Acidification in Tropical Countries
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CHAPTER 1

Acidification and Regional Air Pollution in the Tropics

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1.1 INTRODUCTION

In the late 1960s Scandinavian scientists noticed a systematic increase in the acidity of precipitation and surface waters and suggested that these changes were related to each other and to an observed decline in fish populations in many lakes (Odén, 1968; Swedish Ministry of Agriculture, 1971).

Soon, similar changes were observed in Canada (Beamish and Harvey, 1972) and the United States (Likens *et al*., 1972). It is now clear that emissions of sulfur and nitrogen compounds into the atmosphere over industrialized regions in Europe and North America have profoundly affected the chemical climate within and around these regions throughout much of the 20th century (Swedish Ministry of Agriculture, 1982; NRC, 1986). The present fluxes of sulfur (SO_2, SO_4^{2-}) and nitrogen (NO_x, NO_3^-, NH_3, NH_4^+) to and from the atmosphere in these regions are 10 or more times larger than the estimated natural fluxes (Rodhe, 1976; Bonis *et al.*, 1980; Galloway *et al.*, 1984; Logan, 1983).

These large-scale perturbations of the S and N cycles have resulted in some beneficial and some very significant adverse effects on people and their environment. The beneficial effects include increased supplies of airborne sulfur- and nitrogen-containing nutrient substances and increased weathering of soil minerals. The detrimental effects include widespread acidification of surface- and groundwaters with associated biological consequences, acidification of soils in some regions, an increased rate of corrosion of building materials and monuments, and formation of secondary pollutants, such as ozone, that are toxic to humans and plants.

In light of these significant changes in industrialized regions it is of great interest to examine air pollution and acidification in tropical regions and in particular to address questions such as:

- What are the magnitudes of the fluxes of sulfur and nitrogen to and from the atmosphere in other, less polluted, parts of the world such as the tropics?
- To what extent are today's cycles of sulfur, nitrogen, and atmospheric acidity affected by human activities (industry, agriculture, etc.) in less industrialized parts of the world?
- What is the acidity of precipitation in areas not directly influenced by industrial emissions?
- Do air pollutants from industrialized regions in the midlatitudes of the Northern Hemisphere spread in significant amounts to other latitudes?
- How susceptible are vegetation, soils, and surface waters in different parts of the world to possible future increases in deposition of acidic and acidifying substances?
- What parts of the world contain both susceptible ecosystems and a substantial likelihood of rapid industrialization in the future?

The first of the above six questions was recently addressed in some detail by Galloway *et al.* (1985). That publication, as well as other reviews of the sulfur and nitrogen cycles (e.g. Ivanov and Freney, 1983; Logan, 1983; Robertson and Rosswall, 1986), served as useful starting points for the investigations presented in this book. These reviews, however, clearly show the severe limitations of the data base for preparing quantitative estimates of the regional biogeochemical cycles of S and N, especially for terrestrial ecosystems in tropical and subtropical regions. The fact that a large part of the global human population lives in these regions adds to the importance of studying environmental conditions there.

To the extent that acidification and related changes in the chemical climate are already serious or can be expected to become serious in the near future, additional scientific and public policy questions also become important:

- What is the scientific basis for avoiding or remedying present or future air quality and acidification problems in tropical countries?
- What should be done to increase our knowledge about the biogeochemical cycles of sulfur and nitrogen in the tropics, including the effects caused by human-induced perturbations of these cycles?
- What kind of research and training programs would be helpful in acquiring such increased knowledge?

The main purpose of the SCOPE Project 'Acidification in Tropical Countries' has been to study all the above questions and to report findings to the scientific community, leaders of industry and government, and environmental groups.

During the initial phase of the project, case studies were prepared in several tropical countries to find out what data existed for answering these questions. The case study countries were selected to represent a range of geographical regions and climates. A further prerequisite was the existence of national research groups engaged in studies of the biogeochemical cycling of nutrient elements in the case study regions. Participants at a workshop outside Caracas, Venezuela, in April 1986 presented and discussed draft versions of the case study reports and background papers dealing with scientific aspects of the acidification problem based on work done in North America and Europe.

This chapter summarizes key aspects of the material presented in more detail in the other chapters, and draws some general conclusions.

1.2 DEFINITIONS

We begin by stating some basic definitions and assumptions. The word 'acidification' literally implies a change toward more acidic conditions, e.g. in rain and cloud water, lakes, rivers, groundwater or soils. Such changes may occur as a result of processes taking place slowly by biological and geological processes; more rapidly in connection with short-term climatic fluctuations or volcanic eruptions; or by human activity, such as emission of acid-forming gases into the atmosphere. We emphasize changes due to human activity. As a consequence, the naturally occurring acidic environments in many tropical countries (soils) are not referred to as acidified but simply as acidic.

In a more general sense, we take the word 'acidification' to include all perturbations by human activities of the natural biogeochemical cycles of sulfur (mainly SO_2 and SO_4^{2-}) and nitrogen (mainly NO_x, NH_3, NH_4^+ and NO_3^-) and other acid and alkaline substances (see Table 1.1) as well as the environmental effects of such perturbations. This means that we concern ourselves not only with sulfur- and nitrogen-induced changes in the acidity of air, cloud water, and precipitation and the effects of these changes on surface waters, plants, animals, and engineering materials, but also with secondary effects such as ozone formation caused by emission of nitrogen oxides and volatile hydrocarbons.

Table 1.1 Acid and alkaline substances observed in the atmosphere and their effect on terrestrial and aquatic systems (+ acidifying, – neutralizing, 0 no significant effect)

Substance	Role in acidification	
	Terrestrial	Aquatic
H_2S, SO_2, H_2SO_4	+	+
NO_x, HNO_3	+,0	+,0
HCl, HF	+	+
Organic acids	+,0	+,0
NH_3	+,0,–	0,–
Ammonium salts	+	+
Alkaline dust	–	–

Systems are considered to be sensitive to acidification if they have a low buffer capacity with respect to input of acid and acidifying substances. For aquatic systems, this means that waters with low alkalinity are sensitive to acidification. Sensitive soils are those with low to moderate base saturation and low cation exchange capacity (CEC). Soils with a high anion adsorption capacity, as well as surface waters associated with such soils, can be sensitive to acidification but may not be immediately susceptible due to the retention of anions (e.g. sulfate) in the soil (Galloway, 1988; McDowell, 1988).

We use the words ‘tropics’ and ‘tropical’ in a broad sense, roughly including the latitude belt between 30° S and 30° N. This region includes all tropical rainforests (climate Af according to Köppen’s classification, Köppen and Geiger, 1930), all savannas (Aw, As), most of the arid zones (BS and BW) and parts of warm–temperate, humid climate zones (Cw, Cf), mainly in China.

