusted to pH levels of 4.7, 4, 3.3, 3, and 2.3 with sulfuric acid. Tissue damage appeared on six-week-old seedlings subjected to eleven weeks of intermittent spraying with mists of pH 3 and 2.3. Damage symptoms included pits and necrotic spots .5 to 5 mm in diameter on leaves. Curling and shortening of leaves were observed at pH levels 3 and 2.3.

Roman and Raynal (1980) treated yellow birch seedlings with solutions acidified by addition of a mixture of sulfuric and nitric acids to pH 2, 3, 4, and 5.6. All yellow birch seedlings treated with pH 2 had visible leaf damage, but seedlings exposed to pH 3 and less acidic treatments did not. Similarly, Abrahamsen et al. (1976) observed foliar lesions, predominantly necrotic spots, on downy birch (_Betula pubescens_) at pH 2 and 2.5 on field plots treated with simulated precipitation acidified with sulfuric acid.

Exposure of six clones of hybrid poplar (_Populus_ spp.) to simulated sulfuric acid rain at pH levels from 2.7 to 3.4 produced lesions of several types (Evans et al., 1978). At pH 2.7, up to ten percent of the leaf area was injured after five daily exposures of six minutes each. Injury decreased to about one percent at pH 3.4, while trees on control plots sprayed with a rain of pH 5.7 did not develop lesions. On injured leaves, lesions were accompanied by cell proliferation and enlargement of adjacent parenchyma cells.

Necrotic spots were observed on one-year-old sugar maple by Wood and Bormann (1975) after seven treatments over a fourteen week period with simulated acid rain at pH levels of 3 and below. Similarly, in a study by Roman and Raynal (1980), application of simulated rain acidified with a mixture of sulfuric and nitric acids produced foliar damage on sugar maple at pH levels 3 and 2. Thirty-five percent of the seedlings were damaged at pH 3 with one hundred percent of the seedlings displaying damage at pH 2. Necrotic spots and holes in leaves characterized the injury with damage especially noticeable along leaf margins and tips. Treatments with rain at pH 4 and 5.6 did not produce foliar injury on sugar maple seedlings.

Shriner et al. (1974) reported that willow oak (Quercus phellos) developed necrotic zones on foliage when exposed to simulated sulfuric acid rain of pH 3.2 or lower. In a study by Evans and Curry (1979), however, leaves of clonal pin oak (Quercus palustris) were judged insensitive to simulated sulfuric acid rain since less than one percent of the entire leaf area was injured after plants were exposed to rain of pH 2.5.

Direct injury to conifers exposed to simulated acid rain has also been reported. Field exposure of white pine for two months to simulated rain adjusted to pH 3.2 at the rate of two to four cm per week caused browning of all second-year needles (Shriner et al., 1974). White pine was also the subject of a study by Wood and Bormann (1977) in which seedlings were exposed to one weekly six-hour artificial rain for twenty weeks. Treatments consisted of pH levels 5.6, 4, 3.3, 3, and 2.3, adjusted by the addition of sulfuric, nitric, and hydrochloric acids. Necrotic needle segments up to two mm long appeared on all seedlings exposed to pH 2.3 rains. In contrast to the findings of Shriner et al. (1974), seedlings treated at higher rain pH levels displayed no visible injury.

A single simulated sulfuric acid rain shower of forty minutes duration induced random needle injury on field grown loblolly pine (_Pinus taeda_) seedlings at pH 1.9 to 2.7 (Shriner et al., 1974). Needle symptoms consisted of light yellow bands with central brown spots. Necrotic spots were also produced on scotch pine at pH 2 and 2.5 on field plots treated with simulated precipitation acidified with sulfuric acid (Abrahamsen et al., 1976). In another study, treatment of developing candles and buds with sulfuric acid solutions of pH 1.7 to 2.7 induced either candle necrosis or needle necrosis and chlorosis in field grown scotch pine (Wood and Pennypacker, 1976). Sulfuric acid solutions of pH 3.7 and higher had no effects.

Evans and Curry (1979) suggested that coniferous foliage was rather insensitive to simulated acid rain when compared to deciduous tree foliage. Horntvedt et al. (1980) reported that irrigation of field plots and lysimeters with sulfuric acid acidified groundwater produced necrotic spots on herbaceous plants and birch at pH levels less than 3, but no visible injuries were seen on Norway spruce or lodgepole pine. No effects on surficial wax covering of conifer needles exposed to rain pH levels down to 2.5 were detected by scanning electron microscopy. Coniferous species, such as the jack pine, could thus be less susceptible to growth reduction or nutrient loss from leaves associated with foliar injuries induced by treatment with acid rain.

The "threshold" pH level of simulated acid precipitation that produced observable injury to most plant species was near 3, while no direct foliar injury to plants was reported at pH levels of 4 or above. Beside species susceptibility, the stage of cuticle development and the spray or mist intensity were important factors determining the pH value of precipitation at which injury occurred (Abrahamsen et al., 1976).

Shriner (1980) stated that reports of threshold pH levels producing physical injury in greenhouse experiments must be interpreted with caution, because the growth and morphology of foliage in a greenhouse are often atypical of field conditions. Shriner found that the cuticle plus epicuticular wax layer on field-grown loblolly pine was as much as seventy-five times thicker than that on needles of the same age grown under greenhouse conditions. This suggests that seedlings grown in a greenhouse are much more sensitive to direct injurious effects from acidity than they would be under field conditions.

Another factor to be considered is the ratio of sulfuric to nitric acid in the simulated precipitation, as well as the presence or absence of other toxic or nutrient components. Treatment with sulfuric acid mists composed only of distilled water and acid produced more injurious effects than simulated rains with chemical make-up similar to actual precipitation.

FOLIAR NUTRIENT CONCENTRATION

Nutrient concentration in seedlings serves as a measure of nutrient assimilation. As such, it may indicate changes in nutritional status of seedlings mediated by acid precipitation. Indirectly, acid precipitation affects soil nutrient availability by altering soil pH. The availability of nutrients such as boron, copper, manganese, and iron is increased when soil acidity is increased, while the availability of nitrogen, sulfur, phosphorus, potassium, calcium, and magnesium is reduced (Pritchett, 1979). Solubility and uptake of aluminum and heavy metals also increases in acidified soils. Nutrients added in acid precipitation, such as nitrogen and sulfur, result in altered nutrient assimilation and foliar nutrient concentration. The infertility of the Grayling sand makes the effects of acid precipitation on nutrient relations especially important in the regeneration of jack pine.

Overrein (1980) reported that foliage of scotch pine treated with simulated acid precipitation displayed temporarily increased nitrogen concentration during the first two years of treatment, followed by three years of no difference in nitrogen concentration between acid and control treatments.

Tveite (1980a) reported on foliar nutrient concentrations of three species of conifers in field experiments established on deep, sandy soils derived from glaciofluvial sediments in Norway. After three to six years of treatment with groundwater acidified with sulfuric acid, lodgepole pine saplings exhibited elevated phosphorus, manganese, and iron concentrations in current year needles at pH level 3 as compared to a control pH level of 5.6. Previous year needles had increased concentrations of phosphorus, potassium, manganese, iron, aluminum, and sulfur at pH 3 as compared to the control. Norway spruce saplings exhibited increased sulfur and sulfate concentrations at pH levels 3 and 2.5 for both needle ages, with decreased magnesium concentrations and increased aluminum concentrations in current year needles at pH 2.5. Scotch pine saplings had elevated sulfur and sulfate concentrations at pH 2 for both needle ages. Increased sulfate and lowered magnesium concentrations were found in current year needles at the pH 2.5 treatment. Tveite (1980a) suggested that low magnesium concentrations might indicate the development of magnesium deficiencies in these studies.

Wood and Bormann (1977), in a study of effects of simulated acid rain on nutrient relations of white pine, found that organic nitrogen levels in foliage were lowest at pH 5.6 and highest at pH 2.3. Foliar contents of potassium, magnesium, and calcium were constant between pH levels 5.6 and 3, with decreased foliar contents at pH 2.3. These declines were thought to be the result of low levels of available cations in soils at the pH 2.3 treatment level or due to major increases in foliar leaching expected at this treatment level.

This review indicated that inputs of hydrogen ions, nitrogen, and sulfur in simulated acid precipitation are likely to affect uptake and concentration of nutrients in jack pine seedlings grown on Grayling sand. From this aspect, seedling nutrient concentrations may also be indicative of alteration in soil chemistry occasioned by the influx of acid precipitation. Changes in nutrient uptake induced by acid precipitation may result in altered growth and productivity of jack pine seedlings.

GROWTH AND PRODUCTIVITY

Alteration in growth and productivity of the jack pine seedling is the postulated ultimate effect of acid precipitation on this early life stage due to the combined impacts of physical injury and altered nutrient uptake. An increase or decrease in vigor of jack pine seedlings caused by input of acid precipitation would be a major impact on regeneration in the jack pine-Grayling sand ecosystem.

One year old Aleppo pine (*Pinus halepensis*) seedlings grown in a mixture composed of equal parts of calcareous soil, sand, and manure were irrigated for one growing season with deionized water acidified with sulfuric acid. Growth of seedlings treated at pH level 3.1 was suppressed by eight percent below that of seedlings grown with unacidified deionized water with pH of 5.1 (Matziris and Nakos, 1977).

Similarly, Dochinger (1976) concluded that treatments with acid solutions retarded growth and limited survival of red maple, white ash (*Fraxinus americana*), sweet gum (*Liquidambar styraciflua*), tulip poplar, sycamore (*Platanus occidentalis*), cottonwood (*Populus deltoides*), and American elm (*Ulmus americana*). These results were from a fifteen week study in which one year old seedlings potted in river sand or peat received soil applications of solutions with pH levels 3, 5, or 7. Adverse effects were most in sand medium that received a treatment of pH 3. Shoot growth and seedling survival were higher at higher pH levels and significantly better for plants potted in peat soil.

Acidity of artificial sulfuric acid precipitation did not significantly affect growth of yellow birch seedlings grown in loam soil until pH of misting solutions reached values less than 3 (Wood and Bormann, 1974). Total plant weight, total leaf weight, and stem length of six week old yellow birch seedlings were significantly reduced after eleven weeks of treatment at pH 2.3.

Lee and Weber (1979), in a study on the seedling growth of eleven woody species, concluded that no species had significant inhibition of top growth by simulated sulfuric acid rain also containing a neutral mixture of cations and anions. Seedlings were grown in soil composed of a mixture of clay loam, sand, and gravel. Top growth of Douglas fir and shagbark hickory was stimulated, while growth of sugar maple, flowering dogwood, red alder, white pine, red cedar, staghorn sumac, American beech, yellow birch, and tulip poplar was unaffected by simulated rain as acid as pH 3.

Roman and Raynal (1980) reported that sugar maple seedlings treated at pH 3 exhibited greater leaf weight, total weight, and height after nine weeks than those treated at pH 4 or 5.6. The effect of treatment with pH 2 was a drastic reduction in leaf weight, total weight, and height as compared to other treatments. Seedlings were grown in pots containing a mixture of loamy sand and silica sand. Chemical composition of the treatment solution was based on that of throughfall of a mixed deciduous forest, and was acidified with a mixture of sulfuric and nitric acids.

In the same study, yellow birch seedlings were grown at simulated rain pH levels of 2, 3, 4, and 5.6. Analysis of final seedling weights indicated that growth at the pH 2 treatment was significantly less than growth at the pH 4 and 5.6 treatments. The pH 2 treatment seedlings averaged less than half as heavy as those grown at the pH 5.6 treatment (Roman and Raynal, 1980).

Wood and Bormann (1977) observed increased short-term productivity of white pine seedlings as pH of artificial rain decreased. Rains were solutions of sulfuric, nitric, and hydrochloric acids, and seedlings were grown in sandy loam soil. Total plant weight and total needle weight were significantly lower at pH 5.6 than at all greater acidities, and all growth measures were significantly higher at pH 2.3 than at all other levels. Foliar damage, observed at pH 2.3, was not associated with decline in seedling productivity. High seedling productivity at pH 2.3 was ascribed to the fertilizing effect of the nitrate component of the nitric acid in the rain. Ogner (1980) reported that Norway spruce cuttings irrigated with 200 millimeters per month artificial rain acidified with sulfuric acid and grown over a three-year experimental period exhibited increased dry matter production at pH 2.5 as compared to pH 5.4.

Results of these growth and productivity studies indicated a relationship between soil properties, precipitation chemical properties, and seedling growth. In general, decreased seedling growth was associated with poorly buffered soil, sulfuric acid solution treatments, or extreme pH levels below 2.3 for simulated acid precipitation. Growth of seedlings on soils with higher buffering capacities was not inhibited. Productivity of seedlings treated with simulated acid precipitation containing nitric acid generally increased unless pH level was below 2.3.

Positive growth effects on seedlings were attributed to nitrogen fertilizer effects. Such increases, though were thought to be temporary, as depletion of nutrient cations in soil and from foliage through accelerated leaching might eventually retard growth (Wood and Bormann, 1977). Experiments on the effect of artificial acidification on forest growth under field conditions have shown increased growth the first few years in the acidified plots, followed eventually by decreased growth (Overrein, 1980; Tveite, 1980b).

Short-term growth results from acidification experiments must therefore be treated with caution, due to the positive fertilizer effects of nutrients in precipitation. Long-term effects must be viewed as a balance, or imbalance, between the beneficial and detrimental effects associated with acid precipitation. The short term effects of acid precipitation on growth of jack pine seedlings are important from the aspect that precipitation-induced alteration in growth could influence successful establishment and subsequent survival of seedlings.

Chapter III

LITERATURE REVIEW: EFFECTS OF ACID PRECIPITATION ON FOREST SOILS

The postulated direct effect of the increased input of acid precipitation on soils is soil acidification (Bache, 1978a). Soil acidification processes occur naturally during soil formation as a result of inputs of carbonated water, mineral acids produced during nitrification, and organic acids produced from the decomposition of plant residues (Frink and Voigt, 1977; Bache, 1978a). The increased deposition of acids in precipitation suggests that accelerated soil acidification will occur. Concern exists because many currently stressed soils are remote and forested, and do not routinely receive fertilizers or lime as in the case of agricultural soils (Alexander, 1980). The Grayling sand of northern lower Michigan is a prime example of a remote, forested soil where effects of acid precipitation may become apparent through alteration in soil properties.

The impact of acid precipitation on the chemical properties of soils is relevant to long-term soil productivity. Hypothesized and experimentally tested effects include accelerated acidification, increased leaching of cations, and increased weathering of minerals. Soil anion adsorption modifies the extent of change in soil leaching processes. Input of acid precipitation is believed to increase the solubility of aluminum and heavy metals, leading to toxic effects on plants. Increased deposition of nitrogen in acid precipitation directly influences nitrogen cycling, resulting in indirect effects on forest growth by altering soil properties and uptake of other nutrients. These effects are modified by the inherent susceptibility of the soil to accelerated acidification due to the input of acid precipitation.

SOIL SUSCEPTIBILITY

The susceptibility of soils to effects from acid precipitation is determined by inherent soil chemical and physical properties, precipitation chemistry, and the interaction between these factors. Soil properties determining susceptibility are functions of mineralogy, organic matter content, and the relative development of the soil. These properties determine cation exchange capacity and base saturation, which taken together determine the soil buffering capacity. Soil texture and structure become important from the aspect of reaction of the soil with percolating water from precipitation.

Since the cation exchange capacity is determined by the clay and organic matter content of a soil, it is from this aspect that soil type has the most influence on the rate of soil acidification (Malmer, 1976; McFee et al., 1977; Bache, 1978a). Change in soil acidity in response to acid precipitation is inversely related to buffering capacity, being greatest in poorly buffered soils (Bache, 1978b). Soils with high cation exchange capacity and high base saturation are regarded as being those most resistant to acidifying processes, owing to high buffering capacity.

Soil texture and structure play a role in determining susceptibility of soil to acid precipitation by influencing the extent to which percolating precipitation contacts soil particles and reacts with the soil (Bache, 1978a). Soils with high macroporosity, such as coarse, sandy soils and soils with well aggregated topsoil, allow water to flow uniformly through them. This permits reaction to equilibrium and soil acidification occurs when reaction products are leached out. Soils with poorly developed structure and fine textured soils with uniform particle size have low macroporosity and drainage water travels down relatively few structural cracks or root channels. Incoming water will not react completely with the soil and acidification of the bulk of the soil is minimized (Bache, 1978b). The sand texture of the Grayling soils encourages uniform percolation of rain and leaching of mobilized cations, and thus increases its susceptibility to acidification associated with the input of acid precipitation.

The chemical nature of the precipitation influences its impact on soils. Significant inputs of cations such as Na^+, K^+, Ca^+, and Mg^+ occur along with acids in precipitation.

If the ratio of base cations to hydrogen ions in precipitation is the same as in the soil solution, no net ion exchange will occur. If this ratio is higher in precipitation, soil pH will increase. If lower, base cations in the soil will be replaced and acidification will take place (Wiklander, 1978b). Salts in precipitation may thus diminish the adverse effects of acid precipitation on soils low in buffering capacity.

Generalizations on the type of soils susceptible to acid precipitation are based on those physical and chemical properties of the soil which allow acidification to proceed rapidly in response to small increases in hydrogen ion deposition from precipitation. Soils considered susceptible to accelerated acidification are generally described as slightly acid, sandy soils with cation exchange capacity less than 6.2 meq per 100 grams of soil and low buffering capacity. In soils with these properties, relatively little acidification may lead to striking loss in productivity (Tamm, 1977; Bache, 1978b; Glass et al., 1982). Soils transitional between alfisols and spodosols along with entisols, ultisols, and coarse-textured inceptisols and arenosols are potentially susceptible to accelerated acidification (Malmer, 1976; Petersen, 1978).

The Grayling soils, classified as entisols, are sand throughout and are low in organic matter and clay. The resulting low cation exchange capacity (3-5 meq per 100 gm) and low base saturation (<25%) make these soils very low in buffering capacity. The pervious nature of these soils allows rapid leaching loss of nutrients, especially after disturbance when large amounts of nutrients have been released into the soil. Because of these properties and characteristics, the Grayling sand soils of northern lower Michigan are expected to be susceptible to adverse effects related to the influx of acidic precipitation.

SOIL ACIDIFICATION

The accelerated acidification of soil has been postulated as one likely effect of acid precipitation on soil properties (Malmer, 1976). Stress factors to plants associated with acidic soils include direct injury by hydrogen ions; physiologically impaired absorption of calcium, magnesium, and phosphorus; increased solubility and toxicity of aluminum, manganese, and iron; reduced availability of phosphorus; and deficiencies of base cations. Impairment of biological activities in soils due to acidity include decreased nitrogen cycling and nitrogen fixation (Rorison, 1978). The question as to whether present levels of acid precipitation are accelerating the acidification of soils has been investigated in various laboratory studies.

Overrein (1972) treated four soils ranging in texture from fine sand to clay loam with simulated precipitation acidified with sulfuric acid to pH levels from 2 to 5. In the forty day experimental period, gradual acidification of the soil, starting at the top of the profile and gradually penetrating down through the entire soil column, occurred with the pH 2 treatment. Ogner (1980) reported increased exchangeable acidity in an umbric dystrochrept soil treated for three years with simulated precipitation acidified with sulfuric acid to pH 2.5 as compared to pH 5.4. In lysimeter experiments with iron podzol soil, base saturation and pH were significantly reduced in the O layer by pH 2.5 and 3 treatments (Bjor and Teigen, 1980). Treatment of four silt loam forest soils with simulated rain adjusted to a pH value of 3.2 produced a marked vertical gradient of pH in the soil columns (Alexander, 1980).

Comparable results were produced in field experiments. Application over two seasons of fifty mm per month of pH 3 simulated acid rain to field plots on a podzolic soil increased the acidity of the humus and decreased base saturation (Abrahamsen et al., 1975). Later results from the same experiment demonstrated that soil pH was significantly reduced in O, A, and B horizons of the soil. In contrast, Roberts et al. (1978) reported that application of ten mm per month of pH 3.1 and 2.7 sulfuric acid solutions to field plots on a podzolic soil did not affect the acidity of organic horizons. It was concluded that treatment at such low rates was unlikely to lead to further acidification of strongly acid soils.

Under most experimental circumstances, supply of diluted acid or acidified water resulted in decreased pH and base saturation of soils. However, the concentrations of acid and amounts applied were often considerably greater than in incident precipitation (Malmer, 1976). A factor not included in many studies was the effect of neutral salts in precipitation. Acidification of soils by addition of sulfuric acid without consideration of the natural atmospheric deposition of neutral salts tended to exaggerate the harmful effect of acid rain (Wiklander, 1975).

Estimation of soil acidification due to impingement of acid precipitation on natural ecosystems has been attempted. Linzon and Temple (1980) compared pH of six soil series sampled in 1960 and again in 1978 in Ontario. They concluded that acid precipitation had not noticeably altered soil pH during the eighteen-year period between soil samplings. In contrast, hardwood forest soils in the Adirondacks were markedly less acid in 1939 than the same soil types in 1979. Mollitor and Berg (1980) suggested that this acidification was related to modern inputs of acid precipitation. Mayer and Ulrich (1977) likewise attributed the acidification of the uppermost one to two centimeters in a loess soil in a central European beech forest to acid precipitation. In this upper soil level, pH values as low as 3 were observed.

While soil acidification in these remote forested areas cannot be definitely linked to acid precipitation, deposition of acidity of industrial origin in the vicinities of pollution sources has affected entire soil profiles

(Tamm, 1976; Hutchinson and Whitby, 1977; Baker et al., 1977).

Chemical reactions in soils that tend to counteract excessive acidification depend on the pH-dependent buffering by aluminum in the pH range of 3 to 5 (Ulrich, 1978). Soils containing aluminum ions are well buffered at pH 5, with the pH of maximum buffering decreasing with the increasing concentration of aluminum. Research at the Hubbard Brook Experimental Forest in New Hampshire has indicated that aluminum hydroxides play an important role in the neutralization of acid precipitation entering the soil (Johnson et al., 1972; Johnson, 1979; Johnson et al., 1981). Increased decomposition of clay particles and release of aluminum in response to modest amounts of acidity in rainfall sets a lower limit on soil pH at around 3.5 in unmanaged soils (Frink and Voigt, 1977).

A forest canopy will also effectively buffer acidity of precipitation, reducing direct effects on soil properties (Hoffman et al., 1980). In a regenerating jack pine stand, however, the canopy has been destroyed and the soil is unprotected from incoming acid precipitation.

LEACHING AND WEATHERING

Deposition of acid in precipitation would theoretically result in increased leaching of plant nutrients out of the root zone of soils (Overrein, 1972). Accelerated leaching would lead to a loss of fertility and productivity over a long time period. Under natural conditions, leaching processes are dominated by organic and carbonic acids, while leaching in soils receiving highly acidic precipitation is dominated by sulfuric acid of anthropogenic origin (Cole and Johnson, 1977). If excess anions from acid rain are mobile in the soil, they will be leached from the soil in association with bases from the soil exchange complex. The result of this process would be base depletion. Results of greenhouse, lysimeter, and field studies have generally supported the hypothesis of increased leaching in response to acid precipitation.

Overrein (1972) reported on lysimeter investigations involving treatment of a podzolic forest soil with distilled water-sulfuric acid rain at pH levels 4.3 and 3. At pH 3, dramatically increased leaching of calcium was apparent as compared to distilled water alone or simulated rain at pH 4.3. Similarly, treatment of four soils ranging in texture from fine sand to clay loam with precipitation adjusted to pH values from 2 to 5 resulted in sharply increased leaching of calcium from all soils as the pH of precipitation dropped below 4. Based on these findings, Overrein (1972) concluded that increasingly acidic precipitation represented a definite stress on ecosystems with soils susceptible to acid input.

Wood and Bormann (1977) analyzed leachate from pots containing sandy loam soil in which eastern white pine seedlings were grown and treated with simulated precipitation at pH levels ranging from 5.6 to 2.3. Mean leaching losses of K+, Mg++, and Ca++ rose continuously with rain acidity. While Mg++ and Ca++ leaching losses significantly increased with each increase in hydrogen ion concentration, a significant increase in leaching of K+ was observed only at pH levels of 3 and 2.3. Based on measurements of exchangeable soil cations, losses via leaching and plant uptake were balanced by weathering inputs at pH levels 4 and 5.6. At pH 3.3, decreases in exchangeable Mg++ occurred, while at pH 3 exchangeable K+, Mg++, and Ca++ decreased between 54% and 84% of respective concentrations at higher pH levels. At pH 2.3, exchangeable cation concentrations were reduced to very low levels. Although estimated weathering inputs of K+, Mg++, and Ca++ increased with rain acidity, declines in cation leaching at pH 2.3 over time suggested that supplies of weatherable K+, Mg++, and Ca++ had been greatly depleted.

Hutchinson (1978) investigated the effects of acid leaching on smelter-contaminated and uncontaminated soils. Sulfuric acid solutions were applied at pH levels 2.5, 4.5, and 5.7. The non-polluted soil proved more resistant to leaching, but treatment at pH 2.5 resulted in elevated leaching of aluminum, manganese, iron, and calcium from both soils irrespective of initial soil pH level. Hutchinson suggested that acid rains might cause increased availability of bases over the short term but would inevitably result in a long-term depletion of nutrient reserves of the soil leading to base insufficiency.

Bjor and Teigen (1980) reported that treatment of an iron podzol in lysimeters with pH 2.5 acid precipitation produced net losses of potassium, calcium, sodium, manganese, aluminum, nitrate, and ammonium from the soil profile. At the pH 2.5 treatment, an increased rate of weathering was suggested since the final amount of exchangeable cations in combination with the amount of cations leached were greater than the initial cation content of the soil.

In field experiments on iron podzol soils, treatment with simulated precipitation at pH levels 2.5 and 3 resulted in decreases in calcium, magnesium, and manganese under Norway spruce. Under scotch pine, rain of pH 4 and below decreased content of divalent ions in comparison to the control of unacidified groundwater. In both cases, losses were also found for sodium, potassium, iron, and nitrate (Abrahamsen et al., 1976). In the same study, podzol-brown earth soils exhibited net losses of calcium, magnesium, and aluminum; but with the exception of calcium, net loss of ions was smaller than for the podzol soils.

