Acidification in Tropical Countries
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CHAPTER 4

Potential Effects of Acid Deposition on Tropical Terrestrial Ecosystems

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4.1 INTRODUCTION

In this chapter I present a brief overview of the effects of acidic deposition on terrestrial ecosystems, with emphasis on the tropics. I first examine the data base on acidic deposition and its effects on temperate terrestrial ecosystems, and then attempt to apply the lessons learned in the temperate zone to tropical ecosystems. Although some data are available for tropical ecosystems, they are meager compared with information available for temperate ecosystems. This is due both to a general paucity of information on tropical ecosystems, and to the apparent lack of significant amounts of acid deposition in most of the tropics.

The working question throughout this chapter is, 'What would happen if anthropogenic loading were to increase in the tropics?' Would measurable effects be apparent on terrestrial ecosystems? Can we use lessons learned in the temperate zone to predict the effects of acidic deposition in the tropics?

Deposition of acidic substances to a terrestrial ecosystem is the end result of an intricate web of physical, chemical, and biological processes. Because the components (sulfuric acid, nitric acid, organic acids) as well as total acidity are important in determining effects, I briefly describe factors affecting the chemistry of atmospheric deposition in the tropics.

4.2 WET DEPOSITION

Wet deposition of pollutants is a function of meteorological variables and of the kinetics and equilibria of atmospheric chemical reactions. Precipitation scavenging has been defined as 'the composite process by which airborne pollutant gases and particles attach to precipitation elements and thus deposit to the Earth's surface' (NRC, 1983). The scavenging process can be viewed as consisting of four steps (NRC, 1983): (i) mixing of pollutant and condensed atmospheric water (cloud, rain, snow) within the same airspace; (ii) attachment of pollutant to atmospheric water; (iii) physical and/or chemical reaction within the aqueous phase; (iv) delivery to the earth's surface of pollutant-laden atmospheric water.

Fog and cloud water appear to be especially effective in scavenging pollutants from the atmosphere, and hence may serve as early indicators of increasing anthropogenic inputs of acidic components. Concentrations of H^+ can be an order of magnitude higher in cloud water than is ordinarily found in rainwater (Jacob *et al*., 1985; Weathers *et al*., 1986), and could be an important source of elemental input in some coastal, montane, and desert environments. Cloud water deposition appears to be significant in the water budgets of higher elevation montane forests such as the subalpine balsam fir forest of the White Mountains (Lovett *et al*., 1982; Lovett, 1984) in New Hampshire, USA, the elfin forest found at high elevations in Puerto Rico (Baynton, 1969) and other Caribbean islands, and the cloud forest of eastern Mexico (Vogelmann, 1973). Deserts such as the Namib of South Africa and the Peruvian coastal desert also derive a significant fraction of total water inputs from fog (Walter, 1971a, b).

Acidity of wet deposition in much of the tropics appears to be low relative to most of the industrialized temperate zone (Table 4.1). Total H^+ deposition in many tropical areas will be greater than expected on the basis of pH alone because of higher rainfall. In many parts of the tropics precipitation acidity appears to be buffered by dust and soil particles (Visser, 1961; Dalal, 1979).

The relative contribution of organic acids to total and free acidity in remote tropical sites may be considerably greater than corresponding values for temperate sites. Keene *et al*. (1983) found that weak organic acids (predominantly formic and acetic acids) contribute 64% and 63% of free and total acidity, respectively, in wet-only precipitation samples collected in Katherine, Australia. Average concentration of organic acids was 19.8 μeq/liter. In Virginia, USA, Keene and Galloway (1984) measured organic acid concentrations (formic and acetic acids) equivalent to 16% of free acid-

Table 4.1 Precipitation pH and H^+ deposition at some tropical sites, and the northeastern USA; annual deposition calculated from mean or volume-weighted mean pH where available

Location and Reference	pH Median	pH Range	Sampling frequency	n	Precipitation (cm)	Deposition (kg/ha/year)
Brazil[1]	5.1	4.7–5.7	event	33	–	–
Venezuela[2]	4.6	3.8–6.2	semi-weekly	27	158	0.39
Venezuela[3]	4.8[8]	4.4–5.2	event	14	–	–
Costa Rica[4]	5.3[8]	4.8–6.3	weekly	90	233	0.12
Trinidad[5]	5.8[9]	5.3–6.4[10]	daily	387[11]	109	0.02
Uganda[6]	7.9	5.7–9.8	daily	63	127	0.00
Australia[3]	4.8[8]	4.2–5.4	event	40	–	–
USA[7]	4.1[9]	3.0–5.9	weekly	3200	129	1.02

[1] Stallard and Edmond, 1981.
[2] Steinhardt and Fassbender, 1979.
[3] Galloway *et al*., 1982.
[4] Hendry *et al*., 1984.
[5] Dalal, 1979.
[6] Visser, 1961.
[7] Likens *et al*., 1977.
[8] Volume-weighted mean.
[9] Mean H^+ at six sites expressed as pH.
[10] Range of mean H^+ expressed as pH for six sites.
[11] Total samples collected at six stations.

ity (10.9 μeq/liter). More detailed characterization of both temperate and tropical precipitation is needed to assess whether increased concentrations of organic acids in precipitation are characteristic of tropical areas in general.

At most tropical sites there appears to be excess sulfate beyond that contributed by seasalt aerosols, as well as significant amounts of nitrate. The sources of sulfate and nitrate in rain of remote areas are not fully known. Stallard and Edmond (1981) argue that biogenic production of reduced sulfur from terrestrial and marine sources, and reduced nitrogen from terrestrial sources, are responsible for concentrations of nitrate and sulfate observed in wet deposition in the Amazon basin. Keller et al. (1986) found that nitrous oxide emissions were approximately ten-fold higher from neotropical than temperate soils, which suggests that the importance of biogenic sources of reduced nitrogen may indeed be considerable in the tropics. Andreae and Andreae (1987) suggest, however, that biogenic emission of sulfur species in the Amazon basin may be considerably lower than previously reported. At some tropical sites, industrial activity (Steinhardt and Fassbender, 1979), petroleum refining (Dalal, 1979), or volcanoes (Hendry *et al.*, 1984; Johnson and Parnell, 1986) may influence precipitation chemistry.