1.3 ORIGIN OF THE PROBLEM

Human activities are changing the chemical climate of both developed and developing nations throughout the world. Some of these changes are beneficial for agriculture and forestry because they provide nutrients for the growth of crops and forests or accelerate the natural weathering of soil minerals. Other substances (or the same substances at higher concentrations) are detrimental because they cause stress in plants, animals, or microorganisms; alter surface- and ground-water quality; aggravate nutrient deficiencies in soils; or accelerate the discoloration, weathering, or corrosion of engineering and cultural materials.

Most things human beings do on a large scale influence the chemistry of the atmosphere and in turn the health and productivity of the ecosystems on which the abundance and the quality of human life depends (Cowling, 1985). The largest of all human influences on the chemical climate result from combustion of fossil fuels, urban development, clearing of land by burning natural vegetation, and disposal of excreta from both humans and domestic animals. Human activities influencing the chemical climate include:

- generation of electricity;
- smelting and refinement of metals;
- production and use of concrete, glass, ceramic, and plastics materials;
- refinement and use of petroleum and petrochemicals;
- use of transportation vehicles;
- space and water heating;
- decomposition and incineration of sanitary and solid wastes;
- production and application of fertilizers, pesticides, and other agricultural and silvicultural chemicals;
- disposal of excreta from humans and domestic animals;
- burning of biomass, and farm and forest residues; and
- use of explosive devices in peace and war.

Pollution of air and water by all of these activities is a conspicuous feature of urban and industrial societies throughout the world's temperate and tropical regions. The airborne pollutants of major concern in these regions include toxic gases such as sulfur dioxide, oxides of nitrogen, volatile organic compounds, and carbon monoxide; toxic elements such as lead and fluoride; particulate matter; ozone and other photochemical oxidants; and acid deposition. The first six of these eight types of airborne substances are primary pollutants released directly from stationary and mobile sources; the last two are secondary pollutants formed in the atmosphere by chemical transformation of primary pollutants. Ammonia and alkaline dust are other primary pollutants that have an ameliorating effect on the acidity produced by other pollutants.

These airborne substances and their reaction products are carried by winds and clouds wherever the wind blows. They are then deposited in the form of gases, fine aerosols, and coarse particles, or as dissolved or suspended substances in precipitation. Such deposition processes deliver the airborne chemicals to the surfaces of vegetation, soils, surface waters, and engineering and cultural resources at short or long distances from the original emission sources.

Research in the industrial regions of the world has taught us a great deal about the role of air pollutants in acidification processes. The influence of airborne chemicals in the acidification of air and precipitation is most pronounced in regions where gaseous sulfur and nitrogen oxide emissions are large, and where the air contains only modest amounts of acid-neutralizing substances such as ammonia or alkaline dust containing ammonium, calcium, sodium, magnesium, and potassium. The role of airborne acidic and acidifying substances in the acidification of aquatic and terrestrial ecosystems is most pronounced in regions where soils are naturally acidic and also have very low cation exchange capacity and low sulfate absorption capacity. This usually occurs in areas where the bedrock contains only small amounts of limestone and other acid-neutralizing minerals.

The direct and indirect effects of sulfur and nitrogen oxide pollution has been summarized in Figure 1.1 and in the following paragraphs which are adapted from the publication *Acidification Today and Tomorrow* (Swedish Ministry of Agriculture, 1982). Sulfur dioxide and nitrogen oxides exert both direct and indirect influences on organisms and materials. Foremost among the direct effects are health effects, plant damage, and corrosion due to high sulfur dioxide contents. Direct effects are determined by the concentration of pollutants in the air, and in general they decline rapidly with increasing distances from emission sources. It follows that the direct effects are mainly of a local nature, with a geographical extent of a few tens of kilometers.

Sulfur dioxide and nitrogen oxides are oxidized in the atmosphere to sulfuric and nitric acid. At deposition, these acids cause the following indirect effects:

Examples:

(1) Organisms in water are affected when the hydrogen ion content increases and when toxic metals, leached out of the ground, begin to circulate.

(2) Plants are affected when the chemistry and biology of the soil have been altered by hydrogen and aluminum ions.

(3) Man is affected by (a) drinking water from both surface- and groundwater resources and (b) by eating fish and other aquatic organisms that come to have high metal contents through increased metal solubility due to the influence of hydrogen ions.

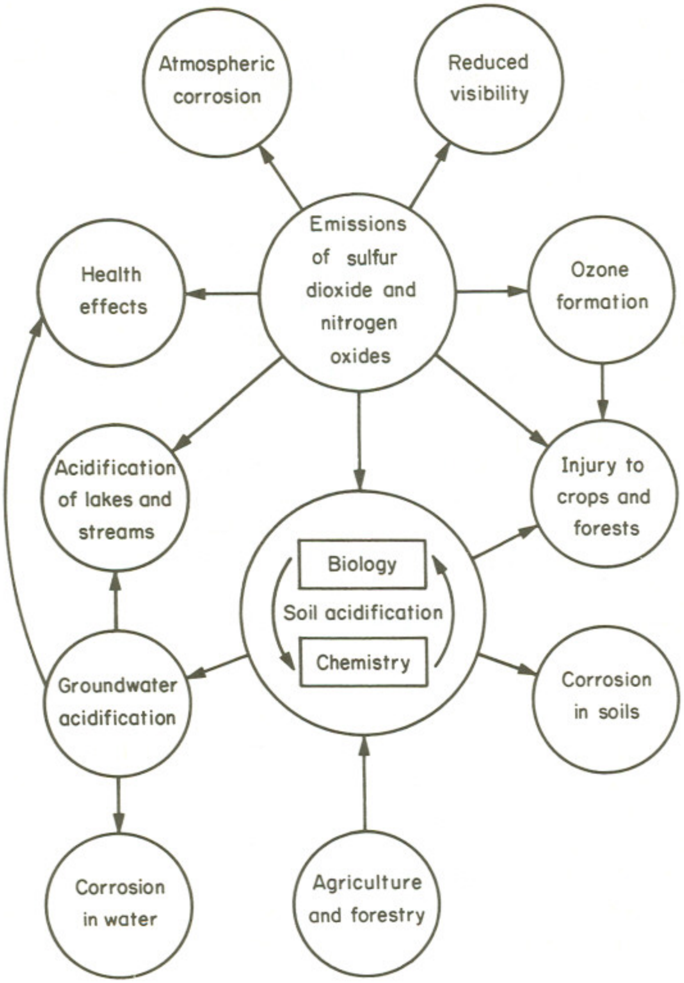

Figure 1.1 Direct and indirect effects of sulfur- and nitrogen-oxide emissions

Although the regional emission density of sulfur and nitrogen oxides in many tropical countries is still far less than those of many temperate-zone industrial countries, some regions of the tropics are catching up quickly. Certain tropical regions are likely to experience severe air pollution and related acidification problems if current trends in urbanization, industrialization, and increased use of fossil or biomass energy sources continue beyond the 20th century (McCormick, 1985).