Increased leaching loss of cations in response to acid precipitation input has also been documented for natural ecosystems. In a forested loess soil, Mayer and Ulrich (1977) reported a loss of aluminum, manganese, sodium, potassium, calcium, and magnesium from mineral soil as a result of incident acid precipitation. These changes were attributed to weathering of silicates and desorption of exchangeable cations, largely in the uppermost one to two centimeters of soil. It was suggested that the loss of magnesium and manganese from this soil could result in a deficiency in the supply of these nutrients.

Mollitor and Berg (1980) compared leaching losses from Adirondack forest ecosystems in response to incident acid precipitation. Soils under a hardwood forest lost sulfate, calcium, magnesium, and sodium at rates in excess of influx in precipitation. Nitrate, hydrogen ions, and potassium were conserved. A conifer site retained nitrate and hydrogen ions, but sulfate and all bases were lost from the rooting zone at rates greater than input in precipitation. Sulfate was considered to be the dominant counterion at both sites facilitating the leaching and accelerated depletion of bases. The conifer site had greater sulfate and organic ion flux than the hardwood site, and a greater loss of cations from the rooting zone than the hardwood site. This combined effect would cause a more rapid deterioration of site quality in coniferous forests than in hardwood forests. In northern lower Michigan, the combination of susceptible soil and coniferous vegetation make the jack pine-Grayling sand ecosystem especially vulnerable to leaching loss of nutrients.

Results in the research reviewed indicated that increased leaching of basic cations from the Grayling soil in response to acid precipitation is likely. The critical level of acid precipitation producing leaching loss of cations was around pH 4, a level which incident precipitation in northern lower Michigan presently approaches. While short term increased nutrient availability may occur due to exchange processes accelerated by acid precipitation, depletion and insufficiency of bases is the likely long term result. While acid precipitation may also produce increased weathering rates in soil, it is a crucial but unknown factor if increased weathering can compensate for increased leaching losses in the jack pine-Grayling sand ecosystem.

SULFATE ADSORPTION

An important factor influencing the effect of acid precipitation on leaching is the degree of mobility of anions, especially sulfate, in the soil. Atmospheric inputs of sulfuric acid provide the dominant source of both hydrogen ions for cation replacement and mobile anions for cation transport in soils of forested areas presently receiving acid precipitation (Cronan et al., 1978; Cronan and Schofield, 1979; Mollitor and Berg, 1980). The effectiveness of sulfuric acid as a soil cation leaching agent is reduced if the soil is a sulfate adsorber (Cole and Johnson, 1977). The sulfate adsorption capacity of a soil is determined by two factors, sesquioxide contents and soil acidity.

Sulfate adsorption capacity is associated with hydrous oxides of iron and aluminum in soils. The higher the sesquioxide content of a soil, the higher the sulfate adsorption capacity (Johnson and Cole, 1977; Johnson, 1978; Wiklander, 1978a). Young soils developed after the last glaciation generally have less sulfate adsorption capacity than soils developed over a longer period (Abrahamsen, 1980). Even in recent soils, those with horizons high in sesquioxide content will have higher anion adsorbing capacity than soils without these properties.

Sulfate adsorption is strongly pH dependent, with greater adsorption occurring at low pH values (Johnson and Cole, 1977). In acid soils, sulfate adsorption reaches a maximum in the pH range from 2 to 4. Non-specific adsorption occurs on surfaces of mineral colloids, particularly hydrated aluminum or iron hydroxides and clay minerals (Frink and Voigt, 1977). Specific adsorption occurs when sulfate ions penetrate the sesquioxide and enter into coordination with two or more ions in the crystal structure (Johnson, 1978). Sulfate adsorption enhances cation adsorption as well, since metal cations are immobilized with sulfate in the soil. This has the net effect of increasing cation exchange capacity of the soil and effectively reducing cation loss through leaching (Johnson, 1978; Singh et al., 1980). If sulfate loading exceeds the capacity of the soil to retain sulfate, leaching losses will occur and a new equilibrium is reached as soil adsorption sites are filled (Reuss, 1977; Johnson, 1978).

Nordstrom (1982) suggests that what has been thought to be adsorption of sulfate in certain soils may actually be related to formation and precipitation of basic aluminum sulfate complexes. He suggested that a continuum, rather than a sharp distinction, exists between pure adsorption and pure precipitation of sulfate in soil. This tendency for sulfate and aluminum to be retained as amorphous aluminum sulfates would be greatest at high rates of sulfate loading in soils more acid than pH 4.5.

The effects of acid precipitation on leaching in areas with high sulfate adsorption capacity will be different from those areas where adsorption capacity is low (Abrahamsen, 1980). Singh et al. (1980) determined that mobility of sulfate and leaching losses of elements were higher in semipodzol than in iron podzol soils treated with simulated acid precipitation. The greater resistance to leaching demonstrated by the iron podzol was attributed to lower pH and higher aluminum content in the B horizon contributing to higher sulfate adsorption capacity.

Similarly, Morrison (1981) treated two coarse sandy soils from mid-aged jack pine stands with simulated acid precipitation. Twenty months of loading at pH 2 were needed to produce a leaching effect related to treatment. The less developed Dupuis soil, a dystric brunisol, was less resistant to leaching than the more developed Wells soil, a humo-ferric podzol. This difference was attributed to greater sulfate adsorption capacity in the B horizon of the

Wells soil. Cation losses under the influence of freely moving sulfate occurred only after intense sulfate loading and saturation of adsorption sites. The results of this study suggested that even coarse, sandy soils such as the Grayling may resist leaching if they have a capacity to adsorb sulfate.

SOLUBILITY AND TOXICITY OF METALLIC ELEMENTS

Soil acidification results in increased solubility and mobility of aluminum, iron, and manganese, as well as heavy metals such as zinc, nickel, cadmium, and chromium (Norton, 1977). Accelerated soil acidification caused by acid precipitation would lead to a release of toxic elements, producing adverse effects on biologically important processes and living organisms (Malmer, 1976).

Transition from geochemical immobility to mobility for elemental aluminum, manganese and iron occurs under oxidizing conditions as soil pH levels decrease from 6 to 4. Both aluminum and manganese have toxic effects on plants through damage to roots, toxicity being greater for the uncomplexed metal ions (Norton et al., 1980).

Abrahamsen et al. (1976) observed increased solubility and mobility of aluminum, manganese, and iron in a podzol, and of aluminum in a podzol-brown earth when the soils were treated with solutions acidified to pH levels 2.5 and 3. Increased leaching losses of these elements were directly related to acidity of leachate. Likewise, Singh et al.

(1980) reported that mobility and leaching of aluminum was higher at simulated precipitation pH levels of 4.3 than at 5.6 for both podzol and semipodzol soils. Cronan and Schofield (1979) suggested that atmospheric inputs of sulfuric and nitric acids in high elevation watersheds in the northeastern United States were responsible for observed increases in soil aluminum solubility and leaching.

Under conditions of increased solubility of aluminum in soil, toxicity may occur. Root growth of many plants is reduced by solution concentrations of aluminum as low as one part per million. Even slight increases in concentrations of aluminum in soil solution could have deleterious effects, and at some critical level roots of trees would show chronic symptoms (Voigt, 1980). Aluminum toxicity to plants in the vicinity of Sudbury, Ontario smelters was believed to be caused by highly acidic rainfall mobilizing aluminum from soils (Hutchinson and Whitby, 1977). In a central European beech forest, concentrations of aluminum and iron in soil solution substantially increased between 1966 and 1973 as a result of acid precipitation (Ulrich et al., 1980). Subsequent decreased fine root biomass was found to be related to the increased aluminum concentration of one to two mg per liter in the soil solution.

Increased acid deposition is believed to interact with heavy metals deposited or already present in forest soils (Nilsson, 1978). Hutchinson (1980) observed that atmospheric transport of pollutants from industrial activity and mechanized transportation leads to widespread heavy metal dispersion. A study by Norton et al. (1980) confirmed that trace and particularly heavy metal influx to forest ecosystems was greatly increased over pre-pollution levels. The organic layers and surface few centimeters of soils are major sites of accumulation of these pollutants. This is also the site of nutrient uptake by plant roots, root hair development, seed germination, seedling establishment, and microbe activity. Concentrations of heavy metals near smelters are known to be phytotoxic and inhibitory of microbial activity, but the investigation of the interaction between acid precipitation and heavy metals in soils has only recently been undertaken (Bohn, 1972; Hutchinson and Whitby, 1977; Freedman and Hutchinson, 1978; Nilsson, 1978).

Tyler (1978) studied the effect of simulated acid precipitation on the leachability of manganese, zinc, cadmium, nickel, copper, and chromium in an organic spruce forest soil. Acid treatments ranged from a pH of 4.2 to one of 2.8. Increased acidity of treatment solution resulted in increased solubility and leaching of metals from the soil. Manganese and nickel were most readily mobilized, followed by cadmium, zinc, copper, and chromium. Very little chromium was released even at a treatment pH of 2.8.

From the standpoint of the present study, acidification of the upper soil resulting in increased solubility of toxic elements is of greatest concern due to the effects on jack pine regeneration. Germination and establishment of jack pine seedlings would take place in such an acidified layer of soil, and would be sensitive to high levels of soluble toxic elements. This effect would be greatest on a site regenerating after logging, but in the absence of fire. On a site regenerating after fire, the ash deposited by the fire would result in an increase in soil pH which would temporarily ameliorate previous acidification of the upper soil horizons.

NITROGEN DEPOSITION INTERACTIONS

Shortage of available nitrogen is the main nutrient factor limiting growth in most forest ecosystems (Abrahamsen, 1980). The amount of nitrogen present in the ecosystem is determined by nitrogen fixation and through influx of nitrogen compounds in precipitation (Hovland and Ishac, 1975). Because nitrogen is readily utilized by forest ecosystems, inputs of nitrogen in available forms in acid precipitation are likely to result in increased tree growth (Abrahamsen, 1980; Mollitor and Berg, 1980). As long as the forest is undisturbed, there is little soil acidification due to increased nitric acid deposition unless the nitrogen ultimately leaches from the soil as nitrate (Tamm, 1977; Johnson et al., 1982).

When the forest undergoes regeneration after clearcutting, fire, or other disturbance, nutrient cycling is much less closed. Rapid nitrification following such disturbances can lead to leaching losses of excess nitrate and rapid net soil acidification due to the release of hydrogen ions during the process of nitrification (Tamm, 1976). Large increases in losses of basic cations and nitrate from a central New Hampshire northern hardwoods forest were caused by just such an increase in microbial nitrification following clear felling and suppression of vegetative regrowth (Likens et al., 1969; Likens et al., 1970).

Effects of changes in the chemical climate can thus accumulate over time and become evident during regeneration of the forest as a result of acidity produced in conjunction with biologic cycling of nitrogen (Tamm, 1977; Frink and Voigt, 1977). This type of accumulating change due to acid precipitation would be especially important in the jack pine-Grayling sand ecosystem where regeneration is keyed to major disturbances.

Increased deposition of nitrogen from the atmosphere can be viewed as comparable to long term application of an incomplete fertilizer which enhances growth and demand for other nutrients, and may eventually promote deficiencies in potassium, magnesium, phosphorus, or micronutrients. For some elements, such as magnesium, this effect would be exacerbated by increased leaching of magnesium from soil caused by acid precipitation (Abrahamsen, 1980). Here again, high susceptibility to leaching and low fertility make the jack pine-Grayling sand ecosystem liable to such nitrogen-enforced deficiencies.

Chapter IV

STUDY SITE CHARACTERIZATION AND ECOLOGY

Susceptibility of the regeneration phase of the jack pine-Grayling sand ecosystem to adverse effects from acid precipitation has been hypothesized. A field site typical of the jack pine-Grayling sand ecosystems of northern lower Michigan was selected to be a source of soil for a greenhouse study of germination and early seedling development. Specific criteria were that the site be undergoing post-burn regeneration with one year old jack pine seedlings present.

SITE DESCRIPTION

In May, 1981, with the aid of the United States Forest Service, a site was selected in the Mio Ranger District of the Huron-Manistee National Forest. The location (Section 12, T25N, R3E, Oscoda County, Michigan) was within the area burned by the Mack Lake Fire on May 5, 1980. The study site was located on Grayling sand in an area of gently rolling outwash plain east of Mack Lake. A pole-sized stand of jack pine, destroyed by fire the previous spring, formerly occupied the site. Among the prominent plant species of the regenerating ecosystem were jack pine seedlings, black oak (<u>Quercus velutina</u>) stump sprouts, sedge (<u>Carex pensylvanica</u>), low blueberry (<u>Vaccinium angustifolium</u>), sweet fern (*Comptonia peregrina*), and ticklegrass (*Agrostis hyemalis*). Minor components included bearberry (*Arctostaphylos uva-ursi*), spreading dogbane (*Apocynum androsaemifolium*), and sand cherry (*Prunus pumila*).

CLIMATE

The lake influence common to many areas of Michigan is minimal at the study site since the region is sheltered by the higher plateau to the west. This creates a continental climate characterized by larger daily, monthly, and annual temperature ranges than experienced in areas at the same latitude but closer to the Great Lakes (Strommen, 1971).

Precipitation is well distributed throughout the year with the summer season, May through October, receiving an average of sixty-one percent of the mean annual precipitation of 67.1 cm. July, with an average rainfall of 7.95 cm, is the wettest month in the Mio area. Summer precipitation is mainly in the form of afternoon showers and thundershowers.

This area of Michigan receives the lowest mean annual precipitation in the state (67.1 cm), compared to an average of 84.3 cm occurring to the west in Crawford County, or to the 91.4 cm falling annually in southwestern lower Michigan (Strommen, 1971; Michigan Department of Agriculture, 1983). Potential moisture evaporation exceeds average precipitation by forty-five percent. High potential evaporation coupled with relatively low annual precipitation make soil moisture replenishment during the fall, winter, and early spring important (Strommen, 1971).

Weekly precipitation samples are currently collected at two sites in northern lower Michigan as part of the National Atmospheric Deposition Program network. These sites are located at Wellston in Wexford County and at the University of Michigan Biological Station in Cheboygan County near Pellston. Data obtained from the analysis of precipitation samples collected between October 17, 1978 and September 15, 1982 at these stations indicated that the volume-weighted mean pH level of precipitation in northern lower Michigan during this time period was 4.50. Samples collected at Wellston had a mean pH of 4.49 and a range of 3.52 to 7.46. Mean pH of samples collected at Pellston was 4.51, with a range from 3.81 to 6.88 (NADP-NC141; NADP Data Reports). Seasonally, precipitation in northern lower Michigan has been most acidic during the summer (Semonin et al., 1981). Mean concentrations of major ions in precipitation collected at the two northern lower Michigan NADP stations between October 24. 1978 and January 6, 1981 are presented in Table 4.1.

All cations, except potassium, had no significant correlation with hydrogen ion concentration. Among the anions present, concentration of sulfate and nitrate displayed a strong significant relationship with hydrogen ion concentration, indicating that sulfuric and nitric acids were the predominant acids in the precipitation falling over

Table 4.1

Ionic Composition and Characteristics of Precipitation

	Mean Concentrations in pH Range (Microequivalents per liter)					
Ion	3.5-4	4-4.5	4.5-5	5-5.5	6-6.5	3.5-6.5
SO4--	148.86	69.79	46.27	48.94	110.50	68.71
NO3-	69.71	42.17	37.22	32.32	63.68	42.65
Cl-	14.85	6.14	6.99	4.63	6.84	6.74
Ca++	26.70	16.44	19.25	25.38	76.47	20.38
Mg++	12.84	7.32	8.07	7.54	21.68	8.32
K+	2.27	.93	.81	.98	2.04	1.02
Na+	13.72	9.49	17.24	7.87	19.43	11.79
NH4+	41.55	26.79	20.43	36.25	63.43	28.01
Ionic Concentration Ratios						
H:SO4	.90	.85	.65	.13	.01	.73
H:NO3	1.95	1.48	.87	.20	.01	1.23
SO4:NO3	2.12	1.49	1.03	1.47	1.49	1.39
Number of Samples						
ALL IONS	6	68	26	7	4	111

<u>Sources</u>: NADP-NC141; NADP DATA REPORT

northern lower Michigan. The ratio of sulfate to nitrate on a microequivalent basis averaged around 1.4. This ratio increased in precipitation samples with pH levels below 4.0 (Nguyen, 1981, pers. comm.). The mean annual deposition per square meter of major ionic constituents in precipitation was as follows: hydrogen, 2 to 3 µg; calcium, 30 mg; ammonium, 30 mg; nitrate, 140 mg; and sulfate, 200 mg (Semonin et al., 1981).

SOIL DESCRIPTION

The Grayling-Rubicon soil association occupies an area of over 373,000 hectares, distributed over fifteen counties in northern lower Michigan (Figure 4.1). The Grayling soil series comprises approximately forty-five percent of this association or 168,000 hectares. Thus, the Grayling soil series and its associated ecosystems cover a major area in northern lower Michigan (Stroesenreuther, 1983).

Soils in the Grayling series are classified as mixed, frigid Typic Udipsamments (USDA, 1976). These excessively drained soils developed in sandy glaciofluvial sediments and are located on outwash plains and lake plains of Wisconsinan age. Slope gradients are dominantly less than eight percent but range from zero to thirty-five percent. Soil pH ranges from 4.5 to 5.0 in the upper 38 cm and from 5.1 to 6.5 between 38 and 152 cm in depth (Veatch et al., 1931; USDA, 1976; USDA, 1981a). Permeability is rapid, while available water capacity and fertility are very low (Corder, 1979). A

Figure 4.1

Location of Grayling-Rubicon Soil Association in Northern Lower Michigan

Sources: USDA, 1981b; Michigan State University, 1981.

typical pedon description of a forested Grayling sand is presented below (USDA, 1976).

A & E--0 to 8 centimeters; black (N 2/) (A), and grayish brown (10YR 5/2) sand, (E); coated and uncoated sand grains mixed throughout the horizon, giving a salt and pepper appearance; moderate organic matter content in upper part; weak medium granular structure; very friable; very strongly acid, abrupt smooth boundary. (5.1 to 10.2 centimeters thick)

Bs1--8 to 23 centimeters; dark brown (7.5YR 4/4) sand; weak coarse granular structure; very friable; strongly acid; clear smooth boundary. (10.2 to 20.3 centimeters thick)

Bs2--23 to 38 centimeters; strong brown (7.5YR 5/6) sand; very coarse granular structure; very friable; medium acid; clear irregular boundary. (10.2 to 35.6 centimeters thick)

BC--38 to 58 centimeters; brown (7.5YR 5/4) sand; single grained; loose; medium acid; gradual smooth boundary. (7.6 to 25.4 centimeters thick)

C--58 to 152 centimeters; light brown (7.5YR 6/4) sand; single grained; loose; medium acid.

The droughty nature of this soil predisposes the jack pine-Grayling sand ecosystem to wildfire. The ash deposited from a fire increases available nutrients such as phosphorus, potassium, calcium, magnesium, and sodium, as well as soil pH. These increases are greatest shortly after a fire, but nutrient levels and soil pH return to pre-burn levels within one to two years after burning (Smith, 1970; Marshall, 1980). Increased solubility of the nutrients deposited in ash increases vulnerability to leaching loss, especially on coarse textured, permeable soils like the Grayling (Smith, 1970; Boyle, 1973). In the present study, the soil chemical properties determined from the analysis of soil samples would be influenced by this "fire effect." Results of soil analyses performed in this study are presented in Chapter VI.

JACK PINE REGENERATION ECOLOGY

Jack pine is an intolerant, pioneer species occupying a variety of sites following disturbance. Within its range of occurrence, jack pine is capable of growing on the driest and most infertile sites. On the Grayling soils of northern lower Michigan, jack pine is considered the edaphic climax. The silvical adaptations of jack pine allow the species to regenerate following wildfire. Serotinous cones remain on the tree for many years resulting in large accumulations of seed in unopened cones (Cayford, 1970; Benzie, 1977). Fire in a jack pine stand hot enough to damage trees produces sufficient heat to cause opening of the cones and subsequent dispersal of seed (Beaufait, 1961).

Jack pine seed usually germinates within fifteen to sixty days under favorable conditions. Where moisture is adequate, germination takes place when air temperature reaches 17.8 degrees Celsius. Both germination and survival are highest on mineral soil and lowest on undisturbed duff. Highest survival follows early spring germination (Fowells, 1965).

Factors hindering germination and early survival are summer droughts and high surface soil temperatures, which frequently kill young jack pine seedlings (Fowells, 1965).

The darker surface of a burned site effectively absorbs solar radiation, resulting in increased soil temperatures that may be sufficient to cause mortality of seedlings (Ahlgren and Ahlgren, 1960).

Seedling establishment is best where the water table is high and where there is some shade. During the first season, the root system penetrates to a depth of 13-25 cm. Average height of wild seedlings is about 5 cm at one year. By the end of the second growing season, jack pine seedlings typically have a dry weight of 1-2 g, a height of 8-10 cm, and root systems 28-33 cm deep (Fowells, 1965).

Seedling growth is very slow during the first three years, but increases rapidly during the following years. During early growth, competition for available moisture and nutrients with Carex sedge is an important factor limiting survival of seedlings. In northern lower Michigan, failure of regeneration after disturbance in jack pine stands may result in the establishment of meadows dominated by sedge. Once established, these meadows are capable of excluding tree and shrub seedling reproduction for many years (Marshall, 1980; Abrams and Dickmann, 1982). Most mortality of jack pine seedlings occurs during the first and second growing seasons, although early spring fires or severe drought conditions may reduce survival and growth of saplings that are up to 2 m in height (Fowells, 1965).

Chapter V

MATERIALS AND METHODS

The experiment to determine the effects of simulated acid rain on early life stages of the jack pine and properties of the Grayling sand growth medium was performed in a greenhouse at the Michigan State University Department of Forestry Tree Research Center. The study was conducted from June to September, 1981.

EXPERIMENTAL DESIGN

Treatments were arranged as a factorial experiment in a randomized complete block design. Blocking was utilized to account for environmental differences within the greenhouse. Five levels of a precipitation pH factor and two levels of a soil horizon factor constituted the factorial arrangement. Soil sampling and soil chemistry determinations incorporated a third factor, depth in soil, as a split plot design with three levels.

DESCRIPTION OF FACTORS

The two levels of the soil factor were chosen as representative of extremes in soil properties that a seedling would experience during germination and establishment on a typical Grayling sand soil. One level consisted of soil from the combined A and E horizons while the second level originated from the upper portion of the underlying Bs1. The combined A-E soil will be referred to as A horizon soil and the Bs1 will be referred to as B horizon soil.

These levels were considered extremes based on the likelihood of exposure of the horizon during regeneration and from a comparison of chemical properties of these upper horizons. Wildfire would expose largely A horizon seedbeds, while other disturbance such as logging or intentional scarification would result in exposure of the upper B horizon. The occurrence of differences in chemical properties between the A and B horizon soils was determined from examination of data from analyses performed by Marshall (1980) on soil from thirty-six jack pine-Grayling sand sites in northern lower Michigan. A horizons were higher in organic matter, exchangeable cations, nitrogen, and phosphorus, but lower in pH, than the underlying B horizons. These differences between horizons were confirmed by soil analyses performed in the present study (Chapter VI). Differences in response between seedlings growing on these two soil horizons to input of simulated acid rain would have management implications for silvicultural techniques used in the regeneration of jack pine.

The depth in soil factor consisted of three levels. Within an experimental unit, these were the top 5 cm of soil, the middle 5 cm of soil, and the bottom 5 cm of soil. This factor was incorporated to allow detection of changes in soil chemical properties with depth as affected by simulated acid precipitation.

The five simulated precipitation pH levels were chosen to represent the range occurring in the precipitation of northern lower Michigan as well as extremes recorded elsewhere in the northeast. Levels initially selected included pH values 2.0, 2.5, 3.0, 4.0, and 5.0. Based on NADP data, a stock rain chemically similar to precipitation in northern lower Michigan was developed (Nguyen, 1981, pers. comm.). This simulated rain was acidified to pH levels below 5.0 by the addition of a .0375 molar sulfuric acid - .025 molar nitric acid solution. Representative chemical composition of the different levels of simulated rain is presented in Table 5.1.

A concentrated stock solution containing 97.3 mg/l magnesium, 271.4 mg/l sodium, 408.8 mg/l calcium, 39.1 mg/l potassium, 504.0 mg/l ammonium, 230.5 mg/l chloride, 1550.0 mg/l sulfate, and 1876.0 mg/l nitrate was utilized for mixing large quantities of simulated precipitation. Deionized water was added to polyethylene carboys to near the twenty liter mark. A sufficient amount of sulfuric-nitric acid solution was added to bring the pH to within .05 units of the desired level. The level of acidity was measured with a Corning 125 glass electrode pH meter. Slight adjustments in pH could be made by adding deionized water or acid solution as needed. Before bringing to final volume, 20 ml of the concentrated stock solution was added

Table 5.1

Approximate Ionic Composition of Simulated Precipitation

Ion	Concentrations at pH Level (Microequivalents per liter) 2.0	2.5	3.0	4.0	4.7
SO4--[1]	10532.3	2169.8	576.0	51.0	32.3
NO3-[1]	3530.3	742.8	211.6	36.6	30.3
Cl-	6.5	6.5	6.5	6.5	6.5
Ca++	20.4	20.4	20.4	20.4	20.4
Mg++	8.0	8.0	8.0	8.0	8.0
K+	1.0	1.0	1.0	1.0	1.0
Na+	11.8	11.8	11.8	11.8	11.8
NH4+	27.9	27.9	27.9	27.9	27.9
H+[2]	9473.5	2995.8	947.4	96.94	18.47
Ionic Concentration Ratios					
H:SO4	.90	1.38	1.64	1.89	.57
H:NO3	2.68	4.03	4.48	2.65	.61
SO4:NO3	2.98	2.92	2.72	1.39	1.07
Other Characteristics					
MEAN pH	2.02	2.52	3.02	4.01	4.73
pH STD DEV	.07	.07	.05	.14	.22
ml H2SO4-HNO3 added per 20 l	2800	570	145	5	0

1 concentrations calculated from ml H2SO4-HNO3
2 concentration calculated from mean pH values

to the carboy to produce an ionic composition similar to incident rainfall (Nguyen, 1981, pers. comm.).