Several variables warrant a tropical–temperate comparison. The conversion of SO_2 and NO_x to sulfuric and nitric acids, respectively, may be affected by increased air temperatures and solar irradiance in the tropics, as described in Chapter 1 of this volume. Given equal amounts of acidic precursors in the temperate and tropical environment, one would predict more rapid production of acidic compounds in the tropics.

With higher precipitation in the humid tropics than in the temperate zone, total deposition may be higher for a given quantity of pollutant emitted to the atmosphere. 'Recycling' of atmospheric moisture within a given air mass may be considerably greater in much of the forested tropics than in temperate areas, allowing for greater opportunity for precipitation scavenging of a given pollutant molecule. In the Amazon basin, for example, it is thought that rainwater falls, evaporates and falls again several times before leaving the basin (Salati and Vose, 1984).

Seasonal changes in the deposition or delivery of acids to temperate ecosystems are important in determining the overall effects of acid deposition. Because acids tend to accumulate in the snowpack of northern latitudes, spring snowmelt can result in pulsed, episodic delivery of acids to terrestrial and aquatic ecosystems even though actual rates of deposition to the earth's surface are relatively uniform. The pulsed input of acid associated with snowpack melting is important in determining the effects of acidic deposition on aquatic ecosystems in the temperate zone (e.g. Jeffries *et al.*, 1979). Seasonal changes in precipitation chemistry and deposition rates do occur in the tropics (Lewis, 1981; Kellman *et al.*, 1982; Hendry *et* *al.*, 1984). Although it usually does not result in episodic inputs of H^+ with the apparent ecological significance of that observed with snowpack melting, examples of fish kills associated with seasonal changes in stream pH are known in Australia (Ayers and Gillett, 1988).

High rates of biomass burning in the tropics might be having significant effects on atmospheric chemistry and the acidity of atmospheric deposition. Destruction of tropical forests (including burning) is apparently a significant factor in the global carbon cycle (Woodwell *et al.*, 1983), and could be important for total acidity and trace gas concentrations as well (Crutzen *et al.*, 1985). Significant amounts of NO_x are released by biomass burning (Crutzen *et al.*, 1985), which upon oxidation would contribute to atmospheric deposition of nitric acid. In addition to trace gas production, however, biomass burning can produce alkaline ash, which can neutralize acidic substances in the atmosphere.

4.3 DRY DEPOSITION

Dry deposition refers to a wide range of processes by which pollutant gases and aerosol particles reach the earth's surface. Both small-scale meteorological conditions at the time of deposition and the nature of the collecting surface affect dry deposition rates. Accurate estimation of dry deposition rates is difficult due to problems in modeling small-scale turbulent diffusion and the biological factors (e.g. stomatal openings) that influence deposition rates. No uniformly accepted method for assessing dry deposition has been developed, although progress has been significant in recent years (e.g. Hicks, 1986; Knapp *et al.*, 1986; Lindberg *et al.*, 1986). Despite difficulties in quantifying dry deposition, measurements to date indicate that it can be a significant fraction of total deposition of N and S, and is generally assumed to be roughly equivalent to wet deposition in the northeastern US (NRC, 1983). Data for remote continental areas with little anthropogenic influence, however, indicate that dry deposition of N and S species is as little as 10%–25% of wet deposition (Galloway, 1985).

Differences in rates of dry deposition in tropical relative to temperate systems might be expected due to differences in ambient humidity and forest canopy structure. Ambient relative humidity, total leaf surface area, surface roughness, and density of stomatal openings would all need to be evaluated for tropical and temperate sites. Most tropical plants have stomata on the underside only, as opposed to temperate plants, which have stomata on upper and lower leaf surfaces. This could have important implications for rates of dry deposition.

Humidity appears to play an important role in regulating rates of dry deposition. Horntvedt *et al.* (1980) found that dry deposition rates of SO_2 increased by as much as ten-fold when leaf surfaces were wet. They also observed that dry deposition rates decreased in the absence of light, presumably due to closure of stomata. Hicks (1986) obtained similar results, finding an increase in dry deposition of N and S during daylight, with highest deposition values generally found in early morning when leaf surfaces were wettest (Figure 4.1). These results from temperate sites suggest that light and humidity regimes might be critical in determining rates of dry deposition in tropical environments. Dry deposition of N and S for a given ambient concentration would appear to be larger in the humid tropics than in the temperate zone due to higher humidity.

