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ACID RAIN INCREASES NUTRIENT LEACHING IN A TOLERANT HARDWOOD FOREST SOIL

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INTRODUCTION

Scientists and natural resource managers have expressed concern that future forest productivity may be threatened by long-range transport of air pollutants (Anon. 1986, Fraser 1989). Trees already harmed by climatic extremes or by insects and diseases may be further damaged by the stress imposed by air pollution. The Federal-Provincial Research and Monitoring Coordinating Committee considers air pollution to be a potential factor in the current episode of forest decline in southern Quebec (Anon. 1990a). This decline is more severe and extensive than declines that have occurred previously in Canada.

The Turkey Lakes Watershed Study

Since 1980, scientists with Forestry Canada, Ontario Region, have studied a mature tolerant hardwood forest 60 km north of Sault Ste. Marie to learn more about the mechanisms of pollutant action on forest ecosystems. Their research has examined the possibility that atmospheric acid deposition contributes to forest decline through soil acidification and nutrient leaching (Fig. 1).

The Turkey Lakes Watershed (TLW) is a 10.5-km^2 area that supports a forest of uneven-aged old-growth hardwoods. The principal tree species is sugar maple (*Acer saccharum* Marsh.), with lesser amounts of other hardwood species, mostly yellow birch (*Betula alleghaniensis* Britton). Forestry Canada's research at the watershed has traced the pathways of water and ions from the atmosphere through the forest canopy, the forest floor, and the mineral soil and on into forest streams.

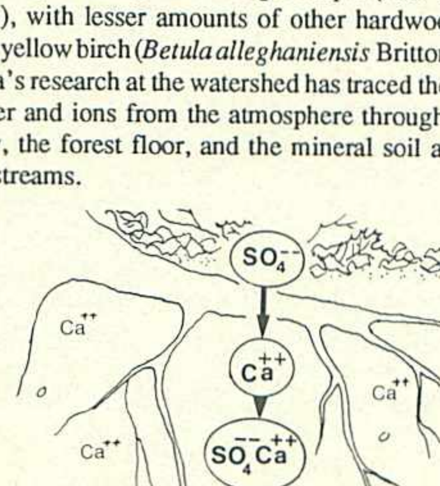

Figure 1. Atmospheric deposition of sulfate anions may promote forest decline by increasing the leaching of calcium and other nutrients critical to tree health.

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SULFATE DEPOSITION

Combustion of high-sulfur coal for power generation and smelting of high-sulfide ores add large amounts of sulfur dioxide (SO_2) to the atmosphere. In 1970, nearly 6,000,000 tonnes of SO_2 were emitted in eastern Canada. Increased pollution control standards and the conversion to low-sulfur fuels have helped to reduce emissions to just over 3,000,000 tonnes per year (Anon. 1990b).

Sulfur dioxide combines with water in the atmosphere to form sulfuric acid (H_2SO_4), which dissociates and enters forest ecosystems in precipitation as hydrogen (H^+) and sulfate (SO_4^{2-}) ions. Sulfate is mobile and may be absorbed by plants, adsorbed (held) by soil minerals, or leached into the groundwater. During the 1980s, precipitation pH at the TLW averaged 4.3. Sulfuric acid was the dominant source of acidifying H^+ ions: SO_4^{2-} deposition in precipitation averaged 29 kg/ha annually.

LEACHING AND ACIDIFICATION

Soil particles have a net negative charge and attract cations in the soil solution to areas of charge called "exchange sites". Nutrient cations compete for a limited number of exchange sites and can displace one another. Available (exchangable) cations in solution may be absorbed by roots, and are a small fraction of the total reserves on a site (Table 1). Cation exchange capacity refers to the ability of a soil to adsorb cations. The amount and type of humus and of clay minerals in the soil determine cation exchange capacity.