Simulated rain at pH levels 4.0 and below was accurately prepared following this method. Due to a drop in pH of deionized water to levels below 5.0, it proved difficult to maintain this pH level over the experimental period. Adding base to bring the pH level up to 5.0 would result in alteration of the background composition of cations in the simulated rain at this level, so the pH level was allowed to drift below 5.0. A final average pH level of 4.73 was realized for this treatment. This level will be referred to as pH 4.7.

EXPERIMENTAL PROCEDURE

On May 16 and 22, 1981, bulk samples of each soil horizon were collected at the Mio study site. Soil was sifted through a 1.3 cm square mesh to remove large organic and mineral material, placed in plastic bags, and transported to the Tree Research Center in East Lansing. Plastic milk cases 30.5 by 30.5 cm square and 26.7 cm deep were prepared to hold the soil used as the experimental unit during the study.

Wooden pallets with the same inside dimensions as the plastic cases and a height of 11.4 cm were placed in the bottom of each case to adjust the depth to 15.2 cm. Pallet tops were constructed of 2.5 cm square pine slats spaced at 2.5 cm intervals to allow for drainage. These slats were covered with fiberglass screen so that the soil would be retained in the case. Thirty-six plastic covered paper plant bands 15.2 cm deep and 5.1 by 5.1 cm square were placed in each case (Figure 5.1).

On June 19. the soil from each horizon was separately composited, mechanically mixed, placed in the prepared cases, and tamped slightly to reduce settling after initiation of treatments. The soil level in each case was brought to .5 cm below the top of the paper bands by adding soil of the appropriate horizon. Five cases containing A soil and five cases containing B soil were randomly assigned to each block. Location of each experimental unit was then randomly assigned within the blocks. Simulated precipitation pH levels were subsequently randomly assigned to each experimental unit within a block. In the greenhouse, cases were placed on wooden pallets with a distance of 30.5 cm between cases. Two additional cases were included to fill up blank spaces between blocks, each case containing half A soil and half B soil. Arrangement of cases in the greenhouse is shown in Figure 5.1.

Jack pine seeds were obtained from Dr. James Hanover, Michigan State University Department of Forestry. The source of seeds was a bulk sample collected from Michigan State Forest Genetics Plantation 3-69 (Section 26, T28N, R7W, Kalkaska County, Michigan). The parent trees from which this seed was obtained represented a wide range of genotypes from jack pine stands throughout northern lower

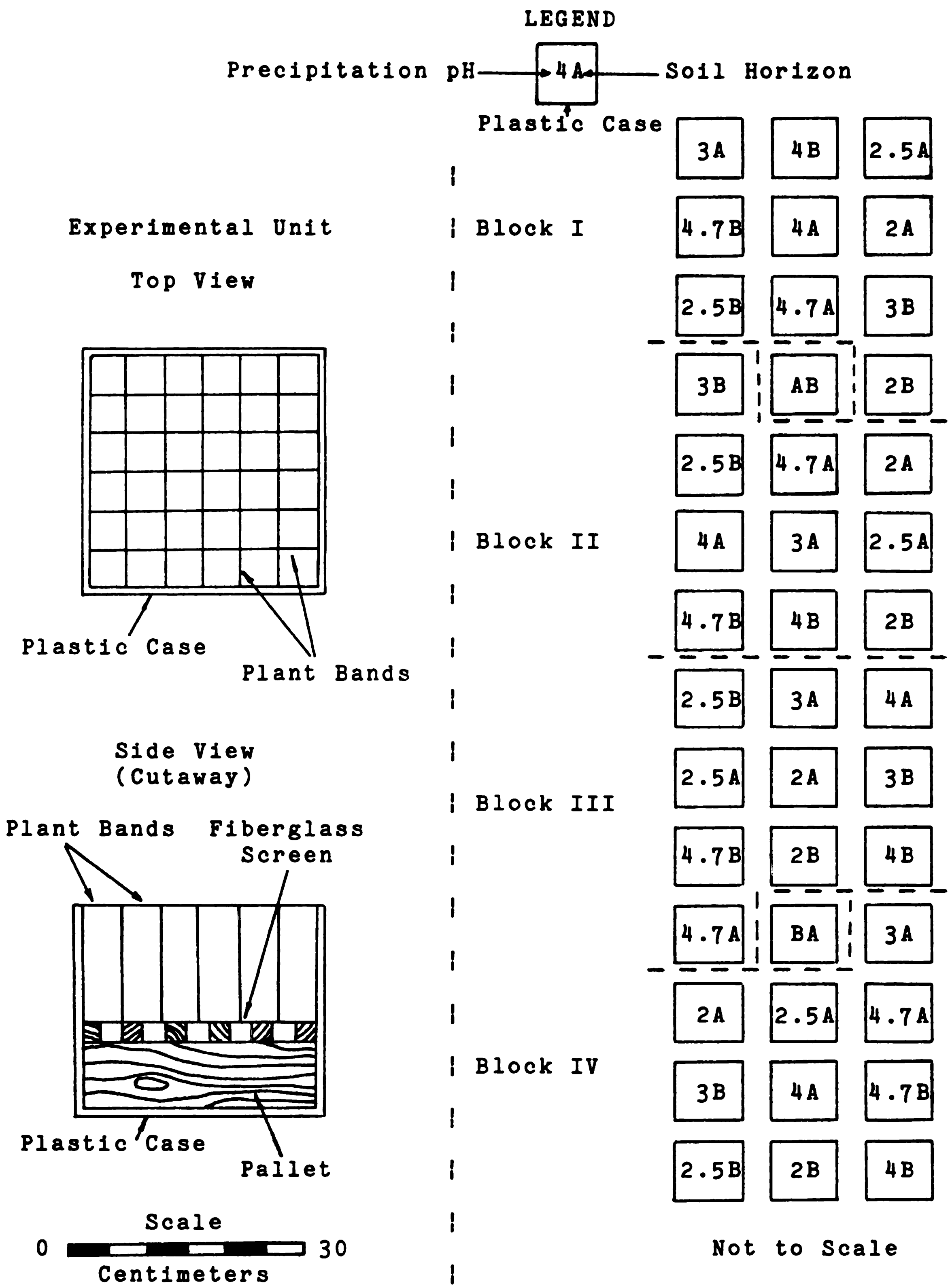

Figure 5.1

Arrangement of Experimental Units in Greenhouse

Michigan. Since the seeds had been subject to insect damage during storage, they were sorted to increase viability based on outward physical appearance. Seeds with dark brown to black coloration, medium to large size, and without obvious damage such as insect holes or cracks in the seedcoat were preferentially selected for use (Schopmeyer, 1974). Forty lots containing 150 seeds each were selected in this manner, and then were randomly assigned to the experimental cases.

On June 24, 2.6 cm of simulated precipitation were applied to each case to settle and moisten the soil prior to sowing seed. Each case received precipitation of the assigned pH level. Seeds were sown on June 25 and covered with 3-4 mm of soil sifted through a 1 mm sieve. Each soil-filled case containing thirty-six bands was sown with four jack pine seeds per band for a total of 144 seeds per experimental unit. Regular treatments commenced on June 26.

The rate of application of simulated acid rain was set at 2.6 cm per week, higher than the average 2.0 cm per week falling in Oscoda County in July. The precipitation amount was increased to allow for overspray and to reduce moisture limitations on seedling survival and growth. Precipitation was applied using Solo 425 Knapsack Sprayers fitted with No-Drift POLIJET yellow tips and pressure control gauges to maintain a constant .4 atmospheres pressure during spraying. Two sprayers were used, one exclusively for pH levels 4.0 and 4.7, and one for pH levels 2.0, 2.5, and 3.0. When changing solutions, sprayers were rinsed twice with deionized water and once with the next spray solution. All rinses were pumped through the sprayer to clear internal mechanisms, spray tubes, and nozzles of the previous spray solution.

The experimental unit being treated was surrounded by an open-topped acrylic plastic shield 43.2 cm square and 43.2 cm deep to prevent overspray or drift onto adjacent experimental units. Volume of rain applied was controlled by calibration of sprayers at the desired pressure with a specific nozzle. To deliver a .85 cm treatment over an area of 930 square cm, 790.5 ml was required. This volume could be delivered in one minute, 23 seconds. Application to each case was timed using a stopwatch. During every treatment, samples of simulated precipitation were collected at each pH level. Determinations were made in the laboratory to monitor pH of solutions delivered from the sprayers. Average simulated precipitation pH values are presented in Table 5.1.

With the exception of treatments on June 24 (2.6 cm), June 26 (1.3 cm), June 29 (1.3 cm), and July 5 (.4 cm), all applications consisted of .85 cm. Treatments were applied on an average of three days per week for the eleven-week duration of the study. During this time, a total of 27.6 cm of simulated rain was applied to each experimental unit. Approximate total deposition of nutrient elements to each experimental unit during the length of the study is presented in Table 5.2.

Table 5.2

Total Nutrient Deposition

Element	Deposition at pH Level[1] 2.0	2.5	3.0	4.0	4.7
Deposition in Milligrams per Experimental Unit					
S	4327.88	891.58	236.78	20.99	13.28
N	1277.29	276.69	85.99	23.15	20.89
Cl	5.91	5.91	5.91	5.91	5.91
Ca	10.48	10.48	10.48	10.48	10.48
Mg	2.49	2.49	2.49	2.49	2.49
K	1.00	1.00	1.00	1.00	1.00
Na	6.96	6.96	6.96	6.96	6.96
Deposition in Kilograms per Hectare					
S	465.9	95.9	25.5	2.2	1.4
N	137.5	29.8	9.2	2.5	2.2
Cl	.6	.6	.6	.6	.6
Ca	1.1	1.1	1.1	1.1	1.1
Mg	.3	.3	.3	.3	.3
K	.1	.1	.1	.1	.1
Na	.7	.7	.7	.7	.7

1 Total deposition during study calculated from ionic concentrations and volume of simulated precipitation applied to an area of 929 square centimeters.

DATA COLLECTION

Daily germination counts commenced July 2 and continued until July 16. Three stages of germination were recorded. Initial germination was defined as the first sign of seed viability, either visible disturbance of the soil surface or protrusion of the hypocotyl in the loop stage, whichever was first noted. Emergence was defined as the stage at which the hypocotyl was erect and free from the soil. Completion of germination was defined as the stage at which the primary cotyledons had fully expanded and shed the seed coat.

Mortality of seedlings was recorded on a daily basis the first two weeks, and on a weekly basis during the rest of the experimental period. Seedlings were judged to be dead when they exhibited obvious symptoms of mortality, such as permanent wilting, cortical collapse, permanent cessation of growth before emergence, or total necrosis of foliage.

Appearance of necrotic tissue, defined as permanent loss of green pigmentation from foliage resulting in brown needle tips or segments, was recorded during mortality counts. Lesions on the lower stems of seedlings grown at more acidic pH levels became evident in mid-July and their presence was recorded during mortality counts. Lesions were defined as fissures or pits in the cortex of the hypocotyl surrounded by dark, discolored, and swollen tissue.

Final mortality counts were taken on September 1. On September 5, visual ratings of the occurrence and degree of foliar necrosis and stem lesions were recorded for each seedling remaining alive.

Foliar necrosis was rated according to the categories presented below.

Rating	Description
1	No necrotic tissue apparent
2	Less than 5% necrotic tissue, confined to tips of needles
3	5 to 15% necrotic tissue, present at needle tips or lower cotyledons
4	15 to 50% necrotic tissue, present at needle tips, lower needles, and lower cotyledons
5	Greater than 50% necrotic tissue distributed over entire seedling

Stem lesion ratings were given based on the scale below.

Rating	Description
1	Absent, no visible damage or discoloration
2	Small, isolated lesion less than 25% of stem circumference, little discoloration of stem
3	One or more lesions 25 to 50% of stem circumference, brown discoloration of stem
4	Lesions greater than 50% of stem circumference, black discoloration of stem

Total heights and root collar diameters were measured for 36 randomly selected seedlings in each case on September 6. If less than 36 seedlings remained alive, height and diameter were measured on all seedlings in the case. Total height, defined as distance from ground to topmost needle tip, was measured to the nearest mm with a steel rule. Diameter was measured at the root collar to the nearest .05 mm with a dial-reading caliper.

SAMPLE COLLECTION

On September 7, all seedling tops were harvested by cutting with scissors at the root collar, except in 18 bands per case where one seedling was left for later study. Harvested tops from each case were placed in labeled paper bags and immediately stored in a cooler until they could be transferred to a drying oven. Tops were dried at 65 degrees Celsius for 48 hours.

Soil samples were taken from each case on September 13. Four bands were randomly selected for division into three equal parts as allowed for in the split plot design for soil depth. Composite samples were made from these four bands consisting of the top 5 cm, the middle 5 cm, and the bottom 5 cm of the soil columns. Soil in the remaining bands not containing living seedlings was gently broken up to allow removal of roots of previously harvested seedlings. Roots were subsequently washed in three rinses of deionized water to remove soil and then oven-dried at 65 degrees Celsius for 48 hours.

After oven drying, total weight of seedling tops and roots was determined to the nearest .001 g on a Sartorius

1205 MP digital balance. This data was used to calculate average top weight, root weight, total weight, and shoot to root ratios. Seedling tops were ground in a Wiley mill and stored in acid washed glass jars prior to chemical analysis. Roots were not chemically analyzed.

Soil samples were allowed to air dry before being sifted through a 1 mm sieve. Soil samples were stored in labeled cardboard cartons prior to subsampling for chemical analysis.

SAMPLE ANALYSIS

Total Kjeldahl nitrogen and total phosphorus of plant tissue was colorimetrically determined on a Technicon Autoanalyzer II following digestion with sulfuric acid (Black, 1965; Technicon, 1977). Determination of total metals (Zn, Mn, Cd, B, Fe, Al, Mg, Cu, K, Ca, Ni, Cr, Na) followed digestion with nitric and perchloric acids. Concentrations were determined using a Spectrametrics SMI III DC-argon plasma atomic emission spectrometer (Blanchar, et al., 1965; Ellis et al., 1976; Sommers and Nelson, 1972).

Soil pH was measured using an Orion Model 901 Ion-analyzer equipped with a combination electrode. A one to one soil to water mixture was stirred three times during a one-half hour period. After fifteen minutes to allow settling of particles, pH was measured in the supernatant (Black, 1965). Soil organic matter was colorimetrically determined using a method developed by Sims and Haby (1971) based on wet combustion with sulfuric acid (Black, 1965). Soil available phosphorus was colorimetrically determined using the Technicon Autoanalyzer II following Bray 1 extraction (Black, 1965; Technicon, 1977).

Exchangeable cations were extracted by shaking soil samples for 30 minutes with 1 N ammonium acetate before filtering. Calcium, magnesium, potassium, and sodium concentrations were determined using DC-argon plasma atomic emission spectrometry, similar to the method of Black (1965) and the Soil Conservation Service (1972). Total Kjeldahl nitrogen, total phosphorus, and total metals for soil samples were determined following the methods cited for plant tissue. Recovery of metals from soil by nitric-perchloric acid extraction is expected to be lower by five to ten percent than concentrations determined after hydrofluoric-perchloric acid digestion. This is due to the inability of the nitric-perchloric method to quantitatively extract elements included in silicate minerals or occluded in well crystalized iron oxides (Sommers and Nelson, 1972). Discussion of total concentrations of soil metals and cations in the present study refers to amounts extracted using the nitric-perchloric acid procedure, and not to concentrations obtained from complete breakdown of soil minerals.

Laboratory analysis of plant tissue included 25 percent replication of samples and inclusion of replicated bulk samples at the rate of three in 40 samples. Soil TKN, TP, and total digests were replicated at 15 percent, also including bulk samples at the same rate. Soil available phosphorus determination included 100 percent replication of samples along with bulk samples at the standard rate. Soil pH determinations were made without replication, but one bulk sample was included between every ten experimental samples. Exchangeable cation soil samples were replicated at a rate of seven percent with one bulk and one blank per 30 experimental samples. Soil organic matter determinations were run without replication, but included one blank and two bulk samples per 30 experimental samples. All results reported include corrections for blank samples.

METHODS OF STATISTICAL ANALYSIS

Data from this study was analyzed on the CDC 6000 computer located in the Michigan State University Computer Laboratory. Statistical calculations and data manipulations were performed using SPSS, the Statistical Package for the Social Sciences (Nie et al., 1975; M.S.U., 1981b). Appropriate transformations were applied to data if needed to meet the assumption of homogeneity of variance. Results of statistical analyses were judged significant when probability levels were less than or equal to .05. Mean separation was accomplished using Tukey's w Procedure. Statistical methods employed and basic assumptions were those described by Steel and Torrie (1980).

Chapter VI

RESULTS AND DISCUSSION: EFFECTS OF SIMULATED ACID PRECIPITATION ON SOIL CHEMICAL PROPERTIES

This chapter presents the results of chemical analyses of the Grayling sand used as the growth medium in this study. Included is a discussion of initial soil properties and a presentation of the results on the effects of simulated acid precipitation on soil pH, basic cations, nitrogen and organic matter, phosphorus, aluminum and iron, and micronutrients. Data for total soil nitrogen, phosphorus, boron, and copper were transformed to a logarithmic scale to create homogeneity of variance. Data for all other variables were statistically analyzed on the original scale of measurement. The experimental design allowed for an assessment of the effects of the precipitation pH factor on soil properties as modified by the soil horizon type and relative depth in the soil, or "soil level." Only those main effects and interactions significantly related to precipitation pH will be presented and discussed.

INITIAL SOIL CHEMICAL PROPERTIES

Five samples were taken from each of the bulk A and B horizon soil samples collected at the field study site. Mean pH levels, organic matter contents, and elemental concentrations determined for the A and B bulk samples are presented in Table 6.1. These mean values are representatitve of the initial soil chemical properties of A and B horizon soil allocated to experimental units.

The A horizon soil was higher in organic matter and in total concentrations of nitrogen, phosphorus, calcium, and manganese. The A horizon was also higher in exchangeable calcium, magnesium, and potassium. The B horizon was higher in pH and total aluminum, iron, magnesium, and potassium. These findings agreed with those of Marshall (1980), as noted in Chapter V. Concentrations of total and exchangeable sodium, extractable phosphorus, and total zinc, boron, copper, nickel, and chromium, were similar for both soil horizons in the present study.

The Grayling sand is low in clay, consequently the cation exchange capacity is largely determined by the amount of organic matter present. The A horizon soil, due to higher organic matter content, would have higher cation exchange capacity than the B horizon soil. This is borne out by the higher concentrations of exchangeable cations in the A horizon soil. The lower pH of the A horizon soil may be a result of its higher organic matter content, since organic matter promotes higher levels of exchangeable hydrogen ions in soils (Brady, 1974). Soils higher in iron and aluminum oxides will have higher pH values since the dissociation of adsorbed hydrogen ions from these oxides is low (Brady, 1974). The higher pH of B horizon soil may

Table 6.1

Initial Chemical Properties of A and B Horizon Soil

Soil	Mean[1]	Std Dev	Mean[1]	Std Dev	Mean[1]	Std Dev
	Soil pH		Total N (%)		Organic Matter (%)	
A	4.40	.02	.095	.006	2.54	.18
B	4.61	.12	.051	.005	1.47	.16
	Total Ca (ppm)		Exch. Ca (ppm)		Total Mg (ppm)	
A	671.4	59.8	105.7	8.8	503.6	21.3
B	597.0	34.9	19.8	3.7	615.4	28.1
	Exch. Mg (ppm)		Total K (ppm)		Exch. K (ppm)	
A	17.2	3.8	479.2	21.7	27.2	2.8
B	5.4	1.5	508.8	24.2	17.3	.9
	Total Na (ppm)		Exch. Na (ppm)		Total P (%)	
A	35.6	1.5	9.3	5.0	.021	.004
B	37.8	2.0	8.5	2.8	.016	.003
	Extr. P (ppm)		Total Mn (ppm)		Total Zn (ppm)	
A	9.52	.34	263.6	18.5	16.1	1.1
B	9.65	.44	159.8	7.3	13.0	.7
	Total B (ppm)		Total Cu (ppm)		Total Fe (ppm)	
A	5.41	.87	2.35	.16	4332	281
B	4.74	.90	2.33	.44	5256	306
	Total Al (ppm)		Total Ni (ppm)		Total Cr (ppm)	
A	4820	193	2.68	.14	4.81	.24
B	6108	221	3.04	.12	4.81	.61

[1] Each mean is based on five samples.

result from its higher content of iron and aluminum and lower organic matter content, since these two conditions would result in lower levels of exchangeable hydrogen ions.

SOIL pH

The most dramatic effect of simulated precipitation on soil chemical properties was an alteration in soil pH. The main effect of precipitation pH was significant, along with the interactions between precipitation pH and soil horizon, and between precipitation pH and soil level. A significant three-way interaction between precipitation pH, soil level, and soil horizon was also present. These results are presented in Table 6.2.

The significant soil horizon by precipitation pH interaction indicated a difference in response to input of acid precipitation depending on the soil horizon treated. Interaction was most evident at precipitation pH 2.0 where A horizon soil was acidified to a greater degree than B horizon soil.

The soil level by precipitation pH interaction was evident in that the soil pH change resulting from precipitation acidity differed depending on soil level. The uppermost 5 cm level of soil displayed the greatest range in soil acidity. The top level of soil exhibited significantly higher pH than middle or bottom levels at precipitation pH levels 4.0 and 4.7. At precipitation pH 2.5 and 2.0, soil pH was significantly lower in the upper 5 cm soil level than

Table 6.2

Soil pH

		Soil pH at Precipitation pH Level[1]				
Soil	Level	2.0	2.5	3.0	4.0	4.7
* A	1	3.29z,d	4.11y,c	4.45x,b	4.62x,a	4.61x,a
	2	3.84y,c	4.36x,b	4.43x,ab	4.50y,a	4.49y,a
	3	4.01x,b	4.34x,a	4.40x,a	4.42z,a	4.44y,a
Mean		3.71c	4.27b	4.43a	4.51a	4.51a
* B	1	3.86z,d	4.13y,c	4.52y,b	4.77x,a	4.76x,a
	2	4.23x,c	4.48x,b	4.65x,a	4.64y,a	4.64y,a
	3	4.08y,b	4.49x,a	4.59xy,a	4.58y,a	4.55z,a
Mean		4.06c	4.37b	4.59a	4.66a	4.65a
AB Mean*		3.88d	4.32c	4.51b	4.58a	4.58a

1 Initial pH: A = 4.40, B = 4.61, AB = 4.50.

* Treatment means followed by the same letter are not significantly different at the .05 level of probability.

Letters x,y,z compare means between soil levels within the same soil horizon - precipitation pH combination.

Letters a,b,c,d compare means between precipitation pH levels within the same horizontal division of the table.

in the middle and bottom soil levels. This interaction illustrated the greater impact of precipitation acidity on the uppermost layer of mineral soil, and the tendency for changes in soil pH to proceed from the top to bottom within a soil profile.

The significant three-way interaction was interpreted from the standpoint that the interaction between soil level and precipitation pH differed depending on the soil horizon (Figure 6.1). At precipitation pH levels 3.0 and 2.5, the upper level of B horizon soil was acidified to a greater degree than the corresponding level of A horizon soil. At precipitation pH level 2.0, acidification was pronounced in all three soil levels in A horizon soil, being most acid in the top level and least acid in the bottom level. On B horizon soil at precipitation pH level 2.0, acidification occurred to a lesser degree in upper and middle soil levels than in A horizon soil. The bottom level in the B horizon soil was significantly lower in pH than the middle level, so acidification did not proceed in the same manner as in A horizon soil.