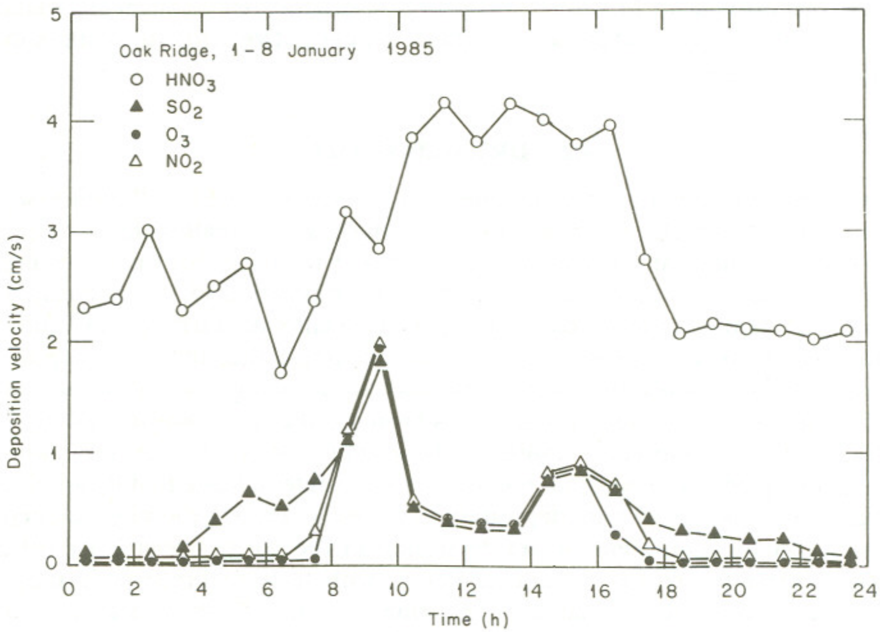

Figure 4.1 Average estimated diurnal cycles of deposition velocities for HNO_3, SO_2, NO_2, and O_3, deduced from seven days of data obtained for a deciduous forest at Oak Ridge. Tennessee, USA. Note the early morning peak in SO_2 deposition velocity associated with increased surface wetness. From Hicks (1986). Copyright 1986 by D. Reidel Publishing Co. Reprinted by permission

4.4 EFFECTS OF ACIDIC DEPOSITION

Assessing the effects of acidic deposition on a terrestrial ecosystem requires a holistic approach in which vegetation, soil, animals, and microorganisms are all considered. The linkages between different compartments in the ecosystem and the magnitude of second-order effects must also be examined.

Following the movement of water through a terrestrial ecosystem provides an effective means of assessing the direct effects of acidic deposition. Much incoming acidity will enter in the aqueous phase, or be transported by the movement of water within the ecosystem. Changes in the chemistry of water moving through a terrestrial ecosystem provide an integrated description of biogeochemical processes at work within the system (Likens, 1984).

An important consideration in assessing the impact of acidic deposition is to distinguish between the intensity of precipitation acidity (pH) and the total quantity of H^+ entering an ecosystem (deposition). Vegetation is more likely to respond to the frequency of highly acidic events, while soils are most likely to be affected by long-term rates of acidic deposition.

The mobility of the anion accompanying H^+ deposition is a determinant of acidic deposition effects (Johnson *et al*., 1982). If incoming H^+ is associated with an anion that is immobilized within the ecosystem, then the associated H^+ must also be retained to maintain electroneutrality. Mobility within an ecosystem is determined by biological processes, such as assimilation or oxidative respiration, and by chemical processes, such as adsorption and anion exchange, which can occur as water moves the acid through the ecosystem. Nutrient limitation within an ecosystem can be important in determining anion mobility. If nitrogen is the nutrient limiting primary production in a rainforest, for example, nitrate would be less mobile than otherwise predicted due to vegetative uptake.

Simple organic acids of low molecular weight, especially formic and acetic acids, are important components of total acidic deposition, especially in the tropics (Keene *et al*., 1983), but they are not likely to be mobile within terrestrial ecosystems due to rapid decomposition. Organic acids found in wet deposition are rapidly oxidized in samples of rainwater alone (Keene *et al*., 1983; Keene and Galloway, 1984), and would likely be rapidly oxidized within a terrestrial ecosystem. Nitrate is somewhat more mobile than organic acids, although in many ecosystems nitrate assimilation by vegetation can exert a measurable impact on nitrogen flux through the system (e.g. Likens *et al*., 1977). Nitrate generally does not participate in soil adsorption reactions, and hence its mobility is controlled predominantly by biological processes. The mobility of sulfate in terrestrial ecosystems is determined in large part by soil adsorption processes, although recent work has shown that rapid microbial uptake of sulfate can occur as well (Swank *et al*., 1984). Because sulfate is generally the most mobile of the three acidic anions common in precipitation, it most often controls the effects of acidic deposition on soils as well as aquatic ecosystems (Galloway, 1988).

4.4.1 Vegetation

Effects of acidic deposition on vegetation can be direct (effects of acid impinging directly on vegetative surfaces) or indirect (through effects of acid deposition on soils or biota). Cuticular (rather than stomatal) absorption appears to be the main avenue by which aqueous solutes enter leaf tissue (Evans, 1984). Foliar wettability, presence or absence of cuticular micropores, and cuticular composition are all likely to determine the susceptibility of vegetation to damage by acidic deposition (Evans, 1984). Visible foliar injury and increased cation leaching are two direct effects of acidic deposition on foliar surfaces, but their occurrence is not widespread (Evans, 1984). Foliar injury under ambient conditions in the field has been documented in only one instance (Evans *et al.*, 1982)

Throughfall pH generally increases under deciduous canopies relative to incident precipitation (Parker, 1983) (Figure 4.2), apparently due to exchange of base cations for H^+ and removal of nitrate by foliar absorption. Laboratory studies have shown that rates of cation and anion loss can increase as a function of the acidity of artificial rain (Wood and Bormann, 1975; Fairfax and Lepp, 1975; Evans *et al.*, 1981; Kelly and Strickland,