It may be instructive to summarize here some of the major differences between tropical and temperate latitudes with regard to acidification processes. In doing so we emphasize that experiences gained from studies of acidification problems in Europe and North America should not be applied uncritically to tropical regions. The following list includes important characteristics of tropical regions.

- Daytime temperature and sunlight intensity are generally high all year long. The intensive sunlight makes many photochemical processes in the atmosphere efficient. Important consequences are a high concentration of the hydroxyl radicals (Crutzen and Gidel, 1983), and strong vertical mixing of air in the lowest layers of the atmosphere. This implies that the air close to the surface is regularly transported to a height of 1–4 km and replaced by air originating from such altitudes.
- In large parts of the tropics average rainfall rates are high, at least seasonally. In these regions, wet deposition is likely to be the major deposition mechanism for sulfur and nitrogen compounds. In regions where precipitation rates are very small and during the dry season, wet deposition processes are not important. Studies of atmospheric chemistry need to include both dry and wet season observations in order to provide a complete picture.
- Winds are relatively steady with little change in direction over extended periods of time, e.g. in the tradewind zones. Areas downwind of a continuously emitting source of air pollution can therefore experience very high average concentrations and deposition over long periods of time.
- Widespread bushfires and grass fires, many of them initiated by man, represent an important source of trace gases (e.g. CO, NO_x, hydrocarbons and SO_2) in the atmosphere.
- Soils in large parts of the tropics, for instance in South America, are naturally acidic, low in cation exchange capacity and high in concentration of aluminum.

The potential for continuously increasing sulfur and nitrogen oxide emissions and for undesirable ecological changes as a result of air pollution in many tropical countries is the principal stimulus for the research that led to this publication.

1.4 ATMOSPHERIC PROCESSES

1.4.1 Sources of Acid Gases and their Precursors

Estimates of tropical emissions of sulfur and oxidized nitrogen are given in Tables 1.2 and 1.3. The numbers are derived mainly from Galloway *et* *al.* (1985), Ryaboshapko (1983) and the chapters of this book. Some recent measurements of NO emissions from tropical soils (Johansson *et al*., 1988; Kaplan *et al*., 1988) are also taken into account.

On a global scale, anthropogenic and natural emissions of sulfur and nitrogen compounds are similar in magnitude. Since most sources of anthropogenic emissions are not distributed uniformly and the atmospheric residence times of most sulfur and nitrogen compounds are limited to a few days, the relative importance of anthropogenic and natural sources varies widely over the globe. In the industrialized parts of the temperate zones, especially in Europe, North America and Japan, anthropogenic emissions dominate over natural emissions.

As Delmas and Servant (1988) discuss, the most significant contributions to the sulfur flux over tropical land areas come from natural emissions from soils and plants (mainly as H_2S), emission of SO_2 from burning of biomass, and emission of SO_2 from combustion of fossil fuels. In some regions volcanoes are a major episodic source. Although industrial sulfur emissions in the tropics are smaller than those in northern temperate latitudes, it is clear that human activities, in the form of industrial processes as well as biomass burning, already represent a major proportion of all sulfur emissions in tropical land areas (Table 1.2).

In a few highly industrialized regions of the tropics such as parts of southeastern Brazil (Moreira-Nordemann *et al*., 1988) sulfur emission density may be comparable to those of industrial regions of North America and Europe.

Table 1.2 Estimated sulfur budget of the atmosphere of terrestrial tropics (between 30° N and 30° S). Unit: Tg S per year (1 Tg = 10^{12} g)

Emissions	
Forest soils and wetlands (mainly H_2S)	5–25
Biomass burning (mainly SO_2)	1–10
Volcanoes (mainly SO_2)	1–10
Soil dust (sulfate)	?
Fossil fuels and industry (mainly SO_2)	6–15
Total	13–60(+)
Deposition	
By precipitation (sulfate)	5–20
Dry deposition (SO_2, sulfate)	2–10
Total	7–30

Table 1.3 Estimated budget of oxidized nitrogen for the atmosphere of terrestrial tropics (between 30° N and 30° S). Unit: Tg N per year

Emissions		
Soils		
Rainforest	2–5	
Savanna	3–8	
Cultivated land	1–6	6–19
Biomass burning		
Plumes	3–6	
Excess soil emissions	0.5–3	3–9
Lightning		0.5–5
Fossil fuel combustion		3–7
Total		13–40
Deposition		
By precipitation		2–10
Dry deposition		
NO_2	<2	
HNO_3	<2?	
Other nitrogen compounds	?	1–5 (+)
Total		3–15(+)

Figure 1.2 shows anthropogenic emissions of SO_2 and NO_x from fossil fuel combustion on the major continents of the world. The large emissions in Europe and North America stand out clearly, and very significant emissions also occur on the Asian continent. More detailed geographical distributions can be inferred from the map of global CO_2 emissions from fossil fuel combustion shown in Figure 1.3 (Marland *et al.*, 1985). Although the detailed distributions of SO_2 and NO_x emissions are likely to differ from that of CO_2, the general patterns are expected to be similar. In Asia, for example, most emissions occur in China. Comparing this emission pattern with the global population density, it is clear that a different pattern would result, with much higher emissions in South Asia and West Africa if, in the future, emissions were to become more proportional to population density.

The largest emissions of oxidized nitrogen compounds occur through soil emissions and biomass burning. Combustion of fossil fuels in transportation vehicles and industrial processes also contribute.