The relative differences in acidification of the upper level of A horizon soil as compared to B horizon soil indicated a difference between soil horizons in buffering effectiveness occurring at different precipitation pH levels. At precipitation pH levels 2.5 and 3.0, acidification was more intense on B horizon soil due to the lower levels of exchangeable cations and resulting higher

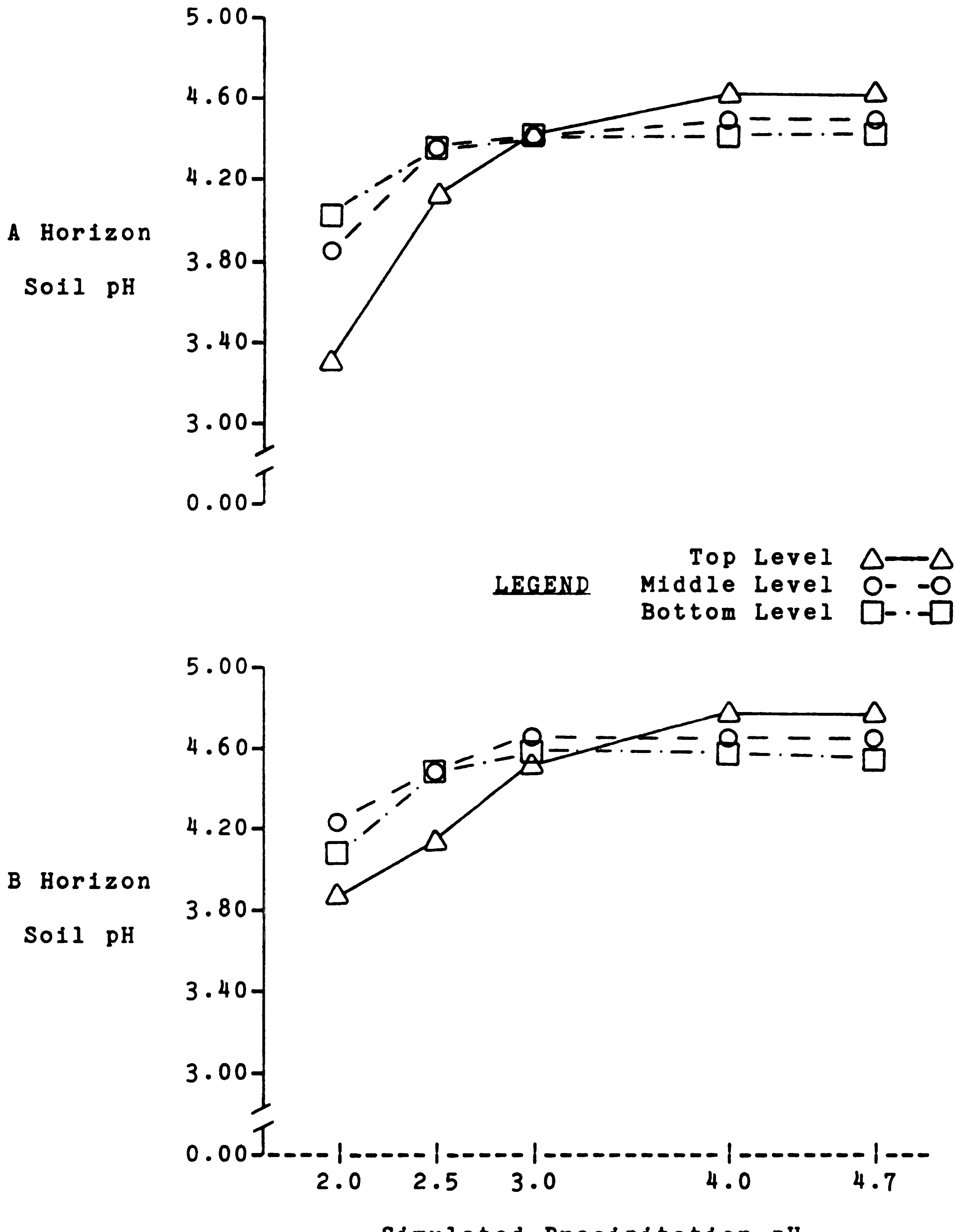

Figure 6.1

pH in Three Levels of A and B Horizon Soil ratio of hydrogen ions to exchangeable cations on B horizon soil as compared to A horizon soil. At precipitation pH level 2.0 on A horizon soil, as exchangeable cations were depleted by leaching, soil pH rapidly declined. On B horizon soil at pH level 2.0, acidification was not as rapid due to higher aluminum and iron buffering coupled with maintenance of levels of exchangeable cations. These effects will be examined in greater detail in conjunction with the discussion of basic cations.

The soil acidification evident commencing at precipitation pH 3.0 and intensifying at pH levels 2.5 and 2.0 can be directly attributed to the input of sulfuric and nitric acids in simulated precipitation. The effectiveness with which these inorganic acids supply hydrogen ions to the soil and produce acidification is noted in Brady (1974). The increase in pH of upper soil levels in both A and B horizon soils at precipitation pH levels 4.0 and 4.7 is consistent with the observation by Wiklander (1978b) that if the cation:hydrogen ion ratio is higher in precipitation than in soil solution, soil pH will increase. At lower precipitation pH levels, the cation:hydrogen ion ratio would be lower in precipitation than in soil solution and soil pH would decrease, as was observed at precipitation pH levels 3.0, 2.5, and 2.0.

Upward movement of salts due to evaporation might also tend to increase soil pH in upper soil levels unless counterbalanced by leaching losses. This process could have influenced the observed pH levels in the upper soil level. At pH 4.0 and 4.7, leaching of cations downward would be less than the accumulation of salts due to evaporation of water from the soil surface. As pH of precipitation decreased, leaching of cations would be accelerated due to the higher exchange with hydrogen ions. Net movement of cations would be downward, and soil acidification would be intensified.

The occurrence of soil acidification and progression from top downward noticeable at pH levels 3.0, 2.5, and 2.0, agree with reports by Overrein (1972), Ogner (1980), Alexander (1980), and Bjor and Teigen (1980). In contrast to the results of a long term field study reported by Abrahamsen et al. (1976), no evidence of soil acidification was present on either soil at pH level 4.0. The elevated pH in the top level of both soils at precipitation pH levels 4.0 and 4.7 observed in the present study, however, may be an artifact of the incremental application of simulated precipitation favoring water loss from soil via evaporation and transpiration over leaching. As such, they may not be a true indication of the rates of soil acidification to be expected under field conditions in northern lower Michigan.

BASIC CATIONS

In this section, the effects of simulated acid precipitation on concentrations of exchangeable and total calcium, potassium, magnesium, and sodium will be examined.

Significant treatment effects on exchangeable calcium included main effects of precipitation pH, interaction between soil horizon and precipitation pH, interaction between soil level and precipitation pH, and the three-way interaction between factors. These results are presented in Table 6.3.

The significant soil horizon by precipitation pH interaction indicated that the effect of precipitation pH depended on soil horizon. On A horizon soil, exchangeable calcium was significantly reduced at pH 2.0. On B horizon soil, no significant differences in exchangeable calcium between pH levels were found.

The significant soil level by precipitation pH interaction indicated that the effect of precipitation pH also differed according to soil level. The significant three-way interaction between factors indicated a difference in the soil level by precipitation pH interaction between soil horizon types (Figure 6.2). On B horizon soil, there was no significant effect of precipitation pH on levels of exchangeable calcium within the three soil levels. In contrast, there was a marked decrease in exchangeable calcium from A horizon soil at precipitation pH levels 2.5 and 2.0. These results indicate a progressive leaching of exchangeable calcium from the upper soil levels of A horizon soil commencing at pH 2.5. Significant decrease in exchangeable calcium also occurred at pH 2.0 in the middle soil level. In the bottom level of A horizon soil,

Table 6.3

Soil Concentrations of Exchangeable and Total Calcium

Soil	Level	Concentration at pH Level 2.0	2.5	3.0	4.0	4.7
		Exchangeable Calcium (ppm)[1]				
* A	1	44.4z,c	77.4y,b	112.3x,a	113.1x,a	115.1x,a
A	2	77.4y,b	128.1x,a	123.3x,a	112.8x,a	113.3x,a
A	3	124.8x,a	124.1x,a	120.6x,ab	108.1x,b	114.6x,ab
Mean		82.2b	109.8a	118.7a	111.3a	114.3a
B	1	23.9	15.1	19.9	23.7	23.8
B	2	25.1	23.7	21.7	19.1	19.7
B	3	25.6	24.7	22.7	20.1	22.0
Mean		24.9	21.2	21.4	20.9	21.8
AB Mean*		53.6b	65.5a	70.0a	66.1a	68.0a
		Total Calcium (ppm, averaged over soil horizon)[2]				
* AB	1	562y,b	588y,ab	604x,ab	656x,a	629x,ab
AB	2	630x,a	610xy,a	562x,a	598xy,a	623x,a
AB	3	598xy,ab	653x,a	614x,ab	582y,b	615x,ab
Mean		596	617	594	612	622

1 Inital exchangeable Ca: A = 105.7, B = 19.8, AB = 62.8 ppm.

2 Inital total Ca: A = 671, B = 597, AB = 634 ppm.

* Treatment means followed by the same letter are not significantly different at the .05 level of probability.

Letters x,y,z compare means between soil levels within the same soil horizon - precipitation pH combination.

Letters a,b,c compare means between precipitation pH levels within the same horizontal division of the table.

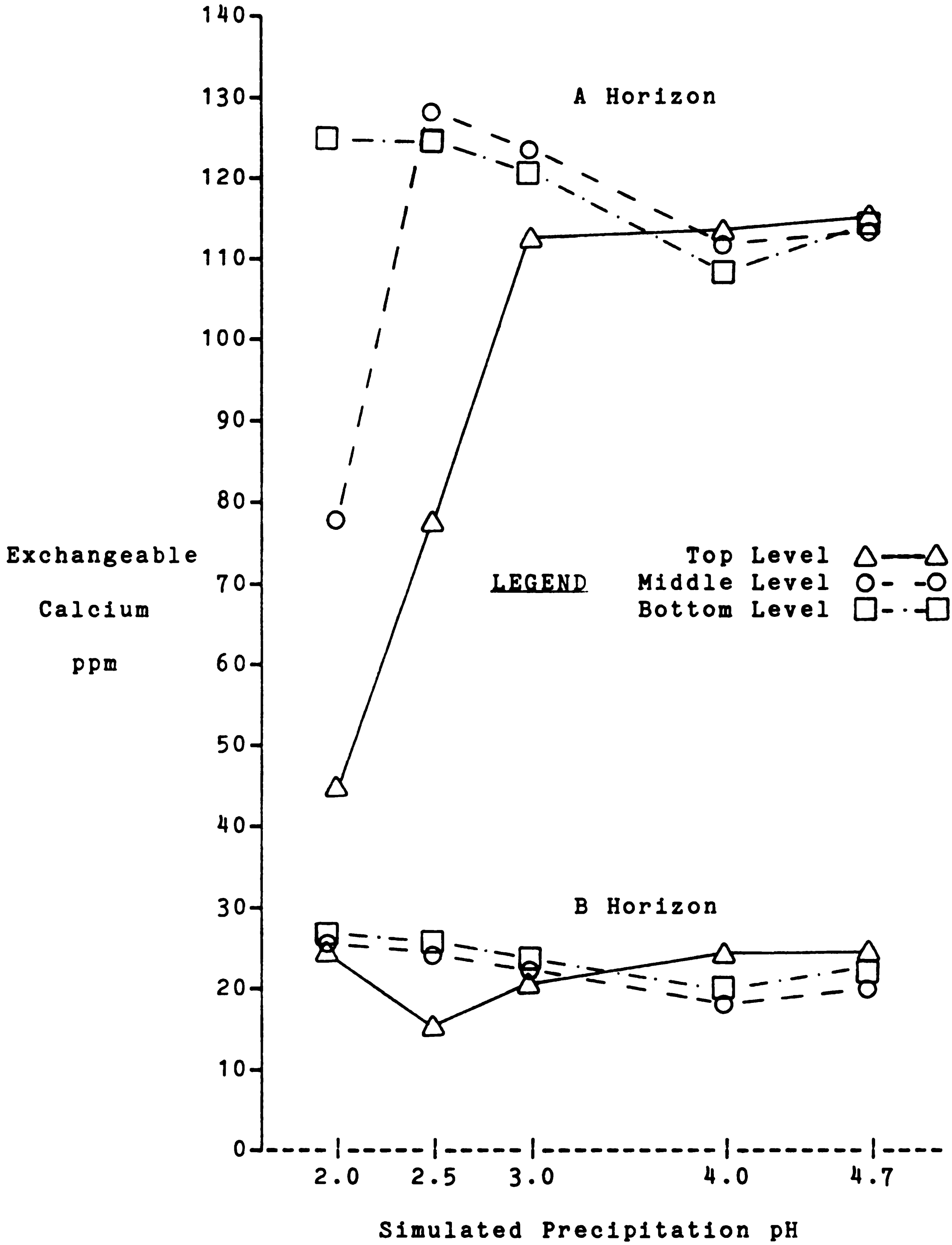

Figure 6.2

Exchangeable Calcium in Three Levels
of A and B Horizon Soil

concentration of exchangeable calcium at pH 2.0 and 2.5 was significantly higher than at pH 4.0, indicating an accumulation of calcium leached from upper soil levels at pH 2.0 and 2.5.

In examining concentration of total calcium (Table 6.3), a significant soil level by precipitation pH interaction was found. In the upper soil level, concentration of total calcium, averaged over A and B soil horizons, was reduced at pH 2.0 as compared to pH 4.0. In the bottom soil level, total calcium was higher at pH 2.5 than at pH 4.0, as a result of an accumulation of calcium at the bottom level of soil at pH 2.5.

These effects are evidence of translocation through the soil column. Increased leaching of total calcium was evident for both A and B horizon soils. The maintenance of levels of exchangeable calcium in B horizon soil suggests that inputs from weathering and precipitation balanced leaching loss on B horizon soil. In contrast, these inputs in A horizon soil were lower than the leaching losses of exchangeable cations from upper levels of soil occurring at pH 2.0 and 2.5.

A significant interaction between soil level and precipitation pH was present for exchangeable potassium, as well as a three-way interaction between factors. These results are presented in Table 6.4. No significant effect of precipitation pH on concentration of exchangeable potassium in B horizon soil was present at any soil level.

Table 6.4

Soil Concentrations of Exchangeable and Total Potassium

Soil	Level	Concentration at pH Level 2.0	2.5	3.0	4.0	4.7
		Exchangeable Potassium (ppm)[1]				
*	1	17.7z,c	20.4y,bc	25.2x,ab	26.1x,a	26.4x,a
A	2	25.8y,a	22.5xy,a	23.1x,a	22.6y,a	22.9y,a
	3	36.7x,a	25.0x,b	24.6x,b	24.4xy,b	25.9xy,b
Mean		26.7a	22.6b	24.3a	24.4ab	25.1a
*	1	13.9y	9.9z	11.6z	13.2y	13.1y
B	2	16.8y	14.6y	15.2y	15.0xy	14.9y
	3	20.9x	19.8x	19.8x	17.7x	20.9x
Mean		17.2	14.8	15.5	15.3	16.3
		Total Potassium (ppm, averaged over soil horizon)[2]				
*	1	471a	463a	472a	479a	466a
AB	2	489a	454ab	445b	446b	475ab
	3	454a	479a	475a	455a	478a
Mean		472	465	464	460	472

1 Initial exchangeable K: A = 27.2, B = 17.3 ppm.

2 Inital total K: AB = 494 ppm.

* Treatment means followed by the same letter are not significantly different at the .05 level of probability.

Letters x,y,z compare means between soil levels within the same soil horizon - precipitation pH combination.

Letters a,b,c compare means between precipitation pH levels within the same horizontal division of the table.

The significantly lower concentrations of exchangeable potassium in the top soil level at all pH levels is evidence of a uniform leaching of potassium in B horizon soil regardless of precipitation pH. In A horizon soil, leaching of potassium from the surface layer at pH 2.0 and 2.5 was evident, as was a noticeable accumulation of potassium in the bottom level at pH 2.0 (Figure 6.3).

Concentration of total potassium was not significantly affected by precipitation pH on either soil horizon, but a significant interaction between soil level and precipitation pH indicated that soil levels were responding differently to precipitation acidity (Table 6.4). Total potassium in top and bottom soil levels, averaged over soil horizons, did not differ significantly between precipitation pH levels. In the middle soil level, total potassium was significantly lower at pH levels 3.0 and 4.0 than at pH 2.0. This difference may be the result of the combined effects of uptake of potassium by jack pine seedlings at pH 3.0 and 4.0, and the accumulation at pH 2.0 of potassium leached from the upper soil level. The retention of potassium in the middle level of soil at pH 2.0 could be the result of higher sulfate adsorption expected in acidified soil, as suggested by Frink and Voigt (1977), and Johnson and Cole (1977). The retention of potassium at pH 2.0 would be consistent with sulfate adsorption, since cations are immobilized with sulfate in the soil (Johnson, 1978). Sandy soils, such as the Grayling, may have considerable sulfate adsorption

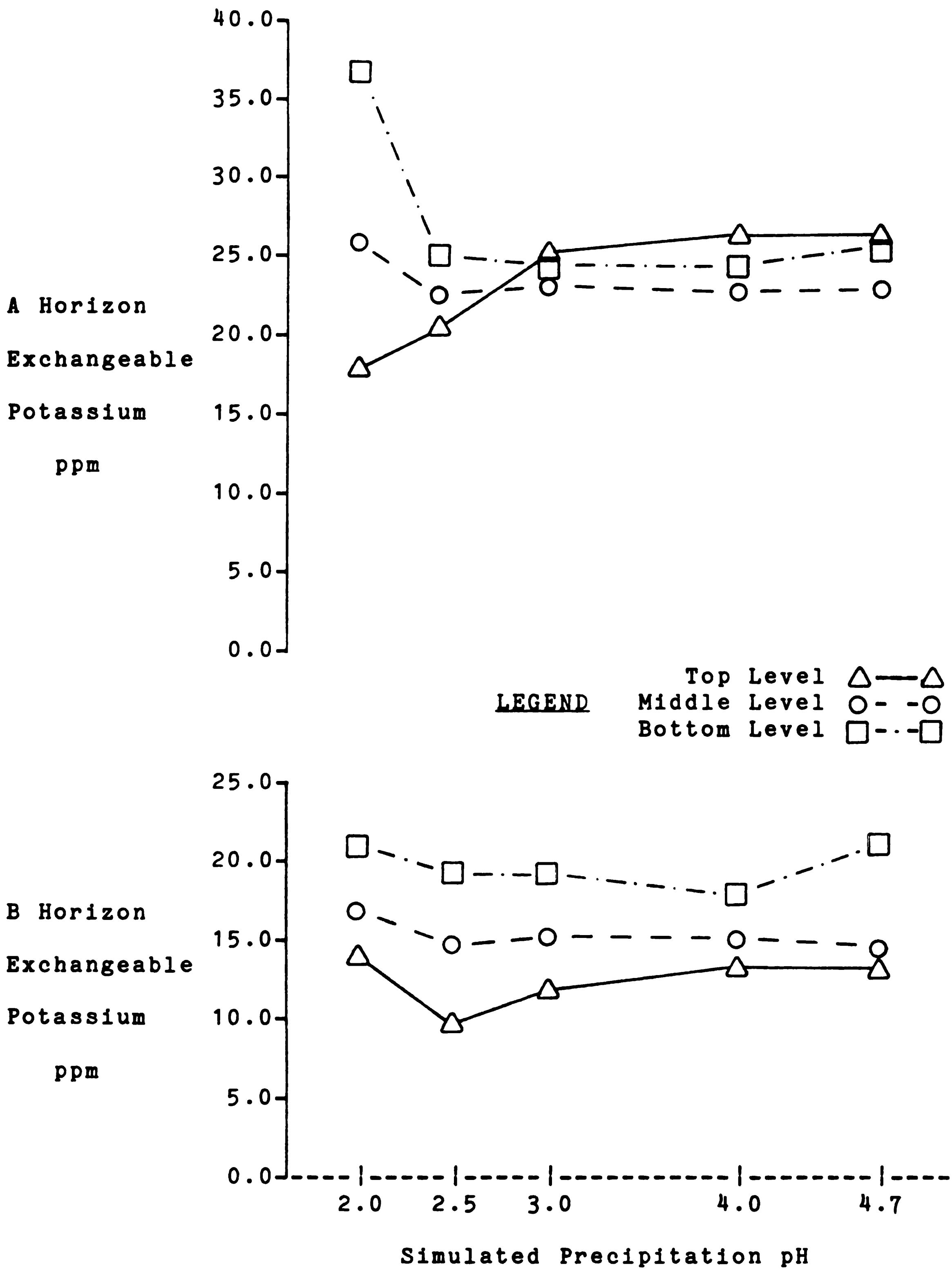

Figure 6.3

Exchangeable Potassium in Three Levels
of A and B Horizon Soil

capacity as was demonstrated by Morrison (1981).

Analysis of exchangeable magnesium data revealed an interaction between soil level and precipitation pH, with the significant three-way interaction between factors indicating a difference between soil horizons in the soil level by precipitation pH interaction (Table 6.5). Exchangeable magnesium in B horizon soil did not exhibit any significant effects related to precipitation pH. In the A horizon soil, exchangeable magnesium was reduced in the upper level at pH 2.5, and in the middle soil level at pH 2.0, suggesting a depletion of exchangeable magnesium due to accelerated leaching.

A significant soil level by precipitation pH interaction was found for total magnesium concentration (Table 6.5). Total magnesium, averaged over soil horizons, did not differ significantly between precipitation pH levels in top or bottom soil levels. In the middle soil level, total magnesium at pH 3.0 was significantly reduced as compared to concentrations at pH 4.7 or 2.0. This may have been due to depletion of magnesium at pH 3.0 by seedling uptake in conjunction with increased mobility of magnesium due to input of acid precipitation. At pH 2.0, magnesium was not subject to uptake by seedlings, and may have accumulated and been retained in the soil in conjunction with adsorbed sulfate.

In contrast to the other basic cations, concentrations of exchangeable and total sodium were not significantly

Table 6.5

Soil Concentrations of Exchangeable and Total Magnesium

Soil	Level	Concentration at pH Level 2.0	2.5	3.0	4.0	4.7
		Exchangeable Magnesium (ppm)[1]				
*	1	18.7x,a	11.6y,b	18.6x,a	19.2x,a	21.8x,a
A	2	10.9y,b	20.8x,a	21.2x,a	18.9x,a	19.3x,a
	3	19.4x,a	20.1x,a	18.5x,a	18.5x,a	19.6x,a
Mean		16.3b	17.5a	19.4a	18.9a	20.2a
	1	7.9	5.5	6.2	8.0	8.6
B	2	6.1	5.2	6.5	5.5	5.1
	3	6.0	7.6	5.6	4.8	5.5
Mean		6.7	6.1	6.1	6.1	6.4
		Total Magnesium (ppm, averaged over soil horizon)[2]				
*	1	526x,a	531x,a	521xy,a	532x,a	519x,a
AB	2	539x,a	516x,ab	479y,b	499x,ab	530x,a
	3	498x,b	529x,ab	549x,a	515x,ab	531x,ab
Mean		521	526	516	516	526

1 Initial exchangeable Mg: A = 17.2, B = 5.4 ppm.

2 Initial total Mg: AB = 560 ppm.

* Treatment means followed by the same letter are not significantly different at the .05 level of probability.

Letters x,y compare means between soil levels within the same soil horizon - precipitation pH combination.

Letters a,b compare means between precipitation pH levels within the same horizontal division of the table.

affected by precipitation pH. This is unexpected in that sodium is one of the most loosely held of the metallic ions and is readily lost in leaching waters (Tisdale and Nelson, 1975). This ease of leaching, however, might account for the lack of differences observed between pH levels in that leaching losses at pH 4.7 would be naturally high, and any increased loss due to increased precipitation acidity would be minor. This hypothesis is supported by the significant soil level main effects present for exchangeable sodium (Table 6.6). Exchangeable sodium, averaged over soil horizon and precipitation pH, was significantly lower in the top soil level than in the bottom soil level. This effect was also suggested by the lower concentrations of total sodium in top and middle soil levels than in the bottom level, but the soil level means for total sodium were not significantly different. The reduction in exchangeable sodium in the upper soil level indicated that leaching of sodium was occurring, but the rate of leaching was independent of precipitation pH or soil horizon type.

With the exception of sodium, the response of basic cations to input of simulated acid precipitation were in general agreement with reports in the literature of increased leaching of cations at pH levels of 2.5 and below. Losses of basic cations were not evident at pH levels 3.0 and 4.0, as reported by Overrein (1972), Abrahamsen et al. (1976), and Wood and Bormann (1977). The short duration of the present study and small amounts of precipitation applied

Table 6.6

Soil Concentrations of Exchangeable and Total Sodium

	Concentration at Soil Level		
Soil	Top(1)	Middle(2)	Bottom(3)
Exchangeable Sodium (ppm, averaged over precipitation pH)[1]			
A	9.6	12.6	12.1
B	8.3	8.4	11.8
Mean*	8.9y	10.5xy	11.9x
Total Sodium (ppm, averaged over precipitation pH)[2]			
A	37.0	36.3	38.3
B	37.3	37.7	38.3
Mean	37.2	37.0	38.3

1 Inital exchangeable Na: A = 9.3, B = 8.5, AB = 8.9 ppm.

2 Inital total Na: A = 35.6, B = 37.8, AB = 36.7 ppm.

* Treatment means followed by the same letter are not significantly different at the .05 level of probability.

per treatment account for the restriction of leaching effects to the lower pH levels.

Translocation of cations displaced by hydrogen ions would be influenced by water movement within the soil. At pH levels 2.5 to 4.7, water movement in the soil was determined by saturated flow, transpiration of seedlings, and evaporation. At pH 2.0, where few seedlings survived, water movement would be determined to a large extent by saturated flow and evaporation. Final cation concentrations in soil levels at pH 2.0 would be the result of a balance between downward leaching with percolating precipitation and upward movement during evaporative water loss. Accumulation of salts would occur in the soil at the point where the two processes balanced one another. This process may be in part responsible for elevated concentrations of total magnesium and potassium noted in the middle soil level at pH 2.0.

Another factor affecting movement of cations is anion adsorption in the soil. Anion adsorption would increase at lower precipitation pH levels due to soil acidification, and would be higher in B horizon soil due to higher aluminum and iron contents. The higher capacity to adsorb anions such as sulfate, and thereby reduce leaching of cations, would account for the lack of decrease in exchangeable cations noted on B horizon soil. In contrast, leaching of exchangeable calcium and potassium was evident on A horizon soil, possibly as a result of higher initial levels of these cations and lower sulfate retention. This result agrees with the findings of Morrison (1981), where higher sulfate adsorption capacity in the B horizon of a sandy soil was related to greater resistance to sulfuric acid leaching. The anion adsorption capacity of the Grayling sand and its relationship to cation retention warrant further investigation.

Loss of exchangeable cations from the upper levels of A horizon soil was also related to soil acidification. Soil pH in the top soil level was positively correlated with exchangeable calcium (.96) and exchangeable potassium (.85). Soil pH in the middle level was positively correlated with exchangeable calcium (.82) and exchangeable magnesium (.72). In contrast, the pH of B horizon soil was not correlated with concentration of exchangeable cations in the top level, and was negatively correlated with exchangeable calcium in the middle (-.39) and bottom (-.46) soil levels.

These correlations support the hypotheses expressed below. Buffering in A horizon soil was associated with concentration of exchangeable cations. The development of acidity in upper levels of A horizon soil was encouraged by leaching, since cations were removed which would compete with hydrogen ions and aluminum on the exchange complex (Brady, 1974). Acidification of B horizon soil, and the lower level of A horizon soil, was not associated with leaching of cations, but would result from the absolute increase in hydrogen ions relative to basic cations. On B horizon soil, acidification at pH 2.0 was less intense than experienced on A horizon soil as a result of the greater buffering capacity imparted by higher levels of iron and aluminum oxides in the B horizon.