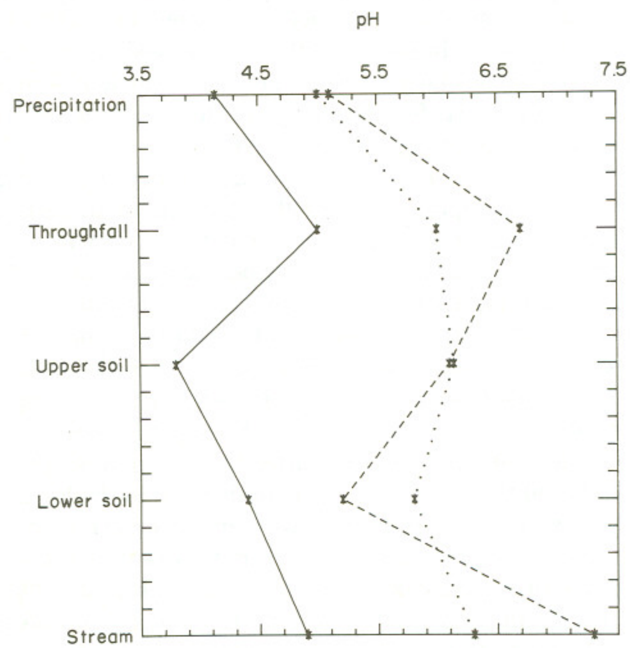

Figure 4.2 pH of precipitation, throughfall, soil solution, and stream water at one temperate (Hubbard Brook; ——) and at two tropical sites (La Selva; · · · and El Verde; – – –). Data for Hubbard Brook, New Hampshire, USA from Likens *et al.* (1977) and McDowell and Wood (1984). Data for La Selva, Costa Rica from McColl (1970); data for El Verde, Puerto Rico from McDowell (1984) and McDowell (unpublished)

1986). Deposition and washing of aerosol particles from leaf surfaces also occurs in the field, however, and this complicates analysis of the actual impact of wet deposition on nutrient leaching from vegetation. Furthermore, in a study in which nutrient loss from leaves increased as a function of pH (Kelly and Strickland, 1986), corresponding declines in nutrient content of vegetative tissues were not apparent. Compensatory mechanisms such as increased mobilization of nutrients from soil might have been responsible for the lack of change in vegetation despite increased foliar losses.

The direct effects of wet and dry deposition of acidic substances on terrestrial vegetation in the temperate zone appear to be significant. Decline of forest productivity, direct mortality, and increased susceptibility to ancillary causes of mortality (e.g. fungus, insect infestation) have all been postulated as effects of acidic deposition. In the Black Forest of West Germany and the Green Mountains of Vermont, USA, striking diebacks of coniferous trees have occurred, and direct or indirect effects of acidic deposition are thought to be possible causes (FRG, 1984; Johnson and Siccama, 1983).

Although acid deposition appears to be a causative agent in forests showing vegetative decline, it is difficult to partition the effects of acid deposition and other pollutants (Bormann, 1985). Ozone, for example, may be elevated when acidity of rainwater or cloudwater is elevated (e.g. Weathers *et al.*, 1986), due to their common origin in a contaminated air mass.

Precipitation in the northeastern USA does not appear to be sufficiently acid to cause much direct foliar injury to crops and trees. In a review of greenhouse and chamber studies of the effects of acid precipitation on crops and trees, Jacobson (1984) found that significant damage occurred only at a pH of 3.5 or less for most species studied. When this is compared with the frequency of rainfall events with a given pH (Figure 4.3), one can see that foliar damage as a result of exposure to ambient precipitation would be predicted only infrequently.

Precipitation acidity does not appear to be affecting growth and yield of US crops (Moskowitz *et al.*, 1985) on a national level. Increases as well as decreases in growth and yield of various crops have been observed (Irving, 1983), but the majority show no effect. No particular crops appear to be especially sensitive to acid deposition, or to synergistic effects with other variables. Moskowitz *et al.* (1985) examined the response of soybeans to precipitation acidity under field conditions in order to model effects of acid deposition on soybean yield on a national basis. They concluded that a reduction in soybean yield may be occurring due to precipitation acidity, but that the decrease was only 10% of the reduction in yield attributable to other factors such as droughts and pests.

In some regions acidic deposition provides potentially significant amounts of nutrients to vegetation. In the southeastern USA, Lindberg *et al.* (1986) estimate that deposition to the forest canopy supplied 40% and 100% of

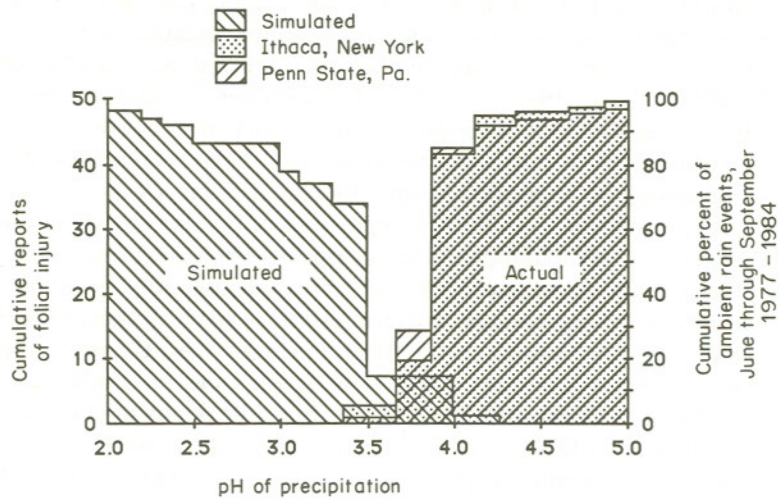

Figure 4.3 Comparison of acidity of ambient rain at two sites in the northeastern USA with acidity causing foliar injury to experimental vegetation grown in greenhouses or chambers. Modified from Jacobson (1984) by G.E. Likens.

the N and S, respectively, needed for woody growth. Dry deposition was a major source of both N and S, with direct foliar absorption an important uptake vector.

Differences in phenology, growth form, and nutrient status are likely to determine differences in the direct responses of tropical and temperate vegetation to acid deposition. A factor that might make tropical forests inherently more susceptible to acidic deposition than their temperate counterparts is the greater average leaf life of tropical vegetation. Leaves of many tropical trees may last up to two years or more, in contrast to a year or less for many temperate trees. Thus, the effects of any environmental insult might be expected to be greater in the tropics where cumulative effects would be more pronounced.