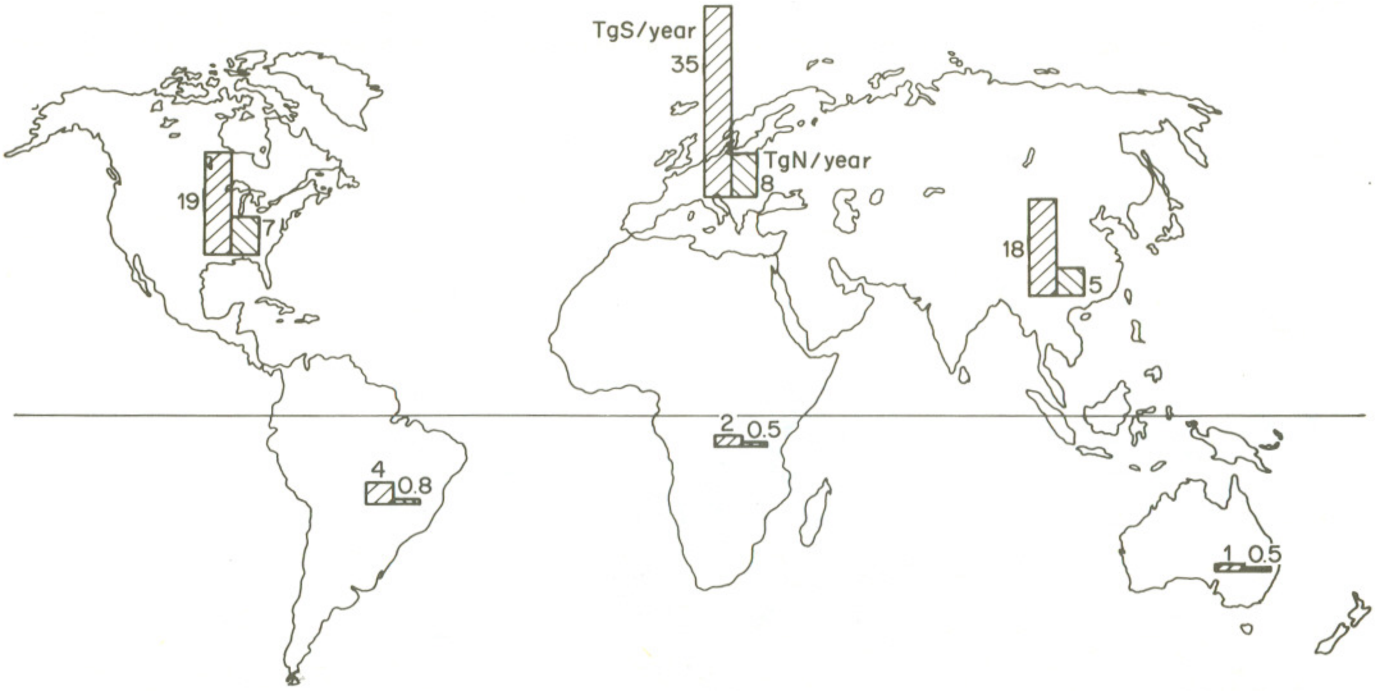

Figure 1.2 Anthropogenic emissions of sulfur dioxide and nitrogen oxides into the atmosphere by continents around 1979. Units: Tg S and Tg N per year. Data from Varhelyi (1985) and Hameed and Dignon (1988)

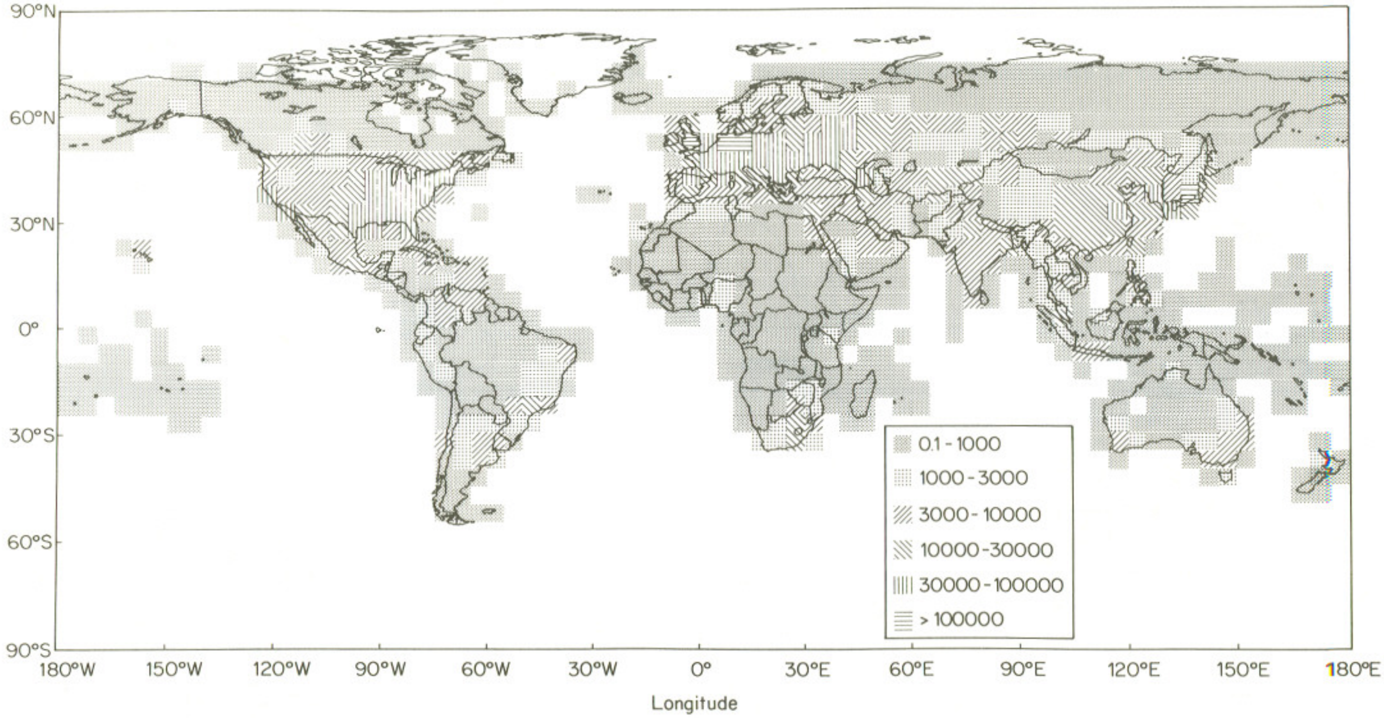

Figure 1.3 CO$_2$ emissions from fossil fuel combustion in 1980 (10^3 metric tonnes of carbon (Marland *et al.*, 1985)). Copyright © *Tellus*. Reprinted with permission.

The magnitudes of sulfur and nitrogen oxide emissions are only moderately well known, thus a need exists for basic information on the area and amounts of biomass burned per year in each tropical country, and for quantitative estimates of natural emissions of sulfur and nitrogen gases in the tropics. These include emissions from soils, plants, lightning, continental wetlands, coastal marshes, and volcanoes (Galbally, 1985; Andreae, 1985).

Organic acids, primarily formic (HCOOH) and acetic (CH_3COOH), have been shown to contribute substantially to the acidity of tropical rain (Keene *et al*., 1983), but little is known about the mechanisms that introduce or produce them within the atmosphere. In a modeling study, Brewer *et al*. (1984) identified some of these organic acids as products of oxidation of non-methane hydrocarbons. It is possible, however, that these acids also arise as partially oxidized products of biomass burning. Biomass burning and volatile emissions of organic compounds from vegetation are likely to be the main sources of non-methane hydrocarbons (Penkett, 1982; Duce *et al*., 1983; Greenberg and Zimmerman, 1984).

Sources of alkaline material in the tropical atmosphere include the emission of NH_3 from volatilization of excreta and fertilizers and from biomass burning. Alkaline dusts arise from soil erosion and from agricultural and mining operations. The magnitude of these emissions is poorly known, although some estimates of the NH_3 source are available (Galbally and Gillett, 1988).