NITROGEN AND ORGANIC MATTER

The main effect of precipitation pH on total Kjeldahl nitrogen concentration was significant (Table 6.7). Nitrogen concentration, averaged over A and B horizon soils, was significantly higher at pH 2.0 than at pH 3.0. This result can be attributed to a combination of causes. Nitrogen deposition per experimental unit was much greater at pH 2.0 (1277 mg) than at pH 3.0 (86 mg). Soil acidification at pH 2.0 would increase anion retention in the soil, which would encourage an accumulation in the soil of nitrate deposited in precipitation. Average total nitrogen uptake per experimental unit by jack pine seedlings was greater at pH 3.0 (110 mg) as compared to pH 2.0 (4 mg), which would also account for some of the difference observed. Uptake of nitrogen was especially important from this aspect on B horizon soil, where total uptake of nitrogen by seedlings was negatively correlated (-.51) with total soil nitrogen. This suggests that soil nitrogen was decreased as a result of uptake of nitrogen by seedlings.

Analysis of organic matter data showed that main effects of precipitation pH were significant, as well as the interaction between soil horizon and precipitation pH (Table 6.7). Organic matter content in B horizon soil was not

Table 6.7

Soil Concentrations of Nitrogen and Organic Matter

Soil	Concentration at pH Level 2.0	2.5	3.0	4.0	4.7
Total Kjeldahl Nitrogen (%, averaged over soil level)[1]					
A	.091	.088	.087	.086	.086
B	.056	.052	.047	.051	.050
Mean*	.074a	.070ab	.067b	.068ab	.068ab
Organic Matter (%, averaged over soil level)[2]					
A *	2.70a	2.57ab	2.53b	2.56ab	2.44b
B	1.67	1.55	1.64	1.58	1.62
Mean	2.18a	2.06b	2.08ab	2.07b	2.03b

1 TKN data statistically analyzed as Log[ppm].
Initial TKN: A = .095, B = .051, AB = .073 %.

2 Initial OM: A = 2.54, B = 1.47, AB = 2.01 %.

* Treatment means followed by the same letter are not significantly different at the .05 level of probability.

Letters a,b compare means between precipitation pH levels within the same horizontal division of the table.

significantly affected by precipitation pH, in contrast to A horizon soil where organic matter was significantly lower at pH levels 3.0 and 4.7 than at pH 2.0. On A horizon soil, the lower organic matter contents at higher precipitation pH levels would result from the higher microbial activity and decomposition of organic matter expected to proceed at the higher pH levels. Soil acidification at pH 2.0 would decrease microbial activity and decomposition, resulting in higher residual levels of soil organic matter.

Organic matter content of B horizon soil was not affected due to the small amount present, low level of exchangeable calcium, and resulting low activity of microbes (Brady, 1974). The organic matter present in the B horizon would not experience rapid decomposition due to its origin from the illuviation of resistant fractions of organic matter transported from upper soil horizons.

The higher organic matter levels found at pH 2.0 in A horizon soil agree with results in the literature. Francis et al. (1980) found a fourteen percent decrease in organic matter decomposition in soil acidified to pH 3.5 as compared to the soil at its natural pH of 4.6. Alexander (1980) found that treatment with pH 3.2 acid rain greatly reduced glucose mineralization rate in four soils, while pH 4.1 had no effect. He suggested that these results indicated inhibition of soil organic matter decomposition.

Reduction in the decomposition of soil organic matter as a result of acid precipitation would affect nitrogen cycling in forest ecosystems by reducing the mineralization of organic nitrogen. This would be important in acid forest soils since rates of nitrification and nitrogen fixation are low and ammonium supplied by the process of ammonification is a principal source of soil nitrogen to trees (Abrahamsen et al., 1975; Tamm, 1976; Alexander, 1978; Pritchett, 1979). Alexander (1980) contended that conversion of organic nitrogen to ammonium does not show a marked pH sensitivity due to the broad range of fungi, bacteria, and actinomycetes that contribute to the process. Tamm (1976) reported that short term increases in ammonification occurred after soil acidification in laboratory studies, but acidification in field experiments showed a tendency to decrease ammonification. Francis et al. (1980) determined that acidification of a sandy loam oak-pine forest soil to less than pH 3.5 caused significant reduction in ammonification as compared to the natural soil pH of 4.6. It appears that in soils more acid than pH 5.0, nitrogen cycling is adapted to ammonification which would be adversely affected only by extreme increases in soil acidity. This conclusion is supported by the results of the present study, in which soil organic matter decomposition was adversely affected only by precipitation pH 2.0 and acidification of soil below pH 4.0.

PHOSPHORUS

Levels of total phosphorus in A and B horizon soils were not significantly affected by precipitation pH (Table

6.8). This result is not surprising, since as soil acidity increases, soluble phosphates are markedly fixed as complex and insoluble compounds of the elements iron, aluminum, and manganese (Brady, 1974). This fixation is most apparent when soil pH is below 5.0, and loss of phosphorus to leaching would be insignificant. Because of the high fixation of phosphorus in acid soils, the expected effect of soil acidification caused by acid precipitation would be a decrease in the availability of phosphorus to plants.

Extractable phosphorus concentrations, however, did not indicate a decrease in phosphorus availability in Grayling sand treated with simulated acid precipitation. The main effect of precipitation pH was significant, with a significant soil horizon by precipitation pH interaction indicating a difference in effect of precipitation pH level between soil horizons (Table 6.8). On B horizon soil, there were no significant differences in extractable phosphorus between precipitation pH levels. In comparison, extractable phosphorus in A horizon soil was significantly greater at pH levels 2.0 and 2.5 than at pH levels 3.0, 4.0, and 4.7. Comparing concentrations between soils, the A horizon was significantly lower in phosphorus at pH levels 3.0 and 4.0, but significantly higher in phosphorus at pH 2.0 than B horizon soil.

Soil extractable phosphorus concentrations were negatively correlated with seedling uptake on both A horizon (-.81) and B horizon (-.65) soils, suggesting that

Table 6.8

Soil Concentrations of Total and Extractable Phosphorus

Soil	Concentration at pH Level 2.0	2.5	3.0	4.0	4.7
Total Phosphorus (%, averaged over soil level)[1]					
A	.015	.012	.013	.013	.013
B	.009	.011	.012	.011	.010
Mean	.012	.012	.013	.012	.012
Extractable Phosphorus (ppm, averaged over soil level)[2]					
A *	10.5x,a	9.4x,b	8.6y,c	8.4y,c	8.7x,c
B	9.3y,a	9.1x,a	9.0x,a	9.1x,a	9.0x,a
Mean	9.9a	9.3b	8.8c	8.7c	8.9bc

1 TP data statistically analyzed as Log[ppm].
Initial total P: A = .021, B = .016, AB = .019 %.

2 Bray 1 extraction. Initial extractable P: A = 9.5, B = 9.6, AB = 9.6 ppm.

* Treatment means followed by the same letter are not significantly different at the .05 level of probability.

Letters x,y compare means between soil levels within the same soil horizon - precipitation pH combination.

Letters a,b,c compare means between precipitation pH levels within the same horizontal division of the table.

extractable phosphorus decreased in response to phosphorus uptake by jack pine seedlings. Average total uptake of phosphorus per experimental unit in seedling tops on A horizon soil (7.3 mg) was more than twice as great as on B horizon soil (3.3 mg) at pH levels 3.0, 4.0, and 4.7. Phosphorus uptake by seedlings at pH 2.5, due to lower survival of seedlings on A horizon soil, was approximately equal for both A (4.6 mg) and B (3.4 mg) horizon soils. Since extractable phosphorus levels were initially equal for both soils, the greater uptake of phosphorus by A horizon seedlings would account for the significantly reduced phosphorus concentration at pH 3.0 and 4.0 on A horizon soil. At pH 4.7, A horizon phosphorus concentration was also reduced below that of the B horizon, but this difference was not significant. At pH 2.5, concentration of extractable phosphorus was similar for both soils. This may be due to the approximately equal uptake of phosphorus from both soils by seedlings at this pH level. At pH 2.0, differences in seedling uptake were not important due to the very low survival of seedlings at this pH level.

The significantly higher extractable phosphorus on A horizon soil could result from a combination of differences between soils and their reaction with pH 2.0 acid precipitation. Since phosphate adsorption in acid soils is mediated by hydrous oxides of iron and aluminum, the lower concentration of extractable phosphorus found on B horizon soil at pH 2.0 was the expected consequence of its higher aluminum and iron content. Organic acids and humus will markedly reduce phosphate adsorption by forming complexes with iron and aluminum compounds (Beek and Van Riemsdijk, 1979; Mott, 1981). The higher concentration of extractable phosphorus in A Horizon soil at pH 2.0 may thus be related to its higher organic matter level and resulting higher content of organic acids than in B horizon soil.

The increased deposition of sulfate at lower precipitation pH levels might also influence the amount of phosphorus extracted from the soil. Sulfate may compete with phosphate for adsorption sites, since the reaction of hydrous oxides with anions is not necessarily determined by the relative displacing power of the anion (Mott, 1981). At precipitation pH levels 2.0 and 2.5, high rates of sulfate input might increase "available" phosphorus through the process of anion exchange. The reaction of sulfuric acid from precipitation with iron and aluminum phosphates in the soil would cause a breakdown of these compounds and a release of phosphate. The presence of sulfate ions would prevent readsorption of some of the phosphate released by reaction with hydrogen ions (Bickelhaupt, 1980). The B horizon soil, with higher anion adsorption capacity, might effectively adsorb both sulfate and phosphate so that no significant increase in extractable phosphorus would be evident.

The confounding effect of seedling uptake of phosphorus at pH levels 2.5 to 4.7 makes an accurate assessment of the effects of acid precipitation on availability of phosphorus based on extractable phosphorus difficult. Average seedling concentration of phosphorus, discussed in the next chapter, was a more sensitive indicator of true phosphorus availability at precipitation pH levels 2.5 to 4.7.

ALUMINUM AND IRON

Precipitation pH did not significantly affect total aluminum concentration on either soil (Table 6.9). Reports in the literature indicated increased leaching of aluminum from soils treated with simulated precipitation at pH levels from 2.5 to as high as 4.3 (Abrahamsen et al., 1976; Hutchinson, 1978; Singh et al., 1980; Bjor and Teigen, 1980). The results of soil analyses in the present study indicated that total aluminum was not reduced significantly by eleven weeks of treatment with precipitation at pH levels as acid as 2.0.

Total concentrations of iron, averaged over A and B horizon soil, were found to be significantly higher at lower pH levels (Table 6.9). These results indicated that loss of iron from the soil, presumably by leaching, was higher at pH levels 3.0 and above than at pH levels 2.5 and below. These results are somewhat anomalous in view of reports in the literature of increased leaching of iron from soils treated at pH levels 2.5 to 3.0 (Abrahamsen et al, 1976; Hutchinson, 1978). The results of the present study, however, may only be indicative that analysis for total iron was a less

Table 6.9

Soil Concentrations of Total Aluminum and Iron

	Concentration at pH Level				
Soil	2.0	2.5	3.0	4.0	4.7
Total Aluminum (ppm, averaged over soil level)[1]					
A	4719	4628	4768	4785	4919
B	5647	5698	5685	5729	5843
Mean	5183	5163	5226	5257	5381
Total Iron (ppm, averaged over soil level)[2]					
A	4462	4312	4075	4051	4147
B	4836	4794	4608	4514	4606
Mean*	4649a	4553ab	4342bc	4282c	4376bc

1 Initial total Al: A = 4820, B = 6108, AB = 5464 ppm.

2 Initial total Fe: A = 4332, B = 5256, AB = 4794 ppm.

* Treatment means followed by the same letter are not significantly different at the .05 level of probability.

sensitive measure of leaching than actual collection and analysis of leachate.

The retention of iron and aluminum at pH level 2.0 may be related to the high influx of sulfate at this level. In acid sulfate soils at soil pH levels below 4.0, aluminum and iron oxides will react with sulfate and cations such as potassium to form minerals which then precipitate (Lindsay, 1979). Such a reaction could also be involved in the retention of both iron and aluminum in the extremely acidified soil at the pH 2.0 level. This hypothesis agrees with the suggestion by Nordstrom (1982) that aluminum and sulfate are retained as basic aluminum sulfates in soils undergoing acidification by sulfuric acid. At precipitation pH levels 3.0 and above, soil reaction in both A and B horizon soils would be in the range reported by Norton et al. (1980) at which solubility of iron occurs. At these precipitation pH levels, leaching of iron could occur, where at pH levels 2.0 and 2.5, high influx and adsorption of sulfate could reduce mobility and leaching loss of iron. The hypothesized interaction between iron, aluminum, and precipitation borne sulfate in the Grayling sand deserves further investigation.

MICRONUTRIENTS

Discussion of the effects of simulated acid precipitation on concentrations of micronutrients includes results on total levels of boron, manganese, zinc, nickel, copper, and chromium. These results are presented in Table 6.10.

Analysis of total concentrations of manganese indicated a significant precipitation pH main effect and a three-way interaction between factors. Depletion of manganese was most evident from the upper soil level of A horizon soil at pH 2.0 (Figure 6.4). Reduction in total manganese from the top level of A horizon soil, and to a lesser extent from B horizon soil, resulted from leaching of manganese in response to extreme acidity. In the bottom level of B horizon soil at pH 3.0, the elevated concentration of manganese may be the result of leaching from upper soil levels and accumulation in the bottom soil level.

Hutchinson (1978) and Bjor and Teigen (1980) reported leaching losses of manganese from soils treated at precipitation pH levels 2.5 and 3.0. While the results of the present study generally agree with the hypothesis that manganese leaching losses would increase at lower precipitation pH levels, strong evidence of this was found only at pH 2.0.

Total nickel concentrations, averaged over A and B horizon, were significantly higher at pH 4.7 than at all lower pH levels. This result was consistent with the expected increased solubility and leaching of nickel from soils receiving acid precipitation.

In contrast to manganese and nickel, total concentrations of boron and zinc tended to be higher at the

Table 6.10

Soil Concentrations of Total Manganese, Nickel, Boron, Zinc, Copper, and Chromium

Soil	Level	Concentration at pH Level 2.0	2.5	3.0	4.0	4.7
		Total Manganese (ppm)[1]				
*	1	142y,b	233x,a	266x,a	254x,a	234x,a
A	2	273x,a	265x,a	239x,a	249x,a	264x,a
	3	257x,a	253x,a	269x,a	242x,a	250x,a
Mean		224b	250a	258a	248a	249a
*	1	108y,b	136x,ab	148y,a	156x,a	140x,ab
B	2	163x,a	147x,a	134y,a	129x,a	146x,a
	3	144y,b	155x,ab	189x,a	140x,b	144x,b
Mean		138	146	157	142	143
AB Mean *		181b	198a	208a	195ab	196a
		Total Nickel (ppm, averaged over soil level)[2]				
A *		2.62b	2.60b	2.67b	2.68b	2.86a
B		2.77b	2.76b	2.82b	2.86ab	3.00a
Mean		2.70b	2.68b	2.74b	2.77b	2.93a
		Total Boron (ppm, averaged over soil level)[3]				
A		3.79	3.72	4.12	3.62	3.56
B		4.20	3.84	3.78	3.76	3.77
Mean *		4.00a	3.78ab	3.95a	3.69b	3.67b
		Total Zinc (ppm, averaged over soil level)[4]				
A *		17.2a	16.9ab	16.1ab	15.8b	16.5ab
B		13.2	13.1	12.5	12.2	12.3
Mean		15.2a	15.0a	14.3ab	14.0b	14.4ab

Table 6.10 (continued)

Soil Level	Concentration at pH Level 2.0	2.5	3.0	4.0	4.7
Total Copper (ppm, averaged over soil level)[5]					
A	2.66	2.46	2.59	2.46	2.62
B	2.09	2.04	1.90	1.92	2.05
Mean	2.38	2.25	2.25	2.19	2.34
Total Chromium (ppm, averaged over soil level)[6]					
A	4.79	4.40	4.42	4.60	4.59
B	4.39	4.56	4.53	4.65	4.59
Mean	4.59	4.48	4.48	4.62	4.59

1 Initial total Mn: A = 264, B = 160, AB = 212 ppm.

2 Initial total Ni: A = 2.68, B = 3.04, AB = 2.86 ppm.

3 Boron data statistically analyzed as Log[ppm].
Initial total B: A = 5.41, B = 4.74, AB = 5.07 ppm.

4 Initial total Zn: A = 16.1, B = 13.0, AB = 14.6 ppm.

5 Copper data statistically analyzed as Log[ppm].
Initial total Cu: A = 2.35, B = 2.33, AB = 2.34 ppm.

6 Initial total Cr: A = 4.81, B = 4.81, AB = 4.81 ppm.

* Treatment means followed by the same letter are not significantly different at the .05 level of probability.

Letters x,y compare means between soil levels within the same soil horizon - precipitation pH combination.

Letters a,b compare means between precipitation pH levels within the same horizontal division of the table.

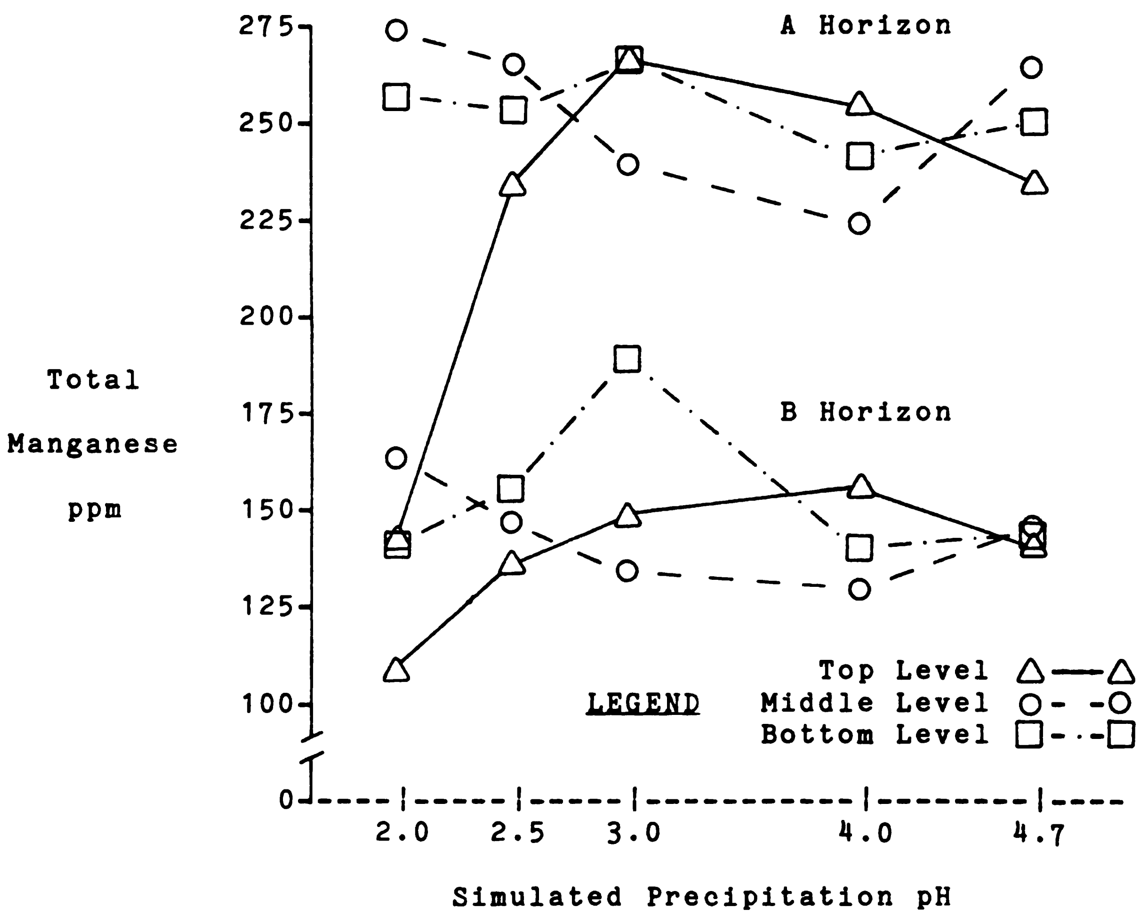

Figure 6.4

Total Manganese in A and B Horizon Soil

lower precipitation pH levels. Most soil boron is retained tightly by the organic fraction, and is released as organic matter decomposes. Boron is also adsorbed by iron and aluminum compounds in the soil (Tisdale and Nelson, 1975). The higher levels of organic matter and iron observed at lower pH levels may be involved in the higher retention of boron at pH levels 2.0 and 3.0. The lower total zinc concentrations at higher precipitation pH levels on A horizon soil may also be related to retention of zinc by organic matter. Total zinc in A horizon soil was positively correlated with organic matter content (.62). Since organic matter content was higher at lower pH levels, total zinc would be correspondingly higher. At higher precipitation pH levels, organic matter decomposition was greater, resulting in an increased release of zinc, uptake by seedlings, and loss in leachate.

Total concentrations of copper and chromium were not significantly different between precipitation pH levels on either soil. This result may be related to differences between elements in relative susceptibility to leaching. The depletion of nickel and manganese observed from Grayling soil is consistent with the results of Tyler (1978), in which manganese and nickel were most readily mobilized from soil treated with acid solutions. The retention of zinc, copper, and chromium at low precipitation pH levels in the present study was evidently related to their relatively higher resistance to leaching as noted by Tyler.

Chapter VII

RESULTS AND DISCUSSION: EFFECTS OF SIMULATED ACID PRECIPITATION ON JACK PINE REGENERATION

This chapter presents results dealing with the response of jack pine seeds and seedlings to the input of simulated acid precipitation. The major topics covered are germination, mortality, physical injury, seedling nutrient relations, and seedling growth. Emphasis is placed on statistically significant effects, except where factors not significantly affected by treatment bear a relationship with other results.

GERMINATION

In analyzing germination data, percent initial germination was based on the original number of seeds sown per experimental unit (144), while percent emergence and completed germination were calculated from the number of initial germinants in each case. Treatment means at each stage of germination are presented in Table 7.1.

A significant interaction between precipitation pH and soil factors indicated that response of initial germination to precipitation pH differed according to soil horizon. Initial germination at pH 2.0 on A horizon soil was significantly lower than at other pH levels on the same soil, but initial germination on B horizon soil did not

Table 7.1

Percent Germination at Three Stages

Soil	Percent Germination at Precipitation pH 2.0	2.5	3.0	4.0	4.7	Soil Mean
	Initial Germination (% of 144 seeds)					
**						**
A	33.7a	72.9b	75.9b	78.9b	81.9b	68.7x
B	72.9b	78.6b	84.9b	76.2b	80.7b	78.7y
pH Mean **	53.3a	75.8b	80.4b	77.6b	81.3b	
	Emergence (% of initial germination)					
						**
A	17.5	78.3	94.1	93.9	94.8	75.7x
B	26.9	97.2	99.2	99.7	99.5	84.5y
pH Mean **	22.2a	87.8b	96.6b	96.8b	97.2b	
	Completed Germination (% of initial germination)					
						**
A	17.1	77.4	91.9	93.9	94.4	74.9x
B	17.6	96.3	98.6	99.3	98.9	82.1y
pH Mean **	17.4a	86.8b	95.2b	96.6b	96.6b	

** Treatment means followed by the same letter are not significantly different at the .01 level of probability. Letters a,b compare pH means or soil x pH interaction; letters x,y compare soil means.

differ significantly between precipitation pH levels. If initial germination is taken as an indication of seed viability, acid precipitation reduced viability of jack pine seed only at pH 2.0 and only on A horizon soil.

Germination is influenced largely by differences in light, moisture, or temperature factors (Schopmeyer, 1974). Effects of light exposure would have been minimal since seeds were covered with soil after being sown. The A horizon soil, with higher organic matter contents, would have higher moisture holding capacity than the B horizon soil (Pritchett, 1979). From this aspect, the A horizon soil should have been more favorable for germination. Due to its darker coloration, however, the A horizon soil may have experienced higher soil temperatures so that evaporation of water from the surface layer would be greater than on B horizon soil. This could result in greater moisture and heat stress to shallow sown jack pine seeds, resulting in reduced germination. While this may explain differences observed between soils, it does not account for the greatly reduced germination observed on A horizon soil at pH 2.0.

The greatly reduced viability of seeds at this soil - precipitation pH combination indicated that a high proportion of the seeds were rendered non-viable between the onset of moisture imbibition and before active germination caused visible disturbance of the soil surface. This effect may be due to differences between soils related to soil pH.

The A horizon soil was slightly more acid with an initial pH of 4.4 than the B horizon soil with a pH of 4.6. If reduced germination was caused directly by increased acidity, the B horizon soil may have buffered the acid input sufficiently so that germination was not reduced.

Abougendia and Redmann (1979) found that germination of jack pine seeds in pH 2.2 and 3.0 buffers was not reduced below that at a reference pH of 6.5. This evidence suggests that hydrogen ion concentration alone may not be sufficient to explain decreased germination at pH 2.0. Instead, the inhibitory influence might arise from the interaction of precipitation pH and soil, suggesting the influence of increased solubility of toxic elements on germination. The A horizon soil, owing to initially lower pH, would be expected to have initially higher concentrations of soluble toxic elements such as aluminum, manganese, or zinc. The input of acid precipitation at pH 2.0 could have been sufficient to increase solubility of these elements at the soil surface to the point that toxic concentrations were present in soil solution. This hypothesis would account for the observed reduction of initial germination on A horizon soil, but requires further experimentation to provide supporting data.

These results are in agreement with results of other studies where reduced germination of conifer seeds was observed on acidified soils (Abrahamsen et al., 1975) or at solution pH levels below 2.5 (Abougendia and Redmann, 1979;

Roman and Raynal, 1980). Treatment with simulated acid precipitation, however, did not result in increased germination at lower pH levels as reported by Roman and Raynal (1980) for white pine at pH 2.4 and 3.0; by Abougendia and Redmann (1979) for jack pine at pH 3.0 and lodgepole pine at pH 2.2 and 3.0; or by Lee and Weber (1979) for white pine, red cedar, and yellow birch at pH levels 4.0, 3.5, and 3.0. That increased germination was not observed in the present study may be due to difference in species, technique, or the media on which seeds were germinated.