Neutralization of acidity in incident precipitation by contact with vegetative surfaces appears to occur in tropical as well as temperate climates (Figure 4.2). Results similar to those presented in Figure 4.2 have been obtained in other tropical forests (e.g. Meguro *et al.*, 1979). A striking example of neutralization of precipitation acidity by tropical vegetation occurs in the vicinity of Masaya volcano in Nicaragua. With the advent of active emission of acidic gases in the early 1950s, cloud forest was replaced by pioneer species such as *Malanthora* and *Lantana* (Johnson and Parnell, 1986). Precipitation acidity (primarily HCl) is apparently neutralized by exchange with K^+ leached or exuded from leaves.

Deposition could be a significant nutrient source for many forests in tropical areas. Low nutrient status in many tropical soils (Sanchez, 1976), combined with the potentially high rates of dry deposition in the tropics for a given atmospheric concentration, suggest that dry deposition may be an important vector for nitrogen and sulfur inputs in currently unacidified regions. Anthropogenic increases in ambient levels of acidity and deposition might further enhance the impact of dry deposition on nutrient cycles.

Recognizing deleterious effects of acidic deposition on tropical vegetation may be hampered by the high biological diversity characteristic of much of the tropics. High biological diversity, especially in the humid tropics, makes reliance on shifts in species abundance as an indication of significant biological change due to acidification very risky. Because of inherent uncertainties in measuring species distributions, the diversity of tropical biomes makes biological changes more difficult to detect than in counterpart temperate ecosystems.

4.4.2 Animals

Direct effects of acidic deposition are generally seen only in those animals which have an aquatic life phase. Pough (1976) found that spotted salamanders in the northeastern USA were vulnerable to low pH during their development in vernal ponds. At pH less than 6.0, cumulative embryonic mortality shifted from less than 1% to greater than 50%. In addition to increased mortality, increases in developmental abnormalities were also observed as a function of pH (Pough and Wilson, 1976).

In neotropical rainforests, amphibians such as frogs and salamanders are an integral part of the biota, with many species and high abundances. They must keep their skin surface moist at all times and would seem vulnerable to acidification of precipitation and cloud water. Many live in bromeliads, which collect rainwater directly. These animals would be exposed immediately to any changes in the pH of incident precipitation.

A second group of animals possibly at increased risk due to acidification would be the mosquitoes and flies with life stages in bromeliads or other water derived directly from precipitation in humid tropical forests. They play an important role in the food web and in the pollination of vegetation. Because tropical forest vegetation relies more heavily on animals as agents of pollination than does temperate forest vegetation (Baker *et al*., 1983), a decline in animal populations could thus have an indirect effect on vegetation as well. Numerous indirect effects of acidic deposition on terrestrial animals might be hypothesized, such as decline in herbivore populations with decline in net primary production. Postulation of indirect effects of deposition on animals must await demonstration of direct effects on vegetation.

4.4.3 Soils

Changes in solution acidity occur as water passes through the forest canopy and into the soil profile of temperate forests. In many soils, organic acidity generated by soil processes (e.g. Figure 4.2) results in a net acidification as throughfall passes through the forest floor, followed by neutralization in underlying mineral horizons. This is particularly true in Spodosols, which are common in the areas of the USA and Europe most affected by acidic deposition.

It is generally agreed that moderately acid soils without large acid neutralizing capacity, such as some Alfisols, are most sensitive to acidification induced by atmospheric inputs (NAS, 1981). The factors that appear most important in regulating the degree of acidification are sulfate retention ability and the ability to supply base cations to soil solution (NRC, 1984). Soils with low sulfate retention capacity and low base saturation are most likely to acidify. Soils with high base saturation such as calcareous soils are able to replenish the pool of cations available for exchange fast enough to prevent acidification of soil solution. The intensity and the duration of acidic inputs will work together to determine the extent to which a soil will acidify and the time course of such acidification. Soils such as Spodosols that generate protons are unlikely to show major changes in pH in the short term (although proportions of weak and strong acids might change), as they are often more acidic than incoming precipitation due to organic acidity (e.g. Johnson *et al.*, 1982; McDowell and Wood, 1984; Cronan and Aiken, 1985). In the long term, however, their rate of acidification would also be controlled by sulfate adsorption and base saturation.

The flow path and velocity with which incoming precipitation moves through a watershed are also important in determining the susceptibility of a soil to acidification and the pH of soil solution (NRC, 1984). Extensive study of the ILWAS study site in the Adirondack Mountains of New York, USA (Cronan, 1985), has shown that the acidity of receiving waters appears to be strongly tied to the flow path of water through the soil. The presence or absence of macropore flow in a soil (through animal burrows, voids left by decomposition of roots, etc.) is an important variable affecting flow path through a soil.

The mobility of sulfate or other anions within a soil can influence the impact of acid deposition on soil chemistry (Johnson *et al.*, 1982) and stream water chemistry (Galloway, 1988). In soils with low sulfate adsorption capacity, such as many Spodosols of the northeastern USA, sulfuric acid from atmospheric deposition is more mobile in soil solution than in soils with higher sulfate adsorption capacity (Johnson *et al.*, 1982) (Figure 4.4). Sensitive soils in which sulfate is mobile will tend to be more susceptible to acidification, with consequent effects on soil chemistry and vegetation.