Some scientists theorize that acidic deposition reduces forest productivity as a result of leaching and acidification effects in forest soils (Malmer 1974, Odén 1976). During leaching, nutrient ions with a positive charge (cations) are removed from the rooting zone in association with strong acid anions (ions with a negative charge), such as SO_4^{2-} and nitrate (NO_3^-) deposited from the atmosphere. Hydrogen ions present in precipitation replace the nutrient ions and thus acidify the soil. In soils already deficient in essential nutrients, leaching and acidification could create nutrient imbalances sufficient to weaken trees and predispose them to damage by natural agents such as frost or pathogens.

Sulfate Leaching

Sulfate ions enter the ecosystem in precipitation. Additional "dry sulfate" particulates deposited on forest vegetation are washed off during rainfall and percolate through the forest floor and the mineral soil. During the growing season, leaching of calcium and magnesium is strongly associated with SO_4^{2-} leaching. As water moves through the rooting zone, these cations move in association with SO_4^{2-} (Foster 1985).

Leaching is regulated within a forest ecosystem. During the growing season, reduced rainfall and water uptake by vegetation retard ion loss from the rooting zone. Early and late in the season, however, water movement and leaching tend to be high. Years of above-average precipitation favor loss of soil nutrients in association with SO_4^{2-} generated by human activities.

THE BENEFITS OF SULFUR EMISSIONS CONTROLS

Control programs underway in Canada (Fig. 2) and the United States aim to reduce SO_2 emissions (Anon. 1990a). Average annual SO_4^{2-} depositions at the TLW in 1986 and 1987 were lower than during the previous 5 years. Further, there was a reduction in SO_4^{2-} concentrations in soil water that was roughly proportional to reduction of SO_4^{2-} in precipitation. This resulted in reduced sulfate-related leaching of calcium and other nutrients from the forest floor and mineral soil. Soil acidification was also reduced because fewer H^+ ions were supplied in precipitation (Foster and Hazlett 1991).

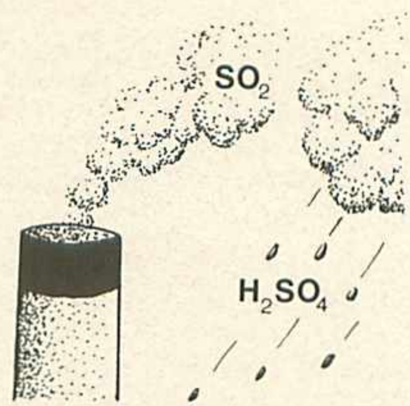

Figure 2. The federal-provincial Canadian Acid Rain Control Program aims to reduce sulfur dioxide emissions to 50% of the 1980 level by 1994.

Sulfate ions tend to be adsorbed by podzolic soils (Morrison and Foster 1987). Before emission controls took effect, SO_4^{2-} ions may have accumulated in the soil. Researchers are concerned that adsorbed SO_4^{2-} may re-enter the soil solution and increase leaching. However, no evidence for this has been found; during the temporary decrease in SO_4^{2-} deposition in 1986 and 1987, the decrease in SO_4^{2-} input was balanced by a decrease in sulfate-related leaching (Foster and Hazlett 1991).

NATURAL VERSUS ANTHROPOGENIC SO_4^{2-} AND NO_3^-

At the TLW, the 1986 growing season was marked by high precipitation and water movement through the soil, which increased leaching associated with NO_3^-. Most of the NO_3^- originated in the soil as a result of naturally occurring nitrification reactions, though some came from the atmosphere. Leaching caused by excess NO_3^- increased enough to offset the reduction in sulfate-caused leaching. Thus, although reduced atmospheric SO_4^{2-} deposition was correlated with reduced leaching by SO_4^{2-}, the *net* leaching of nutrient cations did not decrease (Foster and Hazlett 1991).

Soil acidification and leaching of calcium and magnesium also result from the action of organic acids derived from the decomposition of plant material in the forest floor. These naturally produced acids account for about half the total anions in forest-floor percolate during the growing season (Hazlett and Foster 1989) (Fig. 3).