Seeds may be resistant to highly acidic solutions, but not to toxic factors released in the soil by the same acidic solutions. Likewise, germination on soils with higher buffering capacity would be less susceptible to release of toxic elements that would occur in a poorly buffered, acid soil like the Grayling sand.

Percent emergence at pH 2.0 was significantly lower than at all higher pH levels. Successful emergence of germinants was significantly greater on B horizon soil than on A horizon soil. Percent completed germination closely followed the pattern of emergence, being significantly reduced on both soils at pH 2.0. Percent completed germination was also significantly higher on B horizon soil. High mortality of B horizon germinants at pH 2.0, and the generally higher mortality of A horizon germinants at higher pH levels were the major factors producing the observed results, and are discussed in the next section.

Cumulative germination curves, derived from total numbers of seedlings at each treatment, are presented in Figure 7.1. On A horizon soil, low initial germination at pH 2.0 was evident, as was the reduction in emergence and completion of germination due to increased mortality. On B horizon soil at pH 2.0, initially high germination followed by high mortality resulted in low emergence and lower completed germination. The germination curves for pH 4.7 are also representative of curves at pH levels 2.5 to 4.0 on both soils. The reduced emergence and completed germination on A horizon soil at pH 4.7 is evident when compared to the germination curves for B horizon soil at pH 4.7.

MORTALITY

Mean percent mortality of seedlings, based on number of initial germinants, is presented in Table 7.2. The interaction between precipitation pH and soil was found to be significant, as were both main effects. Interaction arose due to the difference in mortality of seedlings growing on the two soils at pH 2.5. Mortality on A horizon soil was increased at pH 2.5 over that at all higher pH levels, but mortality at pH 2.5 on B horizon soil was significantly lower than that on A horizon soil as well as being not significantly different than mortality at higher pH levels on both A and B horizon soils. Mean percent mortality was significantly greater on A horizon soil than

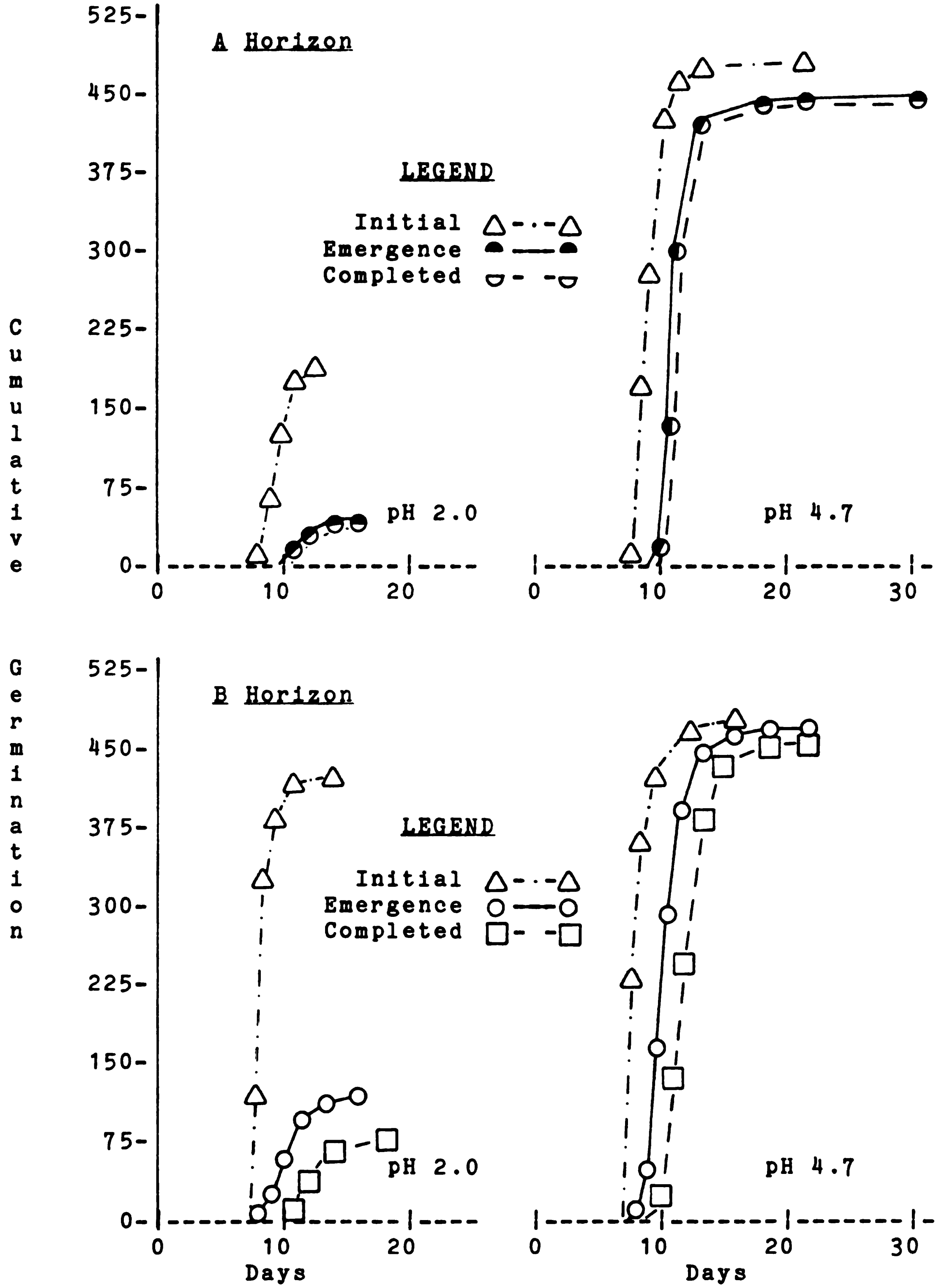

Figure 7.1

Cumulative Germination at Three Stages

Table 7.2

Percent Total Mortality

Soil	Percent at Precipitation pH: 2.0	2.5	3.0	4.0	4.7	Soil Mean
	Mortality (% of initial germination)					
**						**
A	97.4a	42.2b	13.1c	7.9c	7.7c	33.7x
B	95.6a	6.8c	3.9c	2.3c	4.1c	22.5y
pH Mean *	96.5a	24.5b	8.5c	5.1c	5.9c	

Treatment means followed by the same letter are not significantly different at the * .05 or ** .01 level of probability. Letters a,b,c compare pH means or soil x pH interaction; letters x,y compare soil means.

on B horizon soil.

These results can best be explained by describing the pattern of mortality that occurred (Figure 7.2). Greatest mortality at the pH 2.0 level on both soils took place between July 5 and July 10, during the time between initial germination and completion of germination. At this pH, the effects of acidity were acute, causing large scale mortality during the second and third weeks of the study. Mortality on A horizon soil at pH 2.5 also followed this pattern, although mortality was most evident between July 8 and 11, commencing at emergence of seedlings and extending to after completion of germination. Mortality of seedlings on A horizon soil at pH 3.0 and higher also displayed an abrupt rise during the third week of the study, though not as pronounced as at the pH 2.5 level. This suggests that some acute stress caused higher mortality at this time. In contrast, mortality of seedlings on B horizon soil at pH levels 2.5 and above was not noticeably higher at any one period, but accumulated at a fairly constant rate over the eleven week duration of the study, suggesting that mortality was due more to a chronic stress than to an acute one.

Symptoms associated with mortality of germinants during the early stages of the present study were similar to those described for heat injury by Baker (1929) and Smith (1970). Germinants dying in the loop stage exhibited collapse of the hypocotyl and abrupt cessation of growth. These symptoms were evident on A horizon soil at pH 2.5, and on both soils

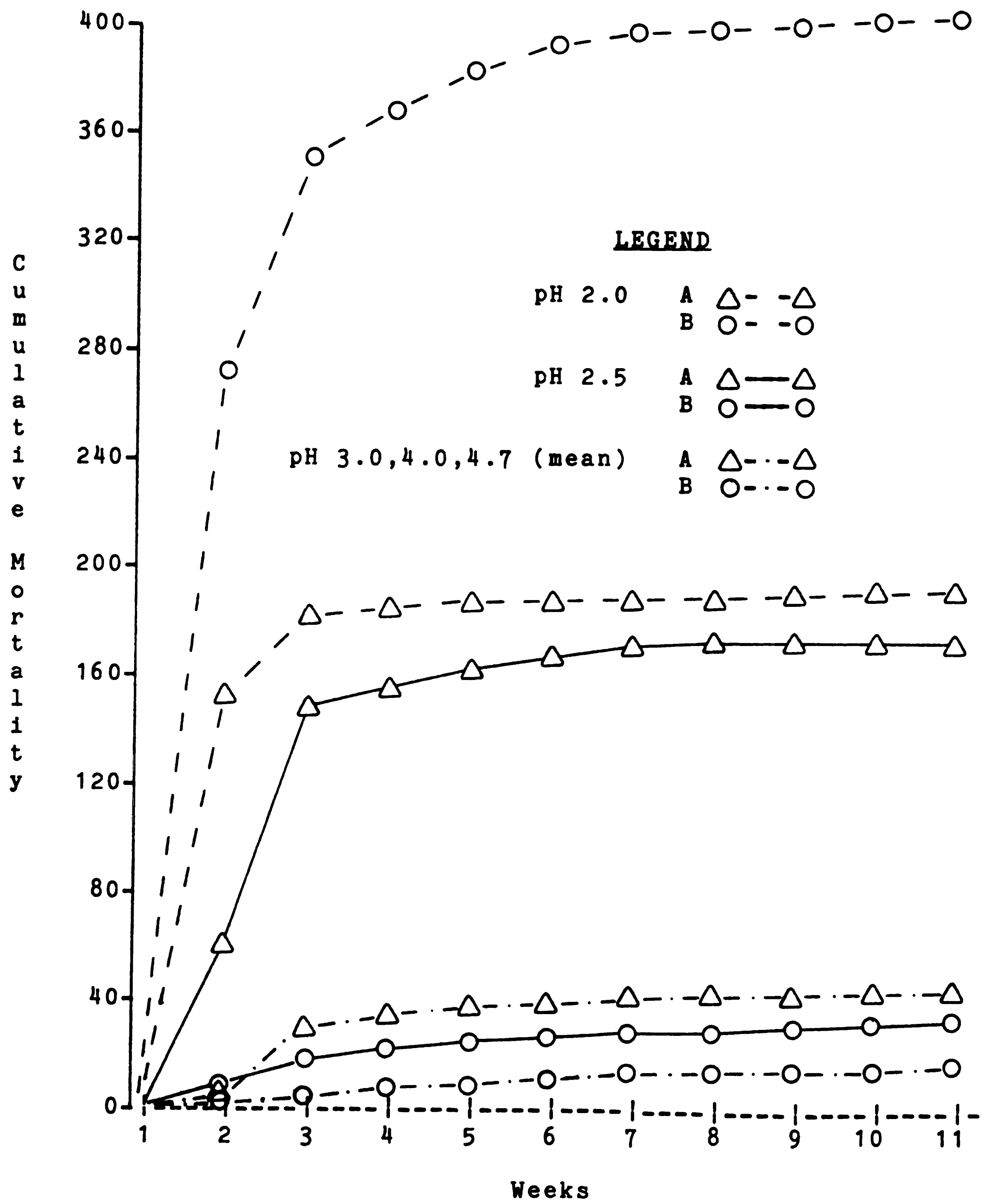

Figure 7.2

Cumulative Mortality of Jack Pine Germinants at pH 2.0. After emergence and until shortly after completion of germination, mortality was preceded by collapse of seedlings at ground level, followed by rapid dessication and death as the seedling lay on the soil surface. Seedling collapse was especially noticeable on A horizon soil at pH 2.5 and below, but also occurred to a lesser extent on A horizon soil at all higher pH levels.

These observations, coupled with high greenhouse temperatures during the second and third weeks of the study, suggest that seedling mortality at lower pH levels may have been associated with heat stress. Maximum daily greenhouse air temperatures ranged between 32 and 36 degrees Celsius during the period of greatest mortality. After the third week of the study, maximum daily temperatures were generally below 30 degrees Celsius. This data is presented in Appendix Table A.1. The higher mortality on darker colored A horizon soil may be associated with higher surface soil temperatures during early stages of germination and establishment (Shirley, 1936; Ahlgren and Ahlgren, 1960; Sims, 1975). The effect of acid input during this stage was to greatly increase mortality at the lower pH levels, suggesting a synergistic effect of heat and extreme acidity. Seedlings under acid stress may be less resistant to heat injury, just as seedlings under drought stress are less resistant to heat injury (Sims, 1975).

By July 16, the beginning of the fourth week of this study, germination at all treatments and on both soils was largely completed. The change in slope of the cumulative mortality curves after the third week of the study suggests that mortality associated with heat stress was greatly reduced after this point.

Increased mortality of seedlings treated with simulated acid precipitation has previously been documented by Dochinger (1976) at pH 3.0 and by Wood and Bormann (1974). Wood and Bormann found 94 percent mortality of two week old yellow birch seedlings exposed to pH 2.3 in comparison to 100 percent survival of six week old seedlings treated at the same pH level. In the present study, low survival of jack pine seedlings at pH levels 2.5 and below due to high mortality during early stages of germination and establishment also demonstrated the sensitivity of very young seedlings to highly acidic precipitation.

PHYSICAL INJURY

Symptoms of injury to seedlings appeared in mid July with the development of necrotic foliage and the occurrence of basal stem lesions, most pronounced at pH levels 3.0 and below. Necrotic tissue developed as orange- or reddish-brown needle segments largely confined to tips of needles. On seedlings grown on B horizon soil under more acidic treatments, necrosis also involved entire cotyledons or lower needles. On both soils at all pH levels, but most pronounced at pH levels below 3.0, seedlings sometimes experienced rapid and total necrosis of foliage resulting in mortality.

Results of chi-square analysis of frequency and severity of occurrence of foliar necrosis by precipitation pH is presented in Table 7.3. A significant overall chi-square indicated that occurrence of necrosis and precipitation pH were not independent. Examination of Table 7.3 reveals a trend of increasing severity of necrosis as precipitation pH decreases from 4.7 to 2.0.

These results generally agree with reports in the literature of necrotic tissue appearing on seedlings after treatment with simulated acid precipitation at pH levels below 3.0. In the present study, necrotic segments developed gradually over time, similar to findings by Wood and Bormann (1977) and Shriner et al. (1974) for white pine and Abrahamsen et al. (1976) for scotch pine. In contrast to the acute injuries observed by Shriner et al. (1974) for loblolly pine, foliar necrosis on jack pine did not appear to be the result of injury from acid over a short time period. Shriner et al. exposed seedlings to treatments consisting of sulfuric acid solutions, but in the present study jack pine seedlings were treated with simulated precipitation containing a neutral mixture of cations and anions as well as sulfuric and nitric acids. An unbuffered sulfuric acid solution may cause injury more rapidly than a solution with chemical constituents other than strong mineral acid.

While related to precipitation acidity, it is likely

Table 7.3

Occurrence and Severity of Foliar Necrosis
by Precipitation pH and Soil Horizon

Precipitation pH   Chi-square = 818.72 **

pH	Number of Seedlings with Necrosis Rating 1	2	3	4	5	pH Total
2.0	0	0	7	12	6	25
2.5	50	215	285	98	24	672
3.0	235	364	199	45	7	850
4.0	306	389	131	18	4	848
4.7	301	418	141	18	3	881
Rating Total	892	1386	763	191	44	3276

Soil Horizon   Chi-square = 1072.32 **

Soil	Number of Seedlings with Necrosis Rating 1	2	3	4	5	Soil Total
A	819	378	247	40	7	1491
B	73	1008	516	151	37	1785
Rating Total	892	1386	763	191	44	3276

** Chi-square significant at .005 level of probability.

that foliar necrosis observed in the present study occurred more as a result of acid-induced alteration of nutritional status of seedlings than as a direct injurious effect of acid in precipitation. Smith (1970) states that necrosis of the distal portions of coniferous needles is also commonly caused by high temperatures, again suggesting interaction between heat stress and acidity as an adverse impact of acid precipitation on seedlings.

As suggested by Shriner (1980), seedlings raised in the greenhouse are likely to be more susceptible to foliar damage from simulated acid precipitation than field grown seedlings of the same age. Bearing this in mind, it is likely that jack pine seedlings in the field would suffer acid-induced injury only at pH levels well below 3.0.

The relationship between foliar necrosis and soil was also examined (Table 7.3). A significant overall chi-square indicated that severity of necrosis and soil horizon type were not independent. Necrosis occurred less frequently and with less severity on foliage of seedlings grown on A horizon soil, while the great majority of seedlings grown on B horizon soil had some degree of foliar necrosis, and with increased severity of necrosis as compared to A horizon seedlings. Given the higher fertility of A horizon soil, the differential occurrence of foliar necrosis between soils again points to an interrelationship between precipitation acidity and seedling nutritional status as a cause of foliar necrosis on the jack pine seedlings studied.

Basal lesions on the stems of seedlings grown at pH levels below 4.0 became evident in mid July. At first appearing as only small, dark circular spots on the cortex of the hypocotyl, these lesions developed into prominent fissures or pits in the lower stems of seedlings that were accompanied by brown to black discoloration and swelling of the root collar.

A significant overall chi-square revealed a dependence between precipitation pH and severity of stem lesions. Examination of Table 7.4 shows that severe lesions involving twenty-five percent or more of the stem circumference (ratings 3 and 4) occurred only at pH levels of 3.0 and below. At pH 4.0, only three seedlings out of 848 displayed small, isolated lesions. At pH 4.7, no seedlings exhibited basal lesions. Analysis of the occurrence of lesions by soil also produced a significant overall chi-square. While this indicated an interaction between soil and lesion occurrence, this relationship was not as strong as those previously discussed. Given this qualification, results presented in Table 7.4 indicate that stem lesions tended to occur more frequently and with greater severity on seedlings grown on B horizon soil.

Symptoms of this nature have not previously been reported as a result of simulated acid precipitation treatments. The occurrence of heat-induced mortality of many seedlings between July 5 and 11 and the observation of stem lesions soon after suggested that the development of

Table 7.4

Occurrence and Severity of Stem Lesions by Precipitation pH and Soil Horizon

Precipitation pH   Chi-square = 2526.91**

pH	Number of Seedlings with Lesion Rating 1	2	3	4	pH Total
2.0	0	0	1	24	25
2.5	70	36	186	380	672
3.0	429	122	221	78	850
4.0	845	3	0	0	848
4.7	881	0	0	0	881
Rating Total	2225	161	408	482	3276

Soil Horizon   Chi-square = 57.53**

Soil	Number of Seedlings with Lesion Rating 1	2	3	4	Soil Total
A	1103	50	133	205	1491
B	1122	111	275	277	1785
Rating Total	2225	161	408	482	3276

** Chi-square significant at .005 level of probability.

lesions was related to heat injury.

Heat injury symptoms on coniferous seedlings are described by Hartley (1918), Korstian and Fetherolf (1921), and Baker (1929). Descriptions of heat-induced lesions do not entirely match the stem injuries noted on jack pine seedlings. Heat induced lesions are generally described as light in coloration, while acid related lesions were very dark. A general characteristic of heat lesion is some sort of constriction in the stem, accompanied by swelling of the stem above the constriction. Jack pine seedlings with acid lesions exhibited swelling of the root collar, but associated constriction of stems was not noted. There did not appear to be a definite orientation to the lesions as in heat injury, although greenhouse conditions may have reduced such a directional tendency. The darker A horizon soil would be expected to heat up more than the B horizon soil, and greater frequency and severity of lesion occurrence on A horizon soil would be expected if they were heat induced. The opposite is true, so it is not likely that the lesions observed in the present study were simply the result of excessive heat.

While heat may have increased susceptibility to this type of lesion formation, the occurrence of lesions at pH levels 3.0 and below and virtual absence at pH levels 4.0 and above suggest that it was the acidity of precipitation that produced their development, possibly through a direct injurious effect. Supporting this view, Evans et al. (1978)

reported that acid induced foliar lesions on hybrid poplar were accompanied by proliferation and enlargement of adjacent parenchyma cells. Such an effect might explain the basal swelling that occurred in conjunction with lesion development. The possibility that the swelling associated with these lesions was also related to alteration in root growth due to soil acidification is discussed in the next section.

SEEDLING NUTRIENT RELATIONS

Results presented in this section are based on chemical analysis of seedling tops at pH levels 4.7 to 2.5. Accurate determination of elemental concentrations for seedlings grown at pH 2.0 was prevented due to the small amount of tissue produced at this pH level. Consequently, this data has been excluded from statistical analysis and discussion of results.

To create homogeneity of variance for statistical analysis, logarithmic transformations were performed on the following tissue concentration data: phosphorus, potassium, calcium, magnesium, copper, iron, manganese, zinc, aluminum, and cadmium. Statements of statistical significance are based on the transformed data. Total Kjeldahl nitrogen, sodium, boron, nickel, and chromium were statistically analyzed on the scale of original measurement. To facilitate comparison with standards of elemental deficiency or excess, true mean concentrations in seedling tops for elements statistically analyzed on a transformed scale are presented. Correlations included in the discussion of results are based on true concentrations and are significant at the .05 level of probability or lower. Results are grouped into discussions of effects of simulated acid precipitation on seedling top concentrations of macronutrients, micronutrients, and toxic metals.

Macronutrients

Elements discussed under this category are nitrogen, phosphorus, potassium, calcium, and magnesium. Sodium, though not considered a major nutrient, is discussed in this section because of its chemical similarity with the other basic cations.

Total Kjeldahl nitrogen in seedling tops was significantly higher at precipitation pH 2.5 than at other pH levels, and significantly higher at pH 3.0 and 4.0 than at pH 4.7 (Table 7.5). The observation of increased nitrogen concentration in seedlings treated at lower precipitation pH levels agrees with reports by Wood and Bormann (1977) and Overrein (1980) of increased foliar nitrogen in conifers treated with simulated acid precipitation. Wood and Bormann attributed this increase to the increased addition of nitrogen in the form of nitric acid in simulated precipitation. In the present study, estimated total deposition of nitrogen per experimental unit during the study period increased from 20.89 mg at pH 4.7 to

Table 7.5

Nitrogen and Phosphorus Concentrations
in Jack Pine Seedling Tops

Soil	Result at pH Level 2.5	3.0	4.0	4.7	Soil Mean
			Total Kjeldahl Nitrogen (%)		
					**
A	2.72	2.07	2.04	1.89	2.18x
B	2.48	2.05	1.89	1.58	2.00y
pH Mean *	2.60a	2.06b	1.97b	1.73c	
			Total Phosphorus (%)[1]		
					**
A	.124	.134	.138	.139	.134x
B	.072	.070	.078	.083	.076y
pH Mean *	.098a	.102ab	.108ab	.111b	

1 Total P statistically analyzed as Log[ppm].

Means followed by the same letter are not significantly different at the *.05 or ** .01 level of probability. Letters a,b,c compare pH means; letters x,y compare soil means.

276.69 mg at pH 2.5. This suggests that increased nitrogen concentration in jack pine seedling tops at lower pH levels is attributable to the increased supply of nitrogen in precipitation at lower pH levels.

Tamm (1976) hypothesized that soil acidification due to acid precipitation may result in temporarily increased accumulation of ammonium from nitrogen mineralization, leading to increased nitrogen availability in forest ecosystems. This process was thought to have produced the increased foliar nitrogen concentrations reported by Overrein (1980). In the present study, decreased rates of organic matter decomposition at lower precipitation pH levels suggested that mineralization of nitrogen was reduced. Based on these results, it is unlikely that enhanced mineralization would account for the increased nitrogen concentrations observed in seedlings grown at lower precipitation pH levels.

Foliar nitrogen concentration for jack pine greater than 1.5% on a dry weight basis is considered adequate (White et al., 1980). Mean nitrogen concentrations from Table 7.5 indicate that this level was exceeded at all treatment-soil combinations. Nitrogen concentrations in conifer foliage are considered high at values greater than 2.0%. Seedlings grown at pH levels below 4.0 had nitrogen concentrations in excess of this value.

Abrahamsen (1980) states that nitrogen is the main nutrient factor limiting growth in most forest ecosystems.

An increase in supply of such a limiting nutrient that produces an increase in plant absorption and growth also results in greater demand for other nutrient elements (Armson, 1973; Abrahamsen, 1980). If availability of other nutrients is not adequate, the greater demand caused by nitrogen input may result in a decrease in the tissue concentration of other elements, termed a dilution effect. As input of nitrogen continues, the dilution progresses and the levels of other elements become limiting. A stage is reached at which the increase in supply of nitrogen may induce deficiency in another element (Armson, 1973). The increased nitrogen deposition from acid precipitation could thus effect growth as well as the sufficiency of other nutrient elements.

Total phosphorus concentration significantly decreased with precipitation pH, being higher in seedlings grown at pH 4.7 than at pH 2.5. Phosphorus levels were significantly higher in seedlings grown on A horizon soils than in seedlings grown on B horizon soils (Table 7.5).

Tveite (1980a) reported elevated foliar phosphorus concentrations in current and previous year needles of lodgepole pine saplings treated with groundwater acidified with sulfuric acid to pH 3.0. Increase in phosphorus concentration may be related to greater root development of the field grown saplings as compared to young seedlings, higher soil phosphorus levels, and the chemical nature of the simulated precipitation.

In the jack pine seedlings studied, phosphorus concentrations were in the low to deficient range (Table 7.5). For jack pine, a phosphorus concentration of .14% is considered low, with levels less than .09 to .10% being deficient (White et al., 1980). Concentrations in A horizon seedlings were in the low range, dropping from .139% at pH 4.7 to .124% at pH 2.5. B horizon seedlings were below the level of deficiency, decreasing from .083% at pH 4.7 to .072% at pH 2.5. Phosphorus deficiency symptoms in conifer seedlings include stunting, red-brown necrosis of lower leaves or cotyledons beginning at tips and proceeding to the base, and decreased root growth (Hacskaylo et al., 1969). In jack pine, phosphorus deficiency may be accompanied by purpling and yellow to gold chlorosis at the tips of primary needles (Armson and Sadreika, 1974). These symptoms closely match the poorer growth, decreased root weight, and increased necrosis observed on B horizon seedlings. Decreased root weight and increased necrosis on A horizon seedlings at lower pH levels may also be related to decreasing phosphorus concentration in seedling tops.