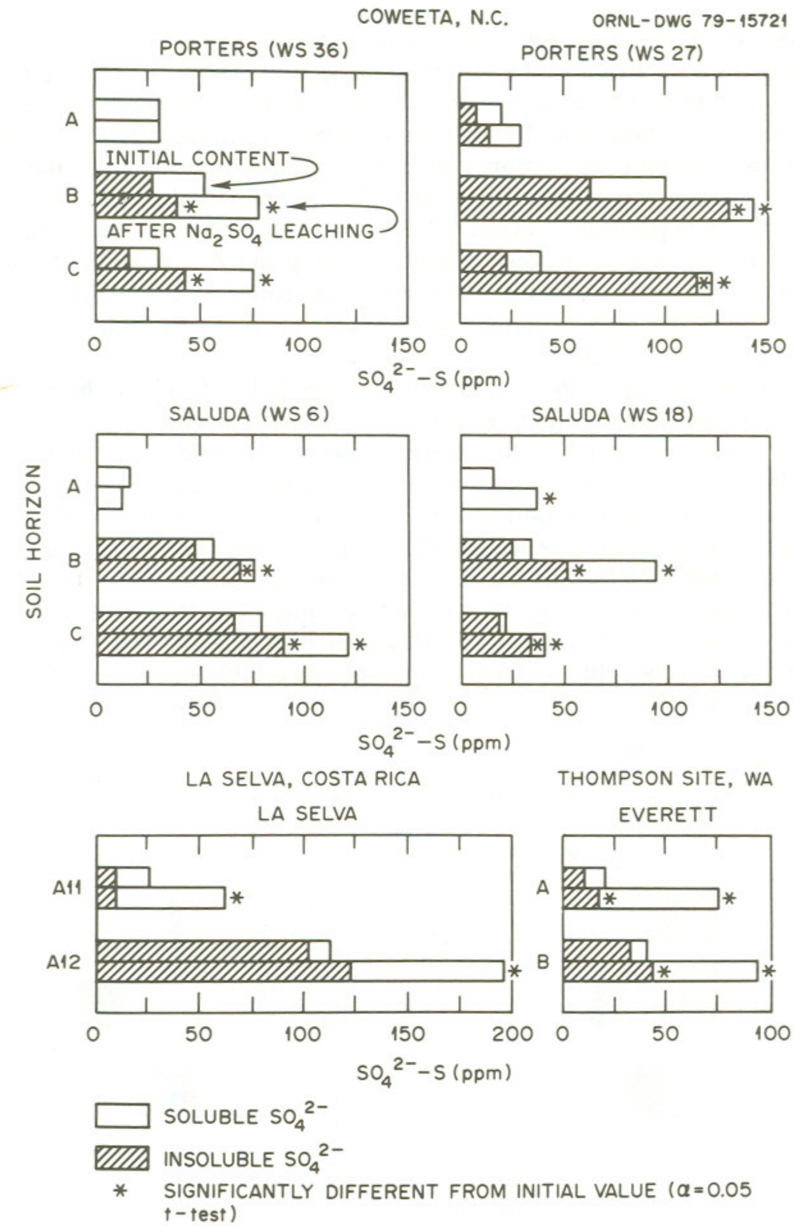

Figure 4.4 Sulfate content of soils from Coweeta, North Carolina, USA; La Selva, Costa Rica; and Thompson site, Washington, USA, before and after leaching with Na_2SO_4 containing 75 ppm S. Total height of bar represents total adsorption, fractioned into water-soluble and water-insoluble components. From Johnson *et al.* (1980). Copyright 1980 by Technomic Publishing Co., Inc. Reprinted with permission

Dissolution of aluminum in soil water appears to be one of the major negative impacts of acidic deposition in many soils. Transport of Al through soil is determined to a large extent by pH and concentrations of fluoride and organic ligands (David and Driscoll, 1984). In Spodosols, Al in upper horizons is transported predominantly in organic complexes, with inorganic ligands gaining importance in lower soil horizons (Figure 4.5). Increased atmospheric deposition of acidity could alter Al transport by changing both dissolved organic carbon concentrations (Chang and Alexander, 1984; Krug and Isaacson, 1984) and soil solution pH. High concentrations of aluminum can damage tree roots, although such effects have not been demonstrated conclusively in the field.

Major influences on the susceptibility of tropical soils to acidification are similar to those for temperate soils. Tropical soils most likely to become acidified with increased acidic deposition would be mildly weathered soils with low sulfate adsorption capacity and low base saturation. Many tropical soils are acidic, highly weathered, and have high concentrations of Fe and Al (Sanchez, 1976), and hence would not be expected to show large changes in acidity with increased acidic deposition (Johnson *et al*., 1982). Figure 1.8 illustrates the location of soils sensitive to acidification (Rodhe *et al*., 1988). However, due to high sulfate adsorption capacities, sensitive soils may not be immediately susceptible to acidification (Galloway, 1988). Figure 4.6 shows such areas with potentially high sulfate adsorption capacities.

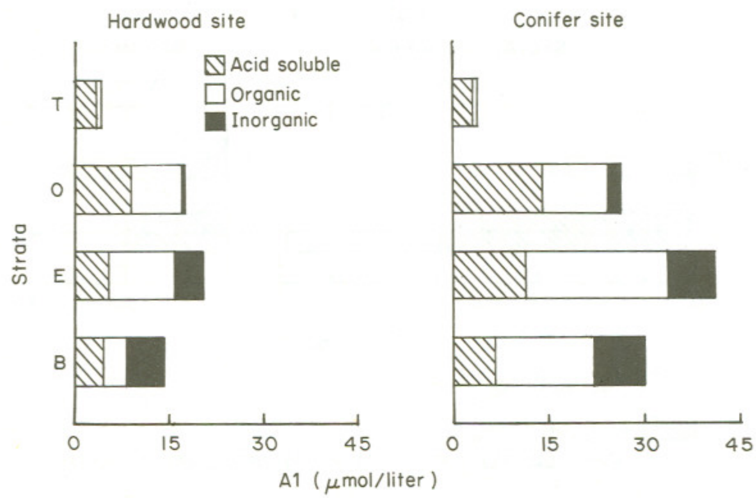

Figure 4.5 Acid-soluble, organically complexed, and inorganic aluminum concentrations in soil solutions from O, E, and B horizons and throughfall (T) at hardwood and conifer sites in New York, USA. Acid-soluble aluminum is thought to be predominantly complexed by organic ligands in a non-labile, or occluded, form. From David and Driscoll (1984). Copyright 1984 by Elsevier Science Publishers B.V. Reprinted with permission