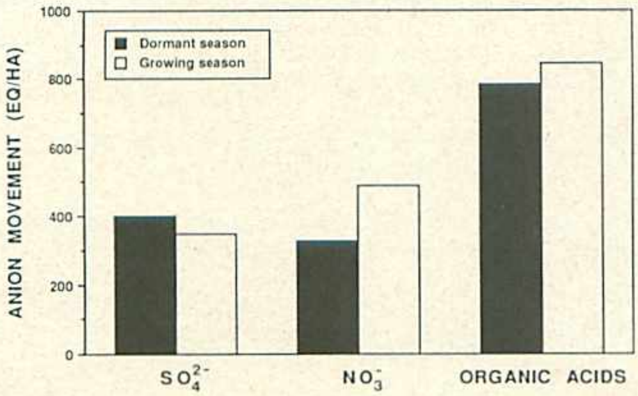

Figure 3. Mean anion movement through the forest floor of a maple-birch ecosystem at the TLW (Hazlett and Foster 1989).

REPLACEMENT OF LOST CATIONS

Table 1. Available and total calcium and magnesium in the forest floor and mineral soil in two old-growth sugar maple stands at the TLW (Morrison 1990).

Level	Magnesium (kg/ha)	Calcium (kg/ha)
Norberg Creek		
Forest Floor: Available	14	162
Total	39	272
Mineral Soil: Available	66	822
Total	64,274	162,100
Wishart Lake		
Forest Floor: Available	16	230
Total	64	381
Mineral Soil: Available	103	1,981
Total	115,986	272,481

Microbial decomposition of organic matter in the forest floor releases inorganic elements, which may occupy exchange sites and nourish trees. In the organic horizons of the TLW soil, calcium is the primary nutrient cation, occupying 28% of the measured cation exchange capacity (Foster et al. 1986). Cycling of organic matter (as litterfall) between vegetation and the surface organic layers counteracts leaching and nutrient uptake by plants.

In forest stands, calcium is localized in stems and bark. Logging removes calcium that would otherwise replenish the forest floor after decay and decomposition of tree biomass. Full-tree harvesting would greatly increase the degree of calcium loss (Morrison 1990).

At the TLW, the effective rooting zone comprises a stony, silty loam ablation till that extends from the forest floor-mineral soil interface to a depth of 50 to 60 cm. Abundant potential plant nutrients are bound in this zone. Gradual natural chemical weathering of this material continuously supplies exchangeable cations such as calcium and magnesium to offset leaching losses. Weathering proceeds slowly and rates vary widely. It is intensified by the action of organic and mineral acids leached from the forest floor in the soil solution. If cations removed from exchange sites by vegetation uptake and leaching are not replaced by the weathering of primary minerals, the supply of exchangable base cations available for plant growth will be depleted.

The Wishart Lake stand is better supplied with available and total reserves of calcium than the Norberg Creek stand (Table 1). Weathering of a somewhat richer till at Wishart Lake has presumably been the origin of the more abundant nutrients at that site. The ability of the Norberg Creek site to sustain either one-time losses, as through full-tree harvesting, or continuous, accelerated losses under the influence of an increased deposition of atmospheric SO_4^{2-} is presumably less than that of the richer site (Morrison 1990). Harvesting stands by the full-tree method must take this difference into account to avoid depleting a site's nutrient potential in subsequent harvests.

CONCLUSIONS

1. Sulfate and NO_3^- anions introduced to the ecosystem by atmospheric deposition caused leaching of calcium and magnesium from the rooting zone.

2. Reduced SO_4^{2-} deposition has been correlated with reduced leaching of nutrient cations, but this may be compensated for by increased leaching by NO_3^-. This finding supports the value of emission-control programs.

3. Naturally occurring anions, particularly NO_3^- and organic acids, contribute significantly to leaching of cations from the soil.

4. Sites vary in their supply of nutrient cations; a site low in exchangable cations might become less productive if subjected to prolonged high levels of leaching. Full-tree harvesting and high levels of acidic deposition would both increase the loss of available nutrients such as calcium and magnesium.

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