Phosphorus appeared to be a limiting nutrient in both soils, and the effect of acid precipitation exacerbated the limitation in two ways. First, the increased input of nitrogen created a larger demand for phosphorus, resulting in reduced foliar concentration of phosphorus at low pH levels. This factor is especially important on B horizon soil, where a negative correlation (-.52) between nitrogen and phosphorus concentrations in seedling tops was found. Second, by decreasing soil pH, acid precipitation may result in reduced availability of phosphorus, again producing a lower phosphorus concentration in seedlings. Supporting this contention, phosphorus concentration in A horizon seedlings was negatively correlated (-.54) with Bray 1 extractable phosphorus. This suggests that phosphorus nutrition of seedlings was impaired at lower soil pH levels even though extractable phosphorus was higher. This result indicates that phosphorus concentration in seedling tops served as a better estimate of availability of phosphorus in the soil than the chemical extraction method employed.

Potassium, calcium, and sodium concentrations in seedling tops increased as precipitation pH decreased. All three elements were significantly higher in concentration in seedlings grown on A horizon soil. These results are presented in Table 7.6.

Differences in concentrations of potassium, calcium, and sodium between seedlings grown on different soils were attributable to the different levels of exchangeable cations present in A and B soils. Levels of exchangeable potassium, calcium, and sodium were all higher in A horizon soil than in B horizon soil, and concentrations of these elements were correspondingly greater in seedlings grown on A horizon soil.

Tveite (1980a) found increased potassium concentrations in foliage of lodgepole pine treated with pH 3.0 simulated

Table 7.6

Potassium, Calcium, Magnesium, and Sodium Concentrations in Jack Pine Seedling Tops

Soil	2.5	3.0	4.5	4.7	Soil Mean
	Result at pH Level				
		Potassium (ppm)[1]			
					*
A	5897	4920	4778	4105	4925x
B	5552	4458	4025	4152	4547y
pH Mean *	5725a	4689b	4401bc	4128c	
		Calcium (ppm)[1]			
*					**
A	2230a	1795b	1672bc	1690bc	1847x
B	1475c	1315d	1305d	1448cd	1386y
pH Mean **	1852a	1555b	1489b	1569b	
		Magnesium (ppm)[1]			
*					**
A	838abcd	946a	894ab	865abc	886x
B	729d	755cd	779bcd	844abc	777y
pH Mean *	783a	850ab	837ab	854b	
		Sodium (ppm)			
					**
A	103.1	93.9	88.7	86.1	92.9x
B	85.1	79.9	79.4	80.2	81.2y
pH Mean *	94.1a	86.9ab	84.1b	83.1b	

1 K, Ca, and Mg data statistically analyzed as Log[ppm].

Means followed by the same letter are not significantly different at * .05 or ** .01 level of probability. Letters a,b,c,d compare pH means or soil x pH interactions; letters x,y compare soil means.

rain. Wood and Bormann (1977), however, found that foliar potassium and calcium contents were constant in white pine treated at pH levels between 5.6 and 3.0, with decreased foliar contents at pH 2.3. The results of Wood and Bormann occurred after a twenty week treatment period with precipitation applied at a rate of 4.2 cm per week. Soil cation leaching and depletion were greater than in the present study, which was of shorter duration and imposed lower weekly rates of precipitation.

The enhancement of potassium, calcium, and sodium concentrations in seedling tops by the input of increasingly acidic precipitation could result from temporarily increased cation availability, as suggested by Hutchinson (1978). Input of excess hydrogen ions in precipitation would result in exchange for cations, temporarily producing higher cation concentration in soil solution. These cations would be available for uptake by seedlings, explaining the increased concentrations in seedlings grown at lower pH levels.

Downward leaching of cations in the soil would also serve to increase availability of these elements to roots in the lower soil layers. _Pinus_ species are capable of adapting to a variety of edaphic conditions by intensive rooting in soil layers most favorable to growth and development (Pritchett, 1979). Effective rooting in this manner could result in increased uptake of cations leached to lower soil producing increased concentrations of cations in seedling tops. Longer periods of leaching, as demonstrated by Wood and Bormann (1977), could produce loss of cations from the rooting zone and reduced availability of these nutrients.

Negative correlations between soil pH and potassium tissue concentration of seedlings on A (-.81) and B (-.92) horizon soil and between soil pH and calcium concentration of seedlings on A (-.82) horizon soil were found in the present study. This supports the view that input of acid precipitation, by causing mobilization of bases, resulted in temporarily increased availability of these nutrients. Indications that this same process may produce accelerated depletion of cations are supported by the negative correlation on A horizon soil between tissue levels of potassium and soil levels of exchangeable potassium (-.60). Tissue levels of potassium increased at the same time soil levels of exchangeable potassium decreased through leaching and accelerated uptake. At some point, further decrease in soil levels of exchangeable potassium could produce a deficiency of this nutrient.

Increased uptake of these nutrients was also associated with increased availability of nitrogen. This is supported by positive correlations between seedling concentration of nitrogen with seedling potassium on both A (.82) and B (.81) soils, and with tissue calcium on A soil (.67). In this study, any increased leaching of potassium, calcium, or sodium from foliage was counterbalanced by the enhanced uptake of cations.

Seedling potassium concentrations fall within the range of 4,000 to 5,000 ppm, and calcium within the range of 1,200 to 7,000 ppm (Table 7.6), considered low but adequate for jack pine (White et al., 1980). Enhanced uptake over a short time period could be viewed as beneficial. Greater demand for these nutrients as a result of acid precipitation over a long time period, however, coupled with inevitable leaching losses from the ecosystem, could result in depletion of soil reserves leading to base insufficiency.

Interaction between soil and precipitation factors for seedling concentration of calcium was significant. Results in Table 7.6 show that for A horizon soil, effects of precipitation pH were similar to main effects in that calcium concentration was significantly higher at pH 2.5 than at all other pH levels. On B horizon soils, the lower levels of exchangeable calcium resulted in a dilution effect on tissue concentration at pH levels 4.0 and 3.0, since increased nitrogen supply would have created increased demand for calcium. Increased acid loading at pH 2.5 would cause increased release of calcium to soil solution, allowing greater uptake and increased tissue concentration at this pH level.

Sodium has been identified as essential in certain crop plants, but its importance in tree nutrition is uncertain. No instances of deficiencies have been reported for forest soils (Pritchett, 1979). The increased sodium concentration observed in jack pine seedlings at lower pH levels would be the result of increased sodium concentration in soil solution, as well as increased uptake accompanying nitrogen input.

Magnesium concentration was greater in A horizon seedlings than in B horizon seedlings, while the main effect of precipitation pH was a significant reduction in concentration at pH 2.5 as compared to pH 4.7. The interaction between soil and pH was significant. Looking at the effect of precipitation pH on seedling magnesium concentration between soils presented in Table 7.6, magnesium concentration in A horizon seedlings tended to rise to the pH 3.0 level and then decreased at pH 2.5. On B horizon soils, the trend is a constant decrease in magnesium concentration in seedling tops as precipitation pH decreases with concentration at pH 2.5 significantly lower than at pH 4.7.

Tveite (1980a) also found decreased magnesium concentrations in Norway spruce foliage at pH levels of 3.0 and 2.5, and in scotch pine at pH 2.5. Similarly, Wood and Bormann (1977) found decreased magnesium concentration in needles of white pine seedlings treated at pH 2.3, and attributed these results to loss of magnesium from the soil due to leaching.

Magnesium concentrations in jack pine seedling tops fell in the range of 600 to 900 ppm (Table 7.6), which is considered critical for jack pine, less than 600 ppm being deemed deficient (Leaf, 1968; White et al., 1980). A horizon seedlings had adequate magnesium supply and were not significantly affected by input of acid precipitation. B horizon seedlings, however, had a lower supply of exchangeable magnesium in the soil, which became limiting in the face of high nitrogen input. Tissue concentration declined as a result of the dilution effect caused by increased nitrogen uptake and growth. This is supported by the negative correlation (-.79) between seedling concentration of nitrogen and magnesium found for B horizon soil. The decreasing concentration of magnesium in B horizon seedlings might have contributed to the greater necrosis of foliage and generally lower growth noted on this soil.

Micronutrients

Seedling tops were analyzed for boron, iron, copper, manganese, and zinc. Boron and iron deficiencies are the most common micronutrient deficiency problems encountered in forest trees (Stone, 1968). Copper, manganese, and zinc are unusual in that all can produce problems related to deficiency and excess (Lepp, 1981). Since deficiencies of all these elements are associated with sandy soils, and their solubility and toxicity are largely mediated through soil pH, the effect of acid precipitation on seedling concentrations of these elements is of interest in this study.

Concentrations of boron and iron in seedling tops were not significantly affected by precipitation pH levels between 2.5 and 4.7 (Table 7.7). Boron concentration was significantly higher in seedlings grown on A horizon soil, but iron concentration was not significantly different between seedlings grown on different soils. A boron concentration of 31 ppm is considered adequate for jack pine (Stone, 1968). Using this level as a comparison, seedlings from both soils and all treatments, with a range in concentration from 26.8 to 32.6 ppm, were adequately supplied with boron (Table 7.7). Since iron concentrations from 50 to 73 ppm are considered adequate for jack pine (Stone, 1968), iron concentrations in seedlings in this study, ranging from 41.9 to 65.6, should have been adequate (Table 7.7).

Tveite (1980a) found increased levels of iron in needles of lodgepole pine treated at pH 3.0. While there was a tendency for iron concentration in jack pine seedlings to increase at lower pH levels in the present study, this effect was not statistically significant.

Copper concentration in seedling tops was not significantly affected by precipitation pH between 4.7 and 2.5, but was significantly higher in seedlings grown on A horizon soil (Table 7.7). Copper concentrations in B horizon seedlings were below the level of 4.6 ppm considered adequate for jack pine and below the level of 2.7 ppm considered deficient for the closely related lodgepole pine (Stone, 1968). According to Lepp (1981) and Stone (1968) copper deficiency can be induced or aggravated on acid,

Table 7.7

Boron, Copper, and Iron Concentrations
in Jack Pine Seedling Tops

Soil	Result at pH Level 2.5	3.0	4.0	4.7	Soil Mean
			Boron (ppm)		
					**
A	31.6	32.6	31.5	31.9	31.9x
B	29.3	29.9	31.2	26.8	29.3y
pH Mean	30.3	31.3	31.4	29.4	
			Copper (ppm)[1]		
					**
A	3.40	3.92	3.60	3.16	3.52x
B	2.27	2.47	2.63	2.65	2.50y
pH Mean	2.83	3.19	3.12	2.90	
			Iron (ppm)[1]		
A	52.5	49.4	49.3	50.4	50.4
B	57.9	65.6	54.2	41.9	54.9
pH Mean	55.2	57.5	51.8	46.2	

1 Copper and Iron data statistically analyzed as Log[ppm].

Means followed by the same letter are not significantly different at the * .05 or ** .01 level of probability. Letters x,y compare soil means.

sandy soils by the addition of high levels of nitrogen. The low copper levels in B horizon seedlings may be aggravated by high input of nitrogen at lower pH levels. The negative correlation (-.74) between tissue concentrations of nitrogen and copper found for B horizon seedlings supports this supposition. Copper deficiency symptoms on first year seedlings involve needle tip burn (Stone, 1968). Here again, apparent nutrient deficiencies in B horizon seedlings may have contributed to the greater degree of necrotic tissue observed on B horizon seedlings.

Manganese concentration significantly increased as precipitation pH decreased. A horizon seedlings had significantly greater manganese concentrations than B horizon seedlings (Table 7.8).

A horizon soil had higher total Mn and lower pH, which together would produce higher availability of Mn to seedlings growing in that soil. The increase in manganese comcentration with decreasing precipitation pH was consistent with the results of Tveite (1980a), in which increased manganese concentrations were found in the needles of lodgepole pine treated with pH 3.0 simulated acid prcipitation. Stone (1968) observed that plant levels of manganese tend to increase with increasing soil acidity, and that high concentrations in foliage and bark of healthy trees was better evidence for physiological accomodation than for toxicity. Manganese concentrations in jack pine seedlings were negatively correlated with soil pH on both A

Table 7.8

Manganese and Zinc Concentrations in Jack Pine Seedling Tops

Soil	Result at pH Level 2.5	3.0	4.0	4.7	Soil Mean
		Manganese (ppm)[1]			
A	902	644	528	533	652x **
B	714	452	396	413	494y
pH Mean *	808a	548b	462c	473c	
		Zinc (ppm)[1]			
A	72.9	63.3	56.6	53.4	61.6
B	66.2	61.0	59.8	57.3	61.1
pH Mean *	69.6a	62.2ab	58.2bc	55.3c	

1 Manganese and Zinc data statistically analyzed as Log[ppm].

Means followed by the same letter are not significantly different at the * .05 or ** .01 level of probability. Letters a,b,c compare pH means; letters x,y compare soil means.

(-.87) and B (-.90) soils, which suggests the influence of decreasing soil pH on increasing manganese availability. Manganese was also positively correlated with seedling nitrogen on both A (.73) and B (.75) soils, suggesting that manganese uptake was enhanced by increased nitrogen supply at lower precipitation pH levels.

Mean manganese concentrations in this study ranged from 396 to 902 ppm (Table 7.8), which fall largely in the range of 35-855 ppm which Stone (1968) reported as being intermediate levels for jack pine. Toxic symptoms were reported as occurrring only at foliar levels greater than 4,400 ppm, precluding the possibility of toxic effects from manganese in the present study.

Zinc concentrations were significantly higher at pH levels 2.5 and 3.0 than at 4.7. Zinc concentrations in seedlings growing on A and B horizon soils were not significantly different (Table 7.8). Zinc concentration in A horizon seedlings was negatively correlated with soil pH (-.87) and positively correlated with tissue nitrogen (.69), again suggesting a relationship between decreased soil pH and increased zinc availability, as well as increased zinc uptake in association with higher nitrogen inputs at low precipitation pH levels.

The range of mean concentrations of zinc found in this study, 53.4 to 72.9 ppm (Table 7.8), fall within the normal range of 52 to 74 ppm reported by Stone (1968). Since deficiencies in most plants occur only at levels below 15 ppm (Collins, 1981), the levels of zinc observed in the present study present no adverse stress related to elemental toxicity or deficiency.

Toxic Elements

Seedling tops were analyzed for nickel, cadmium, chromium, and aluminum. Soil acidification caused by acid precipitation would be expected to produce increased solubility and availability of these elements. The results of seedling top analysis confirmed this as concentrations of aluminum, nickel, chromium, and cadmium significantly increased with decreasing precipitation pH (Table 7.9).

B horizon seedlings were significantly higher in nickel than A horizon seedlings, due to higher total nickel concentration in the B horizon soil. Mean nickel concentration in seedling tops increased from 1.42 ppm at pH 4.7 to 1.78 ppm at pH 2.5. Nickel has not been proven to be essential, but there is evidence that it may be so for trees (Hutchinson, 1981). Non-toxic nickel concentrations of plants growing on uncontaminated soils are usually less than 10 ppm, while toxicity occurs when tissue concentrations are greater than 50 ppm (Hutchinson, 1981). Nickel concentrations found in jack pine seedlings in the present study, while increased by acid precipitation, did not approach levels associated with toxicity.

Chromium concentrations in seedling tops were significantly higher at pH levels 2.5, 3.0, and 4.0 than at

Table 7.9

Aluminum, Nickel, Chromium, and Cadmium Concentrations in Jack Pine Seedling Tops

Soil	Result at pH Level 2.5	3.0	4.0	4.7	Soil Mean
			Aluminum (ppm)[1]		
*					**
A	433ab	282de	278de	244e	309x
B	453a	352bc	334cd	344c	371y
pH Mean **	443a	317b	306b	294b	
			Nickel (ppm)		
					*
A	1.57	1.42	1.38	1.36	1.43x
B	2.00	1.57	1.48	1.48	1.63y
pH Mean *	1.78a	1.49ab	1.43b	1.42b	
			Chromium (ppm)		
					**
A	4.91	4.87	4.57	4.12	4.62x
B	5.15	4.98	4.89	4.68	4.93y
pH Mean	5.03a	4.92a	4.73a	4.40b	
			Cadmium (ppm)[1]		
A	.99	.73	.56	.34	.66
B	.61	.78	.55	.30	.56
pH Mean **	.80a	.76a	.56a	.32b	

1 Statistical analysis of data: Al, Log[ppm]; Cd, Log[ppb].

Means followed by the same letter are not significantly different at the * .05 or ** .01 level of probability. Letters a,b,c,d,e compare pH means or soil x pH interaction; letters x,y compare soil means.

pH 4.7 (Table 7.9). B horizon seedlings were significantly higher in chromium than A horizon seedlings. Peterson and Girling (1981) reported that chromium concentrations in plants are generally less than 1 ppm, although values of 2.6 ppm and higher have been reported for pine needles. Mean chromium concentration in jack pine seedlings increased from 4.40 ppm at pH 4.7 to 5.03 ppm at pH 2.5. The effect of this increase is uncertain, since plants exhibiting chromium toxicity symptoms may not contain much more chromium in tops than normal plants since chromium is accumulated in the roots and initial phytotoxic effects take place there.

Cadmium concentrations also significantly increased as precipitation pH decreased (Table 7.9). The effect of precipitation acidity on cadmium concentration can be attributed to the increased solubility of cadmium as soil pH decreased. Page et al. (1981) stated that if other soil conditions remain unchanged, plant tissue cadmium concentration decreases as soil pH increases. Natural levels of cadmium in plants growing on uncontaminated soils range from .15 to 1.11 ppm, phytotoxic concentrations being largely greater than 5 ppm. The increase in mean cadmium concentration from .32 ppm at pH 4.7 to .80 ppm at pH 2.5 did not approach toxic levels.

The main effects of precipitation pH and soil as well as the interaction between these two factors were found to be significant for aluminum concentration in jack pine seedling tops (Table 7.9). B horizon seedlings had significantly higher aluminum concentration than A horizon seedlings, due to higher total aluminum present in B horizon soil. Aluminum levels in A horizon seedlings were much lower than concentrations in B horizon seedlings at pH levels 3.0, 4.0, and 4.7, but at pH 2.5 concentrations in seedlings grown on both soils were elevated to a similar level significantly higher than at pH 4.0 or 4.7. This response indicated that input of acid precipitation at pH 2.5 increased soluble aluminum in both soils, producing elevation of tissue concentration. Negative correlations between tissue concentration of aluminum and soil pH for A (-.82) and B (-.90) soils supports this explanation.

The elevation of aluminum in seedling tops at pH 2.5 raised the question of aluminum toxicity. Aluminum toxicity is most severe in soils below pH 5.0 (Peterson and Girling, 1981). Soil pH levels in the Grayling sand are normally 5.0 or below, so soluble aluminum is normally present. The very occurrence of jack pine on these soils is evidence that the species must have a certain tolerance to active aluminum. This tolerance may not include resistance to rapid solubilization of aluminum in response to rapid decreases in soil pH produced by highly acidic precipitation, as observed at pH levels 2.0 and 2.5 in the present study.

Most plants contain less than 200 ppm of aluminum, but tolerant species may accumulate higher concentrations in tissue (Peterson and Girling, 1981). The increase in aluminum in jack pine tops may be evidence of this type of tolerance. However, the degree of aluminum toxicity cannot be determined from aluminum content of plant tops. Growth depression occurs, such as witnessed at pH 2.0, but this is a non-specific symptom (Pratt, 1964).

A major indication of aluminum toxicity is induced phophorus deficiency in plant tops, accompanied by an accumulation of both aluminum and phosphorus in the roots (Jones, 1961; Foy and Brown, 1964). Such an effect appears to be implicated in the reduced phosphorus concentration observed in jack pine seedling tops at pH 2.5. The appearance of roots can also be used for diagnosis. Plants suffering from aluminum toxicity generally show injury to roots, which become discolored, swollen, and display inhibition or cessation of growth (Bartlett and Riego, 1972). Purplish discoloration at the base of stems and dieback of leaves from tips may occur (Foy and Brown, 1964). These symptoms become evident long before growth of tops is noticeably affected. Toxic effects are localized in roots, and aluminum is not translocated to other parts of the plant (Pratt, 1964).

The combination of decreased phosphorus concentrations, progressive foliar necrosis, and reduced root weight observed for jack pine seedlings at lower precipitation pH levels match symptoms of aluminum toxicity. Decreased root weight suggests inhibition of root growth due to soluble aluminum, while foliar necrosis, related to other nutrient and environmental factors, could also be related to aluminum toxicity. The discolored, swollen stem lesions may be manifestations of root damage causing overgrowth of root collar tissue due to the lack of transportation to and utilization of photosynthate by the roots. The reduced phosphorus concentrations in seedling tops at pH 2.5, where aluminum solubility is higher due to decreased soil pH, is an indication of the inhibition of phosphorus uptake common in plants subject to aluminum toxicity. The combined evidence of reduced root weight and impaired phosphorus uptake strongly imply adverse effects related to increased levels of soluble aluminum in soil solution. Analysis of root material for aluminum and phosphorus concentration, and soil for soluble aluminum, would supply more evidence to determine if this hypothesis is reasonable.

SEEDLING GROWTH

Because there were few surviving seedlings at pH 2.0 on both soils, growth measurements were taken on a much smaller number of seedlings than at higher pH levels. For this reason, the pH 2.0 seedling data was not included in the statistical analysis of growth measures. The means of this treatment are presented in the appropriate tables for purposes of comparison.

Seedlings showed a trend of increased height as precipitation pH decreased from 4.7 to 2.5, but this effect was not statistically significant. Surviving seedlings at pH 2.0 on both soils displayed reduced height growth as compared to all other treatments. Height growth at pH levels 2.5 to 4.7 was significantly greater on A horizon soil (Table 7.10).

Average seedling root collar diameter at pH 2.5 was significantly increased over diameter at pH levels 4.0 and 4.7 (Table 7.10). Diameter at pH 2.0 generally followed the trend of increased diameter with decreasing precipitation pH. Average seedling diameter on A horizon soil was significantly greater than diameter of seedlings grown on B horizon soil.

Seedling top weight increased as pH decreased, with top weight at pH 2.5 being significantly greater than at pH 4.0 or 4.7. significantly different than that at lower or higher pH levels. Mean top weight at pH 2.0 was lower than mean values at all other pH levels. Top weight was significantly greater for seedlings grown on A horizon soils (Table 7.10).

These results are in agreement with reports in the literature of increased growth for conifers treated with simulated precipitation at pH levels as low as 2.3 (Wood and Bormann, 1977; Lee and Weber, 1979; Ogner, 1980). The only report of decreased growth of coniferous seedlings in response to simulated acid precipitation was for Aleppo pine, which is adapted to calcareous soil and therefore more likely to be susceptible to adverse effects from acidification (Matziris and Nakos, 1977). The reduced height and biomass of jack pine seedlings grown at pH 2.0 was in agreement with the results of Roman and Raynal

Table 7.10

Seedling Height, Diameter, and Top Weight

Soil	2.0[1]	2.5	3.0	4.0	4.7	Soil Mean
Seedling Height (mm)						**
A	43.5	53.2	52.2	51.6	48.2	51.3x
B	39.2	47.1	45.8	44.4	45.6	45.7y
pH Mean	41.0	50.2	49.0	48.0	46.9	
Seedling Diameter (mm)						**
A	.76	.79	.68	.64	.62	.68x
B	.68	.66	.61	.60	.62	.62y
pH Mean	.71	** .72a	.65ab	.62b	.62b	
Seedling Top Weight (mg)						**
A	49.0	64.2	55.8	51.2	48.8	55.0x
B	34.5	44.0	39.0	37.2	38.5	39.7y
pH Mean	40.7	** 54.1a	47.4ab	44.2b	43.6b	

Measurement at pH Level (columns 2.0–4.7)

1 pH 2.0 level not included in statistical analysis or calculation of soil means.

Means followed by the same letter are not significantly different at the ** .01 level of probability.
Letters a,b compare pH means; letters x,y compare soil means.

(1980), in which reduced growth of sugar maple and yellow birch seedlings was reported at pH 2.0.

Wood and Bormann (1977) attributed increased productivity of white pine seedlings at pH 2.3 to the fertilizing effect of the nitrate component of nitric acid in simulated precipitation. The significantly increased growth of jack pine seedlings at pH 2.5 can also be attributed to the increased input of nitrogen in simulated precipitation, along with the enhanced uptake of certain macro- and micronutrients also related to the input of acid precipitation.

Correlation of growth measures and foliar concentration of nutrients for seedlings grown at pH levels 4.7 to 2.5 supports this hypothesis. On A horizon soil, seedling diameter was positively correlated with tissue concentrations of nitrogen (.73), potassium (.81), and calcium (.58), as well as with zinc (.88) and manganese (.71). For B horizon soil, seedling diameter was positively correlated with tissue concentration of potassium (.58). These correlations suggest that increased seedling diameter was the result of improved nutrient availability or uptake associated with decreasing precipitation pH.

However, the observation during measurement that increased stem collar diameter at pH levels 2.5 and 2.0 were associated with the occurrence of basal stem lesions indicates that improved nutritional status was not the only factor influencing seedling diameter. The increased seedling diameter at pH 2.0 in conjunction with decreased height and topweight supports the contention that diameter increase was not due to improved growth alone, but to some extent was a result of an abnormal physiological response to input of extremely acidic precipitation. A relationship between the occurrence of stem lesions, precipitation acidity, and possible aluminum toxicity has previously been suggested. The positive correlations between tissue aluminum concentration and seedling diameter on A (.85) and B (.56) horizon soils support this hypothesis, as do negative correlations between seedling diameter and soil pH for both A (-.83) and B (-.53) soils.

Top weight of seedlings grown on A horizon soil was positively correlated with seedling concentrations of nitrogen (.67), potassium (.67), manganese (.53), zinc (.77), and aluminum (.72). Top weight also had negative correlation with final soil pH (-.74). Top weight of seedlings grown on B horizon soil was positively correlated with tissue concentrations of nitrogen (.68), potassium (.88), manganese (.88), and aluminum (.86). Top weight of B horizon seedlings was also negatively correlated with soil pH (-.87).