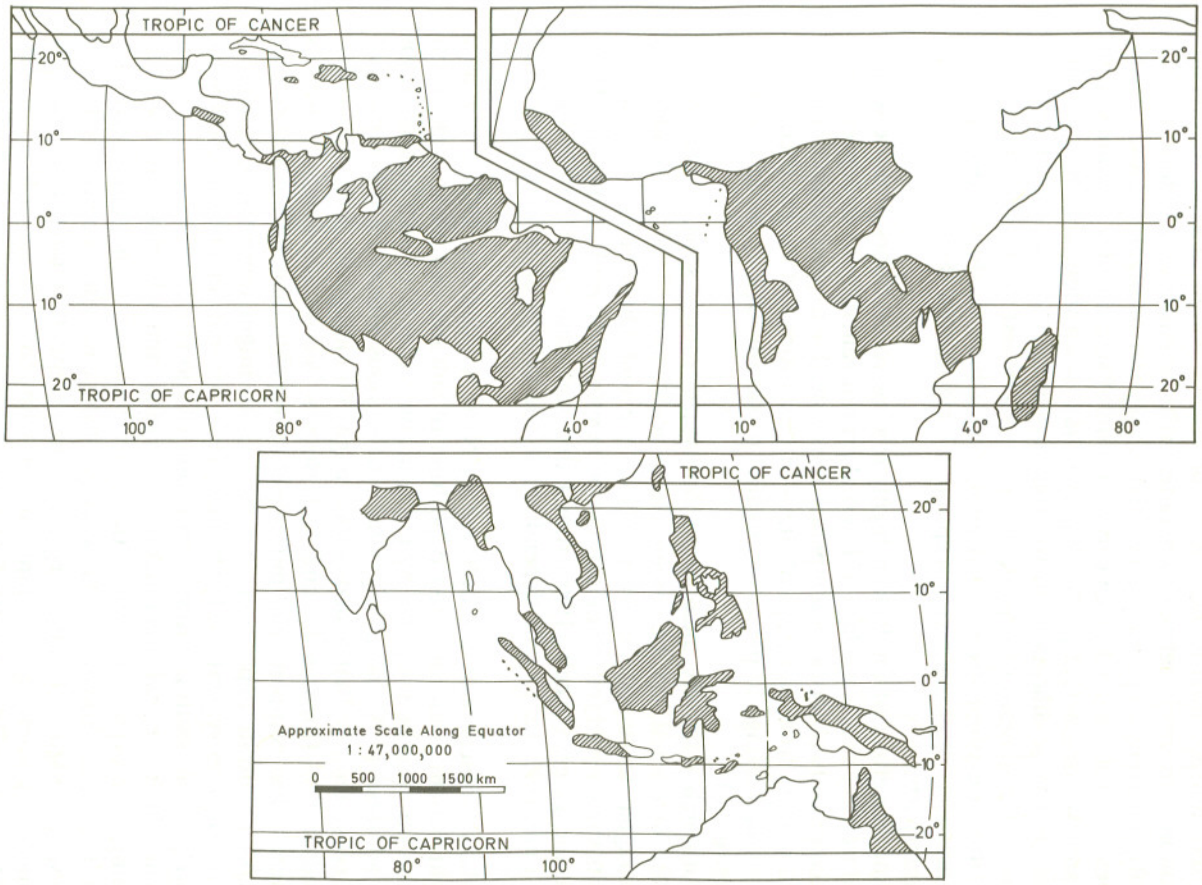

Figure 4.6 Generalized map of tropical soils with potentially high sulfate adsorption capacity (Ultisols, Oxisols, and montane soils in regions of high rainfall). Actual sulfate adsorption capacity will vary with concentrations of organic matter and sesquioxides. Modified and redrawn from Sanchez (1976)

A significant difference between temperate and tropical soils relative to acidification potential is the amount of organic matter in each. Sulfate adsorption is inversely related to organic matter content (e.g. Johnson *et al*., 1980), apparently due to preferential adsorption of organic matter at the expense of sulfate. At a given concentration of sesquioxides (predominantly Fe and Al), one would predict higher sulfate adsorption, and thus less susceptibility to acidification, in the soil with lower organic matter content. Since accumulations of organic matter on the forest floor and in upper soil horizons are often lower in tropical forests than in the temperate zone, tropical soils might be less susceptible to acidification than their temperate counterparts.

Another effect of the lack of highly organic forest floors in more weathered tropical soils is the lack of internal proton generation and depression in pH commonly observed in temperate zone soils due to production of organic acidity. Data from two tropical sites—in Costa Rica and Puerto Rico—show no marked change in pH as throughfall passes through upper soil horizons (Figure 4.2).

Although relatively uncommon, immature tropical soils, which are not highly weathered, can be susceptible to acidification. Typic Durandepts in Nicaragua developed on recent (Holocene and Quaternary) ash fall deposits show very rapid acidification upon exposure to acidic deposition from volcanic gases. Parnell (1986) found that soil solution pH could vary by 1.5 units (pH 4.5 to 6.0) depending on the acidity of incident precipitation.