1.4.2 Atmospheric Transformation and Transport Processes

Two questions are of special importance regarding the transformation of sulfur and nitrogen compounds in the atmosphere: what are the chemical processes that lead to the oxidation of sulfur, nitrogen gases and hydrocarbon compounds in the tropics, and how do these processes interact; i.e. do they tend to stimulate or negate each other? In a study of emissions of SO_2 in tropical Australia, Galbally *et al*. (1982) suggested that the cycling of NH_3 through the atmosphere was enhanced due to the formation of ammonium sulfate aerosol after the oxidation of SO_2 to sulfate in the atmosphere.

In temperate latitudes the transformations of NO_2, SO_2 and non-methane hydrocarbons have been studied in laboratories and by numerical modeling and field observations. The role of hydroxyl radicals in homogeneous gas-phase oxidation is well established; liquid-phase reactions in cloud droplets and heterogeneous aerosol reactions involving ozone, hydrogen peroxide, oxygen, and metallic catalyst reactions have begun to be investigated (Davis *et al*., 1984).

A body of observational and experimental data about these compounds has accumulated from field studies in temperate regions and is used for testing the processes incorporated into modeling studies.

In the tropics, however, there have been no studies of the rate of oxidation of hydrocarbons or nitrogen oxides, and only one study of the rate of homogeneous oxidation of sulfur dioxide to sulfuric acid in the Mt. Isa copper smelter plume in Northern Australia (Roberts and Williams, 1979). This study showed far slower oxidation rates than expected from modeling studies (based on understanding from temperate latitude studies) but the reasons for the difference remain unknown.

Studies of liquid-phase and heterogeneous atmospheric chemical processes in the tropics are also lacking. Due to the intense solar radiation in tropical areas, the higher air and cloud-water temperatures, the different patterns of precipitation (i.e. long dry spells, rainy seasons with persistent daily rain) and different patterns of pollutant emissions (e.g. simultaneous NO_x, HC, SO_2 and CO emissions in biomass burning), the relative importance of many processes may be different in the tropics compared with temperate regions.

Some measurements of the inorganic composition of aerosols exist for the tropical atmosphere, e.g. sulfate, nitrate, ammonium and calcium (Huebert and Lazrus, 1980; Savoie, 1984; Ayers and Gillett, 1988). These data can be used to interpret rainwater composition measurements and to estimate atmospheric rates of scavenging by precipitation, but few measurements of the gas-phase precursors of these inorganic species exist for the tropics. While measurements of non-methane hydrocarbon precursors of organic acids exist (Greenberg *et al.*, 1984; Penkett, 1982; Ayers and Gillett, 1988), little is known about the concentrations of aldehydes (Ferrer, 1987) which, no doubt, are closely coupled with the formation of organic acids. The absence of such information seriously limits our ability to test hypotheses concerning the acidity of precipitation in the tropics (Jacob, 1986).

Another difficulty is that we do not know the identity of all major oxidized forms of nitrogen in the atmosphere. Peroxyacetyl nitrate (PAN) has been identified as a long-lived organic nitrate in the remote atmosphere, and there is evidence of other nitrogen oxides (Fahey *et al.*, 1986). These compounds may form important atmospheric reservoirs of nitrogen oxides, and if they are even weakly soluble in water, their presence will promote long-range transport of acidic nitrogen oxides.

While the basic characteristics of tropical meteorology are well known (e.g. Riehl, 1954), no regional model of atmospheric chemistry has been run using meteorology appropriate to the tropics. Hence, we do not know how the interaction of chemistry and meteorology is likely to affect the composition of the tropical atmosphere. Within closed canopy tropical forests, the diurnal cycle of boundary layer instability/stability observed in temperate regions can be reversed. In the free atmosphere under clear sky conditions, convective mixing can occur within 3 to 4 km depth during the daytime in contrast with the 1 to 2 km depth in temperate latitudes, and strong nocturnal inversions often form. On a much larger scale, persistent steady winds (the trades) occur during long dry spells or during wet seasons with nearly continuous intense rain. Given the steadiness of such a wind system, very concentrated air pollution effects may occur downwind of pollution sources.

Another special feature of tropical meteorology is the formation of deep convective clouds. A fraction of sulfur and nitrogen compounds emitted to or formed within the lowest layer of the atmosphere is carried to higher altitudes by vertical air currents associated with convective clouds. Here, many sulfur and nitrogen compounds may have substantially longer residence times and be transported over longer distances than those closer to the surface (Chatfield and Crutzen, 1984).

1.4.3 Acid Deposition

The primary purpose of this study is to examine the impact of the deposition of acidifying substances on vegetation, soils and aquatic systems in the tropics. The sensitivity or susceptibility of tropical systems to acidifying deposition varies enormously due to differences in vegetation, soil composition, topography, hydrology, etc., and the location of sensitive areas is poorly known. For these studies, measurements of acidifying deposition in sensitive regions must be made. Since this is lacking in most cases, existing sparse knowledge about acidifying deposition in the tropics is reviewed. A list of acidifying substances is presented in Table 1.1.

Two processes cause acidic deposition. Acidic gases and aerosol particles can be incorporated into rainwater or cloudwater and deposited by precipitation or impaction (e.g. in cloud forests). Alternatively, acidic gases and aerosol can be carried by turbulent mixing and molecular diffusion, or gravitational settling and inertial impaction, respectively, to the surface where they deposit and remain on vegetation, soil and exposed water surfaces. In the tropics not much is known about the latter process, called dry deposition, but more is known about the former, called wet deposition.

The concentrations of sulfate, nitrate, ammonium, calcium, and hydrogen ions (pH in rain) have been measured occasionally at many tropical locations during the past century (Eriksson, 1952; Granat *et al*., 1976). Some of these data are unacceptable today because the methods used in collecting, preserving and analyzing the samples in some cases do not conform to current standards for field collection and laboratory analysis practices. Keene *et al*. (1983) made the first measurements of organic acids in tropical rainwater. Figures 1.4 and 1.5, taken from Galloway (1985), illustrate the relative magnitude of these deposition processes for sulfur and nitrogen. Considerable geographical variation in these deposition fluxes is expected due to differences in source strength, prevailing wind patterns and rainfall amounts. Dry deposition of HNO_3 over the continents might be higher than indicated in Figure 1.5. Virtually no measurements of this flux have been made. A higher flux could make up for some of the apparent inbalance in Table 1.3. Because of the very low ionic strength of most rainwater in remote areas, stringent precautions must be taken to avoid contamination in order to obtain representative pH values. Consequently, there are very few reliable measurements of rainwater pH in the tropics. A selection of available data is presented in Table 1.4.

Recent observations show large variations in the acidity of rainwater from region to region in the tropics. Over continental Australia and South America rainwater with pH values in the range 4.3 to 4.8 has been observed (Galloway *et al.*, 1982; Ayers and Gillett, 1988; Sanhueza *et al.*, 1988). Over India the pH values are most often above 6.0 (Khemani *et al.*, 1987). Similar high values are found at some stations in China (Zhao and Sun, 1986; Zhao and Xiong, 1988). Cloud water over Northern Australia has been observed to have pH values as low as 3.8 (Ayers and Gillett, 1988).

The acidity in tropical rainwater can be partially or completely neutralized by ammonia and alkaline soil dusts if they are entrained in raindrops. Particularly over the Asian continent, calcareous material, probably from central Asian deserts, appears to play a major role in determining the pH

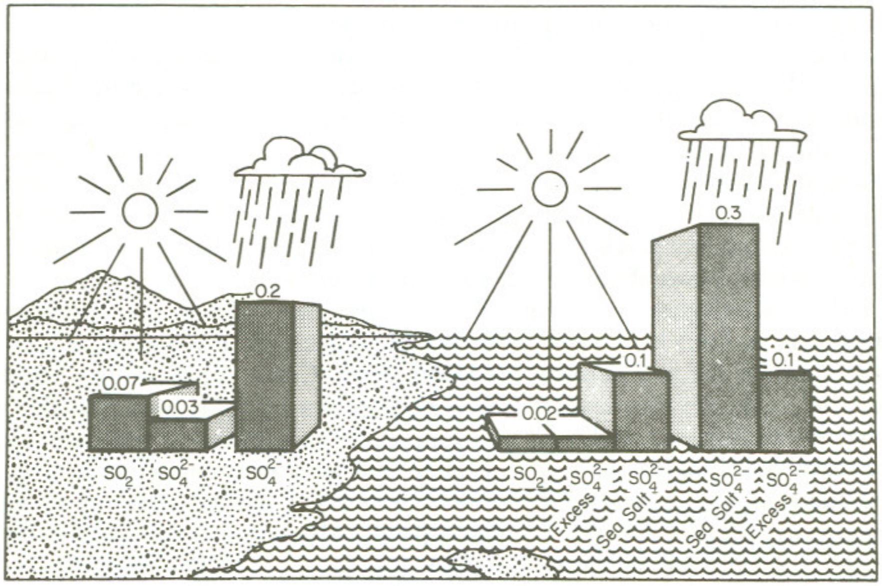

Figure 1.4 Wet and dry deposition rates of sulfur species in remote regions (Galloway, 1985)

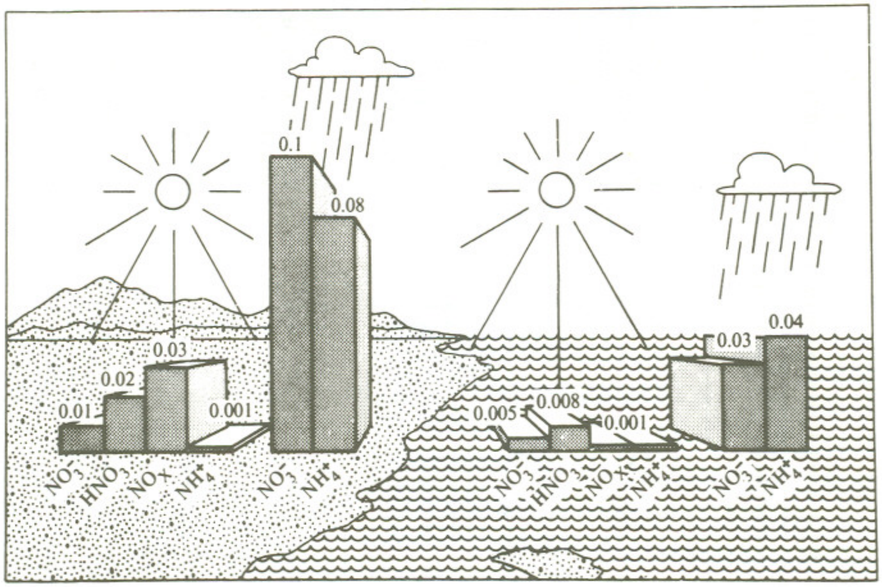

Figure 1.5 Wet and dry deposition rates of nitrogen species in remote regions (Galloway, 1985)

of rainwater (Khemani *et al*., 1987). In other regions, such as the Chinese mainland, large emissions of ammonia contribute substantial neutralizing capacity to the rainwater (Zhao and Sun, 1986).

Dry deposition involves the physical, chemical, or biological uptake of gases and aerosol particles from the atmosphere by soils, natural waters, and vegetation. Our limited understanding of dry deposition in the tropics is compounded in that the uptake velocities (Prospero *et al*., 1983) and atmospheric concentrations of the gases involved remain unknown. Milne *et al*. (1979) provide the only measurement of the uptake rate of gaseous sulfur and nitrogen compounds in the tropics. Dry deposition fluxes for aerosol particles, SO_2, and HNO_3 can be roughly estimated, as in Galloway *et al*. (1985), and are presented in Figures 1.4 and 1.5.

Some conceptual problems concerning concurrent emissions and dry deposition of gases such as NH_3 and NO need to be resolved (Galbally, 1985). From an ecological point of view the net flux is very important; however, we cannot yet in most cases assess the direction of the net exchange of these gases between the atmosphere and the biosphere.

Table 1.4 A selection of measured values of pH in rain and cloud water in remote continental areas in the tropics

Location	Biome	Time	Sampling range	Average	Reference
Australia					
Katherine	savanna	event	4.0–5.4	4.8	Galloway *et al*, 1982
Jabiru	woodland	event	3.9–5.4	4.4	Ayers and Gillett, 1988
W. Australia	woodland	1 month	?	5.0	Hingston and Gailitis, 1976
Groote Eylandt	woodland	event	?	4.3	Langkamp and Dalling, 1983
Venezuela					
San Carlos	rainforest	event	4.0–6.7	4.7	Haines *et al*., 1983
Camburito	savanna	event	3.0–5.5	4.4	Graterol, 1984
La Paragua	savanna	event	4.0–5.6	4.8	Sanhueza *et al*., 1988
Joaquin del Tigre	savanna	event	4.2–5.8	5.1	Sanhueza *et al*., 1988
Parupa	savanna	event	4.5–5.6	5.0	Marti, 1986
China					
Luizhang		event		4.7	Zhao and Xiong, 1988
Keyang		event		4.6	Zhao and Xiong, 1988
Shisun		event		4.7	Zhao and Xiong, 1988
Nigeria					
Warri		?	5.2–5.9		Nriagu *et al*, 1985
India					
Pune (rainwater)			7.0–8.0		Khemani *et al*., 1987
Pune (cloud water)			6.3–7.6	6.9	

Other species besides acidic pollutants are carried by the atmosphere. All sixteen elements needed by plants for normal growth and development (C, H, O, N, P, S, K, Ca, Ma, Mg, Cu, Zn, Fe, Cd, Mo, B) are dispersed in the atmosphere and can be taken up by plants either directly through foliar organs or through roots. Whenever nutrient deficiencies exist in tropical soils, atmospheric deposition of airborne nutrient substances may be expected to help relieve the deficiencies and thus increase plant growth and development. Many tropical soils are deficient in nitrogen or sulfur, or both. Increased plant growth may be expected in such areas if the deposition of these compounds is enhanced, although little is known about the geographical distribution of soils with nutrient deficiency problems.

To estimate future effects, it is necessary to obtain projections of future emission density patterns from which deposition patterns can be calculated using atmospheric models. Deposition monitoring programs should be established to determine a baseline for detecting future changes.

1.4.4 Ozone in the Tropical Atmosphere

Ozone (O_3) is a natural component of the troposphere. It is transported down from the stratosphere or formed by photochemical reactions within the troposphere, i.e. photolysis of NO_2 followed by a combination of atomic and molecular oxygen.

$$NO_2 + h\nu \longrightarrow NO + O$$
$$O + O_2 + M \longrightarrow O_3 + M$$

Because of a rapid reaction between NO and O_3

$$NO + O_3 \longrightarrow NO_2 + O_2$$

the above reactions do not lead to a net accumulation of O_3 unless NO can be converted back to NO_2 without loss of O_3. Such reactions are accomplished by chemical species (peroxy-radicals) formed during oxidation of hydrocarbons (HC) and carbon monoxide (CO). Emissions of NO_x, HC, and CO into the atmosphere are therefore conducive to the accumulation of ozone. This is particularly true in the tropics with a high intensity of sunlight. Tropical sources of O_3 precursors include motor vehicles and combustion of both biomass and fossil fuels, as well as natural processes, e.g. NO_x produced by lightning and soils and volatile HC produced by forests and other tropical vegetation (Logan, 1983). Biomass burning represents a particularly important source of NO_x, HC, and CO in tropical areas (Evans *et al*., 1977; Logan, 1983; Crutzen *et al*., 1985).

Measurements of O_3 and other trace gases in the Brazilian atmosphere by Crutzen *et al*. (1985) clearly indicate that high concentrations of O_3 in savanna regions during the dry season are caused by photochemical reactions involving emissions from biomass burning. Average O_3 concentrations were found to be substantially higher over the savanna region (Cerrado) than over the humid forest (Selvas) (Figure 1.6). Similar large-scale increases in O_3 concentration are likely to occur in other parts of the tropics where biomass burning is common, e.g. Africa. Fishman *et al*. (1986) recently published a spectacular view of a large 'ozone cloud' over Brazil during the burning season (August).

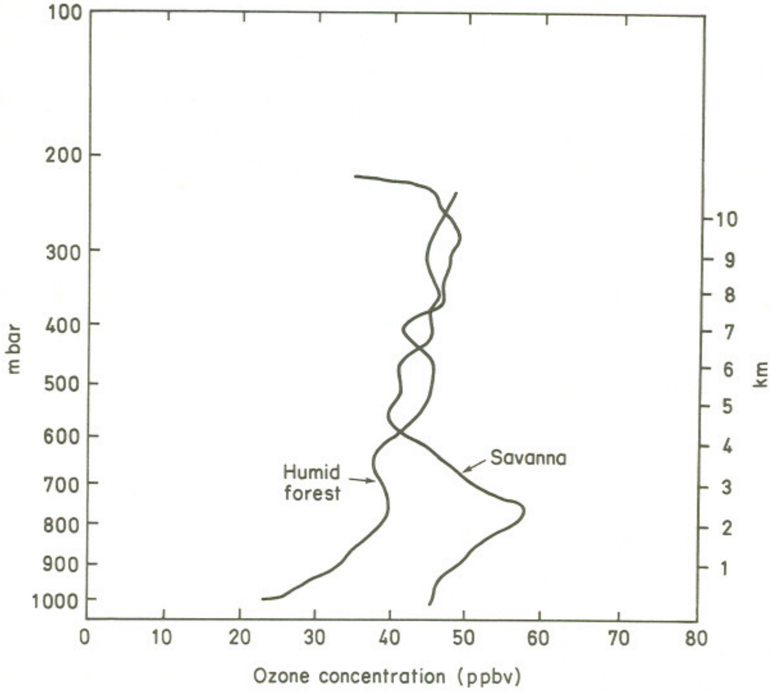

Figure 1.6 Average profiles of ozone concentrations (volume mixing ratios) over the tropical, humid forest, and savanna regions of Brazil (Crutzen *et al*., 1985). The air above the savanna regions is influenced by emission from biomass burning

Tropospheric ozone in the tropics is important from both atmospheric and biological perspectives. Ozone has a fundamental influence on the oxidation capacity of the atmosphere, since the molecule itself is a primary reactant, and also because the photolysis of ozone produces hydroxyl radicals, which in turn play a very important role in the cycling of other trace gases. Ozone absorbs radiation in the infrared, causing warming of the earth's surface by the so-called 'greenhouse effect' and ozone and other photochemical oxidants are toxic components that cause injury to humans, plants, and animals at elevated concentrations. Such injury is known to occur in many urban areas in both tropical and temperate regions, and on regional scales in North America and Europe. It is not known whether large-scale elevated ozone concentrations in the tropics are causing injury to vegetation.

Improving our knowledge about O_3 in the tropical troposphere is essential, particularly concerning possible effects of increased O_3 concentrations caused by human activities.

1.5 BIOLOGICAL AND OTHER EFFECTS OF POLLUTANTS

1.5.1 Effects on Terrestrial Ecosystems

Airborne pollutant chemicals can affect terrestrial ecosystems in two major ways: (1) by direct toxicity and (2) by changing soil nutrient availability. Present knowledge of each of these mechanisms is discussed in turn.

1.5.1.1 Direct Toxicity and Other Injurious Effects

Direct effects of S- and N-containing air pollutants on tropical vegetation can only be inferred from what is known about tropical crops cultivated in polluted areas. Specific studies on natural vegetation types in the tropics are lacking. Foliar injury to tropical crops in the field has been documented in only one case (Evans *et al.*, 1977). Laboratory studies have shown increased leaching of both anions and cations from the canopy with artificial rain (see McDowell, 1988 and references therein). In highly industrialized areas in Brazil Moreira-Nordemann *et al.* (1988) observed damage to surrounding vegetation, but the direct effects of acidification in this case cannot adequately be separated from those of gaseous pollutants. The diversity of tropical ecosystems and possible site-specificity together with limited resources for researching environmental problems in most tropical countries, hinder better understanding of the problems.

1.5.1.2 Changing Acidity of Tropical Soils

In the acid soils common in most areas of the tropics aluminum (Al) dominates the exchange complex up to a pH between 5.0 and 6.0. Al precipitates at pH values greater than 6.0. Organic matter acidity is associated with carboxylic acid and phenolic groups, both of which behave as weak acids.

Tropical soils vary with regard to the types of ion exchange complexes present. In many soils, aluminum and iron sesquioxides and some clays are responsible for anion absorption. This important property influences the direct impact of sulfate loading and associated problems like phosphorus (P) immobilization. Both phosphate and sulfate compete for anion absorption sites in tropical clay soils. Acidification of such soils can lead to increased weathering rates of soil minerals, increased leaching of bases, and solubilization of trace metals that could bring about toxicity. Soils with low cation exchange capacity (<6 meq/100 g) (Sanhueza *et al*., 1988) and low exchangeable Ca are often considered to be most sensitive to acidification. Further increases in Al saturation and/or its concentration in the soil solution would be a major consequence of acidification in many tropical soils.

Predictions of the effects of increasing acid deposition on tropical soils must consider the texture, base saturation, cation exchange capacity (CEC), organic matter content, clay mineralogy, and Ca content of the soils in question. Special emphasis must be given to anion mobility including sulfate adsorption, nitrate availability, and the role of organic anions. Phosphorus fixation capacity and heavy metal availability influence soil sensitivity to acidification. Improved understanding of root distribution in relation to soil morphology could help interpret sensitivity to acidification.

Two types of soils are likely to be sensitive to deposition of acidic or acidifying substances from the atmosphere: soils that are already acidic, in which Al could be mobilized by additional anion leaching; and soils that could show a substantial decrease in base saturation.

Tropical soils less likely to be sensitive to acidification include: soils with high organic matter content; soils currently receiving heavy loads of alkaline dust (Zhao and Xiong, 1988); and neutral or calcareous soils with a high acid-neutralizing capacity such as those occurring in large parts of the Indian subcontinent or Australia, where soils typically have pH ranging from 5.5 to 6.5 or higher.

The rapid deforestation taking place in the tropics is an important acidifying mechanism. Emissions of SO_2 and NO_x from the often accompanying burning of biomass, the export of bases with biomass harvest, and increased leaching of acid-neutralizing cations are thought to play important roles in this context.

1.5.1.3 Conclusions Regarding Effects on Terrestrial Ecosystems

Some general statements about the susceptibility of different parts of the tropics to acidification can be made based on the above considerations and the global soil map shown in Figure 1.7.

The most important responses, particularly in surface waters, to increased acid deposition can be expected in regions where the soils have natural low pH, low exchange capacity, and high Al saturation. Thus, areas with the following soil types were considered to be most sensitive to acid deposition: Oxisols, Inceptisols, Spodosols, and Ultisols. However, factors such as alkaline dust, neutralizing gases, soil texture, or anion adsorption capacity can ameliorate possible effects.

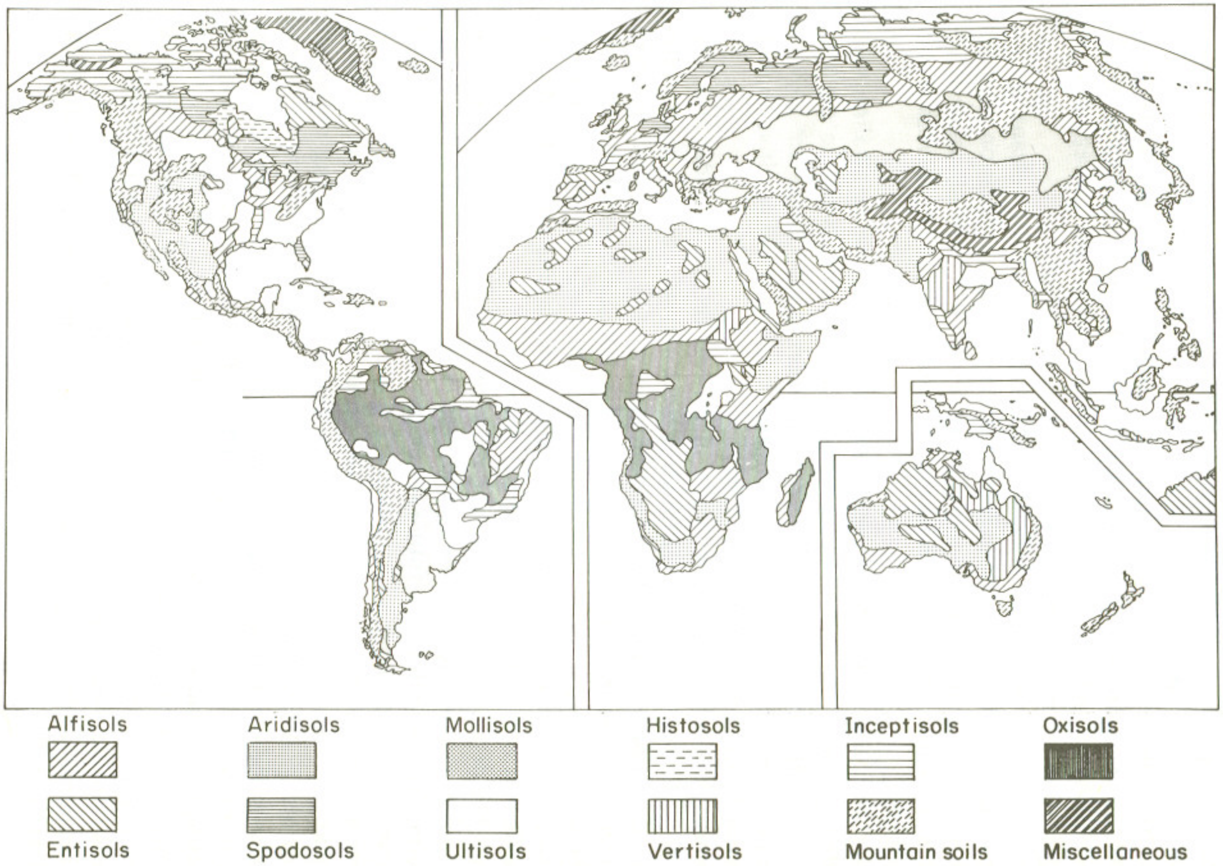

Figure 1.7 Soil types of the world. Based on data from *Soils of the World Map*, Soil Geography Unit. US Department of Agriculture, Hyattsville. Maryland, USA

The case study on China indicates that southern China has large areas of potentially sensitive soils while northern China, with its higher emission rates, is less prone to acidification due to abundant neutralizing dust particles from calcareous soils.

In tropical Australia, soils are generally less acid than in similar latitudes in Africa or South America. If sulfate adsorption capacity is similar to that cited by Ayers and Gillett (1988), one would expect little susceptibility to acidification, except possibly in the northeastern corner.

In parts of southeastern Asia, soils other than those of volcanic origin might be as sensitive as those in southeast China. High population densities will make the acidification problem more severe if industrialization accelerates. Soils in southwestern