These correlations provide evidence to link top weight to the increased input of nitrogen, which was also accompanied by increased availability and uptake of other essential nutrients. The increased uptake of aluminum, while not bearing a biological relationship with increased growth, is evidence that increased solubility of aluminum had occurred in the soil due to input of acid precipitation and resultant decrease in soil pH.

On A horizon soil, lower survival at pH 2.5 raises the question if growth was affected by reduced stand density as well as by acid precipitation treatments. After consideration of factors discussed below, the conclusion was that all growth measures, except seedling diameter on A horizon soil, were not significantly affected by survival.

If survival influenced growth on A horizon soil to a significant extent, this should appear as a strong interaction between precipitation pH and soil horizon in the statistical analysis of growth measures. This was not apparent, and no interactions involving these factors were statistically significant for any of the seedling growth measures (Tables 7.10, 7.11, Figure 7.3). The restriction of root growth to soil within individual plant bands, and the tendency for survival at pH 2.5 to occur as multiple seedlings per band explains why lower stand density did not become a major growth determining factor.

Analyses of variance with survival as a covariate were performed on growth measures at pH levels 2.5 to 4.7 for A and B horizon soils separately. Survival did not serve as a statistically significant covariate for any growth measure except seedling diameter on A horizon soil. For this growth measure, adjustment for survival resulted in the effect of precipitation pH being judged not significant.

Table 7.11

Seedling Root Weight, Total Weight, and Shoot to Root Ratio

Soil	Measurement at pH Level: 2.0 [1]	2.5	3.0	4.0	4.7	Soil Mean
Seedling Root Weight (mg)						*
A	30.0	27.8	34.2	34.2	33.5	32.4x
B	20.5	25.5	27.5	30.2	33.0	29.0y
pH Mean	24.6	* 26.6a	30.9ab	32.2ab	33.2b	
Seedling Total Weight (mg)						**
A	79.0	92.0	90.0	85.5	82.2	87.4x
B	55.0	69.5	66.5	67.5	71.5	68.8y
pH Mean	65.3	80.8	78.2	76.5	76.9	
Shoot to Root Ratio						**
A	2.65	2.40	1.62	1.53	1.46	1.75x
B	1.76	1.73	1.44	1.24	1.19	1.40y
pH Mean	2.14	** 2.07a	1.53b	1.39b	1.32b	

1 pH 2.0 level not included in statistical analysis or calculation of soil means.

Means followed by the same letter are not significantly different at the * .05 or ** .01 level of probability. Letters a,b compare pH means; letters x,y compare soil means.

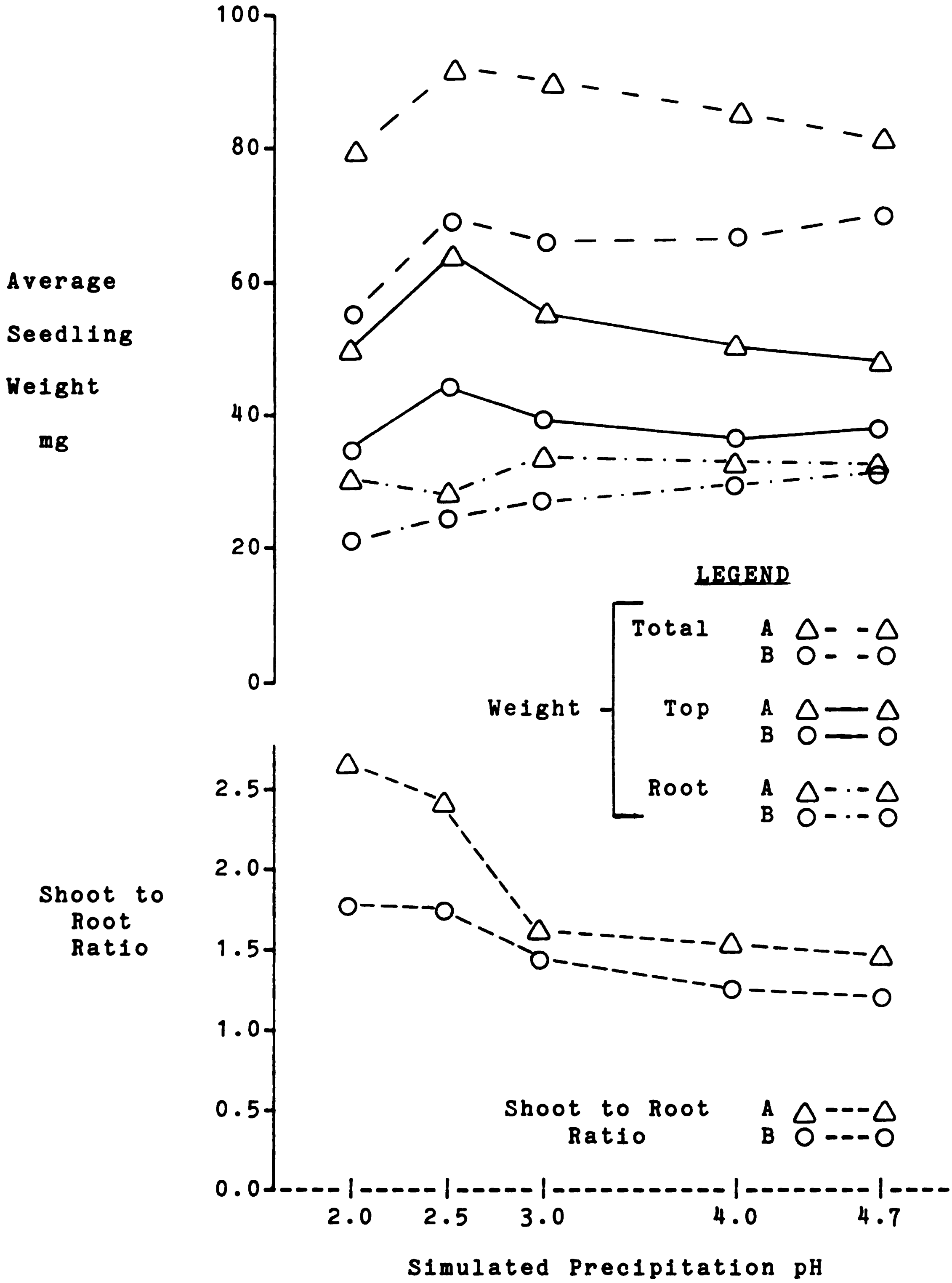

Figure 7.3

Jack Pine Seedling Weight and Shoot to Root Ratio

Due to the confounding effect of lower survival on seedling diameter on A horizon soil, largely at pH 2.5, the means should be viewed with some caution and with the realization that increased seedling diameters at lower pH levels on A horizon soil were not entirely attributable directly to precipitation pH effects. At pH levels 2.0 and 2.5 on both soils, increased stem diameter due to abnormal growth response should also be considered. All other growth measures and relationships were attributable to effects directly related to precipitation pH.

In contrast to other growth measures, average seedling root weight decreased with a decrease in precipitation pH (Table 7.11, Figure 7.3). Mean root weight at pH 2.0 was lower than at all higher pH levels, following the trend of decreasing root weight with decreasing precipitation pH. Seedlings grown on A horizon soil had significantly higher root weights than seedlings grown on B horizon soil.

Application of large amounts of nitrogen fertilizer to conifers has been reported to have a negative effect on root development, especially on phosphorus deficient soils (Pritchett, 1979). High nitrogen inputs at lower precipitation pH levels could thus inhibit root growth, especially on B horizon soil where phosphorus was low. Jack pine root weight was negatively correlated with seedling nitrogen on both A (-.55) and B (-.78) soils, supporting the hypothesis that high nitrogen input inhibited growth of roots at precipitation pH levels below 3.0.

Another factor likely to produce the observed decrease in mean root weight was reduced soil pH and resultant increased solubility of aluminum. Increased solubility of aluminum produces toxic effects on roots leading to growth inhibition (Pratt, 1964; Bartlett and Riego, 1972). Hoyle (1971) reported strong inhibition of root growth of yellow birch by soluble aluminum, especially in the presence of magnesium or sulfur deficiency. Jack pine seedling root weight was negatively correlated with tissue concentration of aluminum (-.55) on A horizon soil. This correlation would be consistent with the hypothesis that reduced soil pH and increased aluminum solubility contributed to reduced root weight at lower pH levels. On B horizon soil, the inhibition of root growth due to the interaction of low magnesium levels with increased aluminum solubility is suggested by the positive correlations between root weight and soil pH (.52), and root weight and seedling magnesium (.75). The lower mean root weight of seedlings grown on B horizon soil as compared to A horizon soil may result from higher total aluminum content and lower soil fertility, especially deficiencies in phosphorus, magnesium, and copper, noted in B horizon soil.

Average total weight of seedlings was not significantly affected by precipitation pH levels between 4.7 and 2.5 (Table 7.11, Figure 7.3). This was a result of the counter-balancing effect of increasing top weight and decreasing root weight. Total weight at pH 2.0 was much lower than at all higher pH levels. Seedlings grown on A horizon soil exhibited significantly higher total weight than seedlings grown on B horizon soil. The differences between soils can be attributed to the overall higher fertility of A horizon soil, and to the negative effects of phosphorus, magnesium, and copper deficiencies on the growth of B horizon seedlings.

Shoot to root ratios were calculated from the ratio of mean top weight to mean root weight for each experimental unit. The mean ratio at pH 2.5 was significantly higher than ratios at all higher pH levels (Figure 7.3). The mean shoot to root ratio at pH 2.0 followed this trend. A horizon seedlings had significantly higher shoot:root ratios than B horizon seedlings, due to the greater top growth of A horizon seedlings (Table 7.11).

Increased shoot to root ratios are the normal result of nitrogen fertilization, since nitrogen stimulates an increase in growth hormones that promote top growth at the expense of root growth (Pritchett, 1979). The combination of a large top and small root system results in a seedling poorly adapted to moisture or nutrient stresses, since the smaller root system is less capable of supplying the demands of the larger top. This observation is in agreement with results of Bensend (1943), in which drought resistance of jack pine seedlings grown with above-optimum nitrogen supply was reduced compared to those grown at the optimum or lower.

Successful germination and early establishment of seedlings was significantly higher on B horizon soil. All seedling growth measures, however, were significantly higher for seedlings grown on A horizon soil. The reduced vigor of seedlings on B horizon soil demonstrated the importance of the A horizon in nutrient supply to developing jack pine seedlings on the Grayling sand.

Silvicultural methods of regenerating jack pine involving extensive scarification to expose mineral soil seedbeds may effectively remove the A horizon soil which is also the soil layer highest in available nutrients and lowest in toxic elements. If scarification of a Grayling sand site to obtain regeneration is necessary, removal of the A horizon should not be so severe or extensive that roots of newly germinated seedlings cannot readily extend into this soil layer.

Jack pine established on A horizon seedbeds would be more resistant to long term adverse effects related to input of acid precipitation than jack pine growing in a Grayling sand denuded of its shallow A horizon. Jack pine rooted in the A horizon would be less likely to develop nutrient deficiencies, especially those exacerbated by the influx of nitrogen in acid precipitation.

Chapter VIII

SUMMARY AND CONCLUSIONS

This chapter includes a summary of the study and major significant effects of simulated acid precipitation on soil properties of the Grayling sand and on jack pine regeneration. Following this summary, the conclusions drawn from the study are presented.

SUMMARY

The impingement of precipitation with an average pH between 4.4 and 4.6 on sensitive soils suggested that the susceptibility of the jack pine-Grayling sand ecosystem of northern lower Michigan to adverse effects of acid precipitation should be studied. A greenhouse experiment was designed to examine the effects of simulated acid precipitation on the germination, survival, and early growth of jack pine seedlings. The effects of simulated acid precipitation on the chemical properties of the Grayling sand A and B horizon soil used as growth media in the study were also investigated.

Treatments consisted of a stock rain, chemically similar to precipitation in northern lower Michigan, acidified to pH levels 2.0, 2.5, 3.0, 4.0, and 4.7 by the addition of a sulfuric acid-nitric acid solution. The study was carried out over a period of eleven weeks from June to

September, 1981 at the Michigan State University Tree Research Center. Approximately .85 cm of rain was applied to each experimental unit three times a week for a total of 28 cm of precipitation during the time period of the study.

Input of sulfuric and nitric acids in simulated precipitation produced pronounced soil acidification throughout both soils at precipitation pH levels 2.5 and 2.0. At pH 3.0, the top five cm of soil was acidified relative to values at pH levels 4.0 and 4.7. B horizon soil evidenced relatively greater acidification at pH 3.0 and 2.5 than A horizon soil, but A horizon soil was acidified more intensely at pH 2.0 than B horizon soil. The changes in soil pH were most pronounced in the top five cm of both soils.

Discussion of soil analysis results in terms of total elemental concentrations refers to values obtained from nitric-perchloric acid extraction unless otherwise indicated. The nitric-perchloric acid procedure does not result in absolute digestion of all minerals or iron oxide crystals. Concentrations thus determined are somewhat lower than derived from methods involving quantitative digestion of all soil minerals and sesquioxides.

Exchangeable calcium, potassium, and magnesium were reduced in A horizon soil at precipitation pH levels 2.5 and 2.0, most noticeably in the upper levels of soil. This reduction was attributed to desorption of cations from the exchange complex by excess hydrogen ions in precipitation, followed by leaching of the cations to deeper soil levels or out of the soil entirely. Concentrations of exchangeable calcium, potassium, and magnesium were not affected by precipitation pH on B horizon soil. Total calcium was reduced in the top level in both soils at pH 2.0. Levels of total potassium and magnesium were not significantly affected by precipitation pH in either soil. Concentrations of total and exchangeable sodium were not significantly affected by precipitation pH, but displayed an equal reduction in concentration from upper levels of A and B horizon soil at all precipitation pH levels.

Total Kjeldahl nitrogen concentration, averaged over A and B horizon soils, increased as precipitation pH decreased, being significantly higher at pH 2.0 than at pH 3.0. Similarly, organic matter in A horizon soil was significantly reduced at pH levels 3.0 and 4.7 as compared to pH 2.0. Organic matter in B horizon soil was not significantly affected by precipitation pH. Lack of correlation between organic matter and soil nitrogen suggested that increased deposition of nitrogen in precipitation at pH 2.0 was responsible for the observed increase in soil nitrogen concentration.

Levels of total phosphorus (Kjeldahl digestion) in the soil were not affected by precipitation pH. Bray 1 extractable phosphorus was significantly higher in A horizon soil at pH levels 2.5 and 2.0, but extractable phosphorus in B horizon soil did not differ significantly between pH levels.

Total aluminum concentrations in A and B horizon soils were not significantly affected by precipitation pH. In contrast, total iron concentration was higher at pH 2.0 than at pH levels 3.0, 4.0, and 4.7 in both soils. Retention of iron at pH 2.0 may have been related to high influx and adsorption of sulfate at this pH level.

Total manganese was reduced in the top five cm in both A and B horizon soils at precipitation pH level 2.0. Total nickel concentrations were found to be significantly reduced in both soils at pH levels below 4.7, indicative of a high susceptibilty to leaching loss of this element in response to influx of acid precipitation.

In comparison, total concentration of boron was higher at pH levels 2.0 and 3.0 than at pH 4.0 and 4.7. Total zinc in A horizon soil was also significantly higher at pH 2.0 than at pH 4.0. Retention of boron and zinc may have been related to higher residual organic matter content at pH 2.0 and to adsorption by iron and aluminum oxides.

Total concentrations of copper and chromium were not significantly different between precipitation pH levels on either A or B horizon soil.

Initial germination of jack pine seeds was significantly reduced at pH 2.0 on A horizon soil, but was not affected on B horizon soil. Emergence of seedlings and completion of germination was reduced on both A and B horizon soils at pH 2.0, and on A horizon soil at pH 2.5.

Initial germination, emergence, and completion of germination were all significantly higher on B horizon soil than on A horizon soil.

Total mortality of seedlings at pH 2.0 for both soils was similar and significantly greater than at higher precipitation pH levels. Mortality on A horizon soil was also increased at pH 2.5. Mean mortality of seedlings was found to be higher on the A horizon than on the B horizon soil. The higher mortality noted at pH levels 2.5 and 2.0 was evidently related to decreased resistance to heat stress during the early stages of regeneration at these pH levels. The high mortality of jack pine seedlings at pH 2.5 and 2.0 during the early stages of germination and establishment demonstrated the sensitivity of very young seedlings to highly acidic precipitation.

Physical injury to seedlings became evident as the development of foliar necrosis and basal stem lesions. These symptoms were most pronounced at pH levels 2.5 and 2.0. Foliar necrosis developed over time and appeared to be related more to alteration of nutritional status of seedlings than directly to acid-induced injuries. Basal lesions developed gradually from small spots on the cortex of the hypocotyl, eventually becoming prominent fissures accompanied by swelling of the root collar and brown to black discoloration of the lower stem. Lesions were most severe at pH levels 3.0 and below.

Accurate determination of elemental concentrations in tops of seedlings grown at pH 2.0 was impaired because of the small amount of tissue produced at this pH level. Consequently, only data for pH levels 2.5 to 4.7 was included in the statistical analysis.

Nitrogen concentration in seedling tops increased as precipitation pH decreased, and was significantly greater in seedlings grown at pH 2.5 than at pH 4.7, whereas phosphorus concentration in seedling tops was significantly lower at pH 2.5 than at pH 4.7. Phosphorus concentration was in the low range for A horizon seedlings, and in the deficient range for B horizon seedlings. Both nitrogen and phosphorus were higher in seedlings grown on A horizon soil.

Potassium, calcium, and sodium concentrations in seedling tops significantly increased as precipitation pH decreased. Potassium and calcium were greater at pH 2.5 than at all higher pH levels, and potassium was higher at pH 3.0 than at pH 4.7. Sodium was significantly higher at pH 2.5 than at pH 4.0 or 4.7. Increased uptake of these nutrients was associated with mobilization by acid input and enhanced availability of these bases in the soil. Increased availability of nitrogen from precipitation also resulted in increased uptake of these nutrients. All three elements were significantly higher in concentration in seedlings grown on A horizon soil.

Magnesium concentration in A horizon seedlings was not significantly different between pH levels. In contrast, in B horizon seedling tops, magnesium was significantly reduced at pH 2.5 as compared to pH 4.7. Although A horizon seedlings were significantly higher in magnesium than B horizon seedlings, magnesium concentrations were in the critical range for jack pine on both soils. Magnesium was especially limiting on B horizon soils due to low levels of exchangeable magnesium.

Concentrations of boron, copper, and iron in seedling tops were not significantly affected by precipitation pH levels between 2.5 and 4.7. While boron and copper were significantly higher in seedlings grown on A horizon soils, iron concentrations did not differ significantly between seedlings grown on either soil. Copper concentrations in B horizon seedlings were below the level considered adequate for jack pine.

Manganese concentration was significantly greater in seedlings grown at pH 2.5 than at all other pH levels, and significantly higher at pH 3.0 than at pH levels 4.0 or 4.7. A horizon seedlings were higher in manganese than B horizon seedlings. Zinc concentrations in seedling tops were higher at pH levels 2.5 and 3.0 than at 4.7, but were not significantly different between seedlings grown on A and B horizon soils.

Concentrations of aluminum, nickel, chromium, and cadmium in seedling tops significantly increased with decreasing precipitation pH. Nickel concentration was greater at pH 2.5 than at pH 4.0 and 4.7. Chromium and cadmium concentrations were higher at pH 2.5, 3.0, and 4.0

than at 4.7. Based on observed concentrations, levels of nickel, chromium, or cadmium toxic to seedlings did not occur at any precipitation pH level. Levels of chromium and cadmium were significantly higher in seedlings grown on B horizon soil. Aluminum concentrations were significantly higher in seedlings grown at pH 2.5 than at pH levels 3.0, 4.0, or 4.7, and higher in B horizon seedlings than in A horizon seedlings.

The low number of surviving seedlings at pH 2.0 necessitated exclusion of this seedling measurement data from statistical analysis. Growth results at this pH level are included in the summary for comparison only.

Jack pine seedlings displayed significantly increased top weight and seedling diameter at pH 2.5 as compared to pH 4.7. Seedling height also increased as precipitation pH decreased to 2.5, but this effect was not significant. Height and top weight of surviving seedlings at pH 2.0 was noticeably depressed, while seedling diameter followed the trend of increasing with decreasing precipitation pH. Increased seedling top weight was attributed to a fertilizing effect of the nitrate component of simulated precipitation. Increased seedling stem collar diameter at pH levels 2.5 and 2.0 was associated with the occurrence of basal lesions, and was discounted as a reliable estimate of growth.

Average seedling root weight decreased with precipitation pH, being significantly lower at pH 2.5 than at 4.7. This trend was also evident at pH 2.0. Decrease in root weight was attributed to a combined effect of increased nitrogen deposition favoring top growth, and increased solubility of soil aluminum producing inhibition of root growth. At pH 2.5, the reduced phosphorus concentration in seedling tops combined with reduced root weight suggested that aluminum toxicity was a factor at this pH level.

Average total weight of seedlings was not significantly affected by precipitation pH levels of 2.5 to 4.7. Total weight at pH 2.0 was reduced below that at all other pH levels. Shoot to root ratios, however, were significantly greater at pH 2.5 than at all higher pH levels. Shoot to root ratios at pH 2.0 were also elevated. This imbalance of root and top suggested that seedlings grown at pH 2.5 would be less adapted to moisture or nutrient stresses than seedlings grown at higher precipitation pH levels.

All growth measures were significantly higher for seedlings grown on A horizon soil than for seedlings grown on B horizon soil.

CONCLUSIONS

Evidence of acidification of the Grayling sand soil was found only at precipitation pH levels 3.0 and below. Based on this result, present levels of acid precipitation in northern lower Michigan are not likely to cause rapid acidification of the Grayling soil over a short time span.

Accelerated loss of cations from the Grayling soil in response to simulated acid precipitation was largely restricted to pH levels 2.5 and 2.0. This result indicated that present levels of acidity in precipitation are unlikely to cause accelerated loss of nutrients from Grayling soil during a short time period.

The results of this study did indicate that if average precipitation acidity were to approach pH values below 3.0, rapid acidification and nutrient depletion from the soil would occur. The long term effects of present levels of precipitation acidity on soil properties of the Grayling sand were not determined and require assessment under field conditions. The results of the present short-term study at pH levels 4.0 and 4.7 should not be extrapolated to predict an absence of long term effects of acid impingement on Grayling soil properties.

Simulated acid precipitation at pH levels 3.0 and above did not adversely affect jack pine seed germination or seedling establishment in a greenhouse environment. Based on these findings, it appears that the level of acid precipitation presently occurring in northern lower Michigan does not adversely impact early stages of jack pine regeneration. A decrease in precipitation pH to levels below 3.0 would result in reduced regeneration success and in adverse physiological adaptation of jack pine seedlings.

Increased deposition of nitrogen with decreased precipitation pH served to stimulate growth of seedlings down to the pH 2.5 level. Influx of nitrogen in precipitation apparently will lead to increased growth of jack pine seedlings in northern lower Michigan, even if enhanced productivity is at an imperceptible level. Increased growth resulting from input of nitrogen to the jack pine-Grayling sand ecosystem could also create greater demand for other nutrients, leading to induced nutritional deficiencies of elements such as phosphorus, magnesium, and copper. For this reason, the influence of acid precipitation on long term changes in soil fertility and productivity of the jack pine-Grayling sand ecosystem is uncertain, and requires further study.

Germination and survival of jack pine seedlings were higher on B horizon soil, but all growth measures were significantly greater for seedlings grown on A horizon soil. Higher nutrient availability on A horizon soil prevented seedlings from developing the nutrient deficiencies evident in seedlings grown on B horizon soil. This result is of significance to acid precipitation research and in choice of silvicultural methods in that jack pine germinated and grown on A horizon seedbeds would display greater resistance to the development of nutrient deficiencies that potentially accompany chronic, long-term input of acid precipitation to the jack pine-Grayling sand ecosystem in northern lower Michigan.

APPENDIX

APPENDIX

Table A.1

Maximum Daily Greenhouse Temperatures[1]

Date	Degrees C[2]	Date	Degrees C[2]	Date	Degrees C[2]
6-25-81	35.6	7-23-81	28.9	8-20-81	----
6-26-81	30.0	7-24-81	----	8-21-81	----
6-27-81	----	7-25-81	----	8-22-81	----
6-28-81	36.1	7-26-81	28.9	8-23-81	27.8
6-29-81	38.9	7-27-81	----	8-24-81	27.8
6-30-81	30.0	7-28-81	27.8	8-25-81	26.7
7-01-81	30.0	7-29-81	27.2	8-26-81	27.8
7-02-81	30.0	7-30-81	28.9	8-27-81	24.4
7-03-81	----	7-31-81	----	8-28-81	----
7-04-81	----	8-01-81	----	8-29-81	----
7-05-81	34.4	8-02-81	30.6	8-30-81	29.4
7-06-81	36.1	8-03-81	28.9	8-31-81	32.2
7-07-81	35.6	8-04-81	33.3	9-01-81	31.1
7-08-81	35.6	8-05-81	28.3	9-02-81	----
7-09-81	32.2	8-06-81	28.3	9-03-81	----
7-10-81	----	8-07-81	----	9-04-81	----
7-11-81	----	8-08-81	----	9-05-81	----
7-12-81	32.2	8-09-81	29.4	9-06-81	30.6
7-13-81	32.2	8-10-81	28.3		
7-14-81	26.1	8-11-81	26.7		
7-15-81	25.6	8-12-81	----		
7-16-81	28.3	8-13-81	30.6		
7-17-81	----	8-14-81	----		
7-18-81	----	8-15-81	----		
7-19-81	32.2	8-16-81	28.3		
7-20-81	30.6	8-17-81	----		
7-21-81	26.7	8-18-81	27.8		
7-22-81	28.3	8-19-81	----		

1 For dates where no maximum temperature is recorded, degree reading for first date immediately following missing data represents maximum temperature attained since previously recorded high temperature.

2 All temperature readings in degrees Celsius.

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