Many tropical soils are deficient in N or S (Sanchez, 1976), and thus might benefit from increased deposition of sulfuric and nitric acids. Such optimism must be tempered by the realization that large acid influxes from the addition of N and S might have deleterious effects on other parts of the ecosystem, or that added sulfate might be biologically unavailable due to adsorption (Figures 4.4 and 4.6). Because nitrate adsorption in soils is generally less complete and more easily reversible than sulfate adsorption, uptake of nitrate deposition on tropical soils might represent a significant source of N to vegetation. High sesquioxide contents in some tropical soils, however, can result in nitrate adsorption (Kinjo *et al*., 1971).

The effects of acid precipitation on organic anion leaching in soils containing little organic matter in the upper horizons, such as many tropical forest soils, are unknown; the work published to date examines only acid forest soils with high initial organic matter content. Acidification generally reduces the leaching of organic anions from soil (Chang and Alexander, 1984; Krug and Isaacson, 1984; Hay *et al*., 1985). Decreased leaching of organic carbon from soil might affect metal speciation, with subsequent effects on mobility and toxicity. Unbound metal species are generally more soluble at low pH, and their effects on the biota are more deleterious. Binding with organic or inorganic ligands increases mobility (decreases chemical activity) and generally decreases toxicity as well.

4.4.4 Microbial Processes

Acidic deposition affects microbial processes in soils, but the insufficient number of published studies precludes broad generalization. Several steps in the nitrogen cycle are affected by pH, although the results of laboratory experiments are often contradictory. Nyborg and Hoyt (1978), and Like and Klein (1985) reported that nitrogen mineralization increased under more acid conditions; others have found that pH had no effect (Novick *et al.*, 1984) or decreased rates (Stroo and Alexander, 1986) of N mineralization in forest soil samples. Nitrification in three forest soils from Vermont, USA, was unaffected by simulated acid rain, but inhibited in forest soils from New York (Novick *et al.*, 1984). Rates of denitrification generally decrease at low pH (Figure 4.7). The extent to which N cycling in tropical soils would be affected by increased atmospheric deposition of nitric acid and sulfuric acid is unclear. The results of Stroo and Alexander (1986), however, suggest that inhibition of N mineralization may be more pronounced in tropical forest soils, which often contain lower soil organic matter content than those of temperate regions.

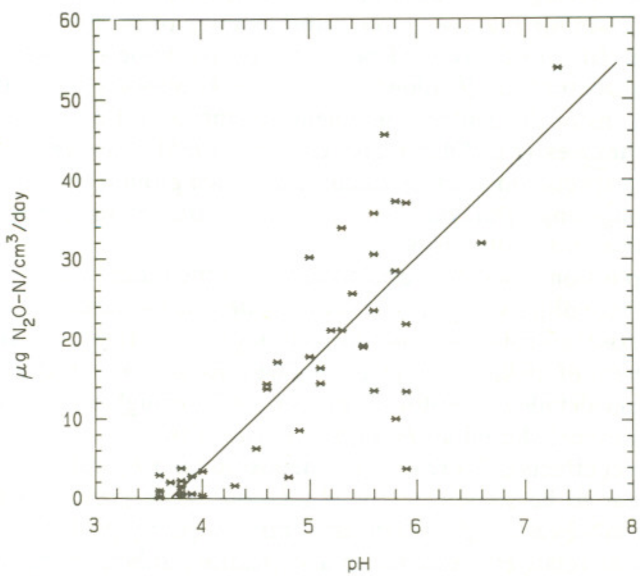

Figure 4.7 Correlation between denitrification rates and soil pH from some Spodosols and peats. From Muller *et al.* (1980). Copyright 1980 by American Society for Microbiology. Reprinted with permission

Of particular concern in the tropics is the often delicate balance between nutrient immobilization and mineralization. In relatively nutrient-poor systems, such as the Amazonian rainforest (Salati and Vose, 1984), tight recycling of nutrients from decomposing leaf litter into the root mat, and hence into the vegetation, is thought to be critical to maintenance of primary productivity. The effects of acid deposition on nitrogen cycling would therefore be important in nutrient-poor tropical environments. In addition, mycorrhiza, also important in nutrient cycling in tropical forests, are disrupted by acidification (Stroo and Alexander, 1985).

4.5 SUMMARY

Anthropogenic emissions of acidic precursor substances are likely to rise with economic development in the tropics. The rapidity with which the emissions are oxidized to acids, the effectiveness with which they are deposited, and several of their deleterious effects on terrestrial ecosystems are all likely to increase as one moves from the temperate zone to the tropics. Early warning of acidification is urgently needed for currently unspoiled areas in the tropics.

Monitoring of fog and cloud chemistry holds promise as an early warning tool in monitoring acidic deposition. The increased concentrations of most ionic species in fog relative to rain removes some of the analytical uncertainties associated with analysis of rainwater of low ionic strength. Monitoring sulfate concentrations (Galloway *et al.*, 1984) appears to be the most effective means of determining incipient acidification. Careful application of tracer techniques (e.g. Olmez and Gordon, 1985), however, seems crucial in data interpretation because establishing 'background' levels requires ruling out long-range transport as a possible source of nitrate and sulfate in precipitation in remote areas.

Dry deposition deserves special attention in the humid tropics, where environmental conditions appear to maximize deposition rates. New approaches to dry deposition collection and measurement are needed for tropical sites. Development of artificial collector surfaces, measurement of deposition velocities, and detailed monitoring of rain and throughfall chemistry within individual events should all be pursued vigorously.

The direct effects of increased acid deposition in tropical terrestrial ecosystems appear to be significant for vegetation, some groups of animals and microbial processes. High sulfate adsorption capacity probably makes many tropical soils relatively resistant to acidification, although rapid soil acidification has already been demonstrated at one tropical site. Emphasis on soil microbiology and soil water chemistry seems essential to understanding the potential effects of acidic deposition on nutrient-poor tropical ecosystems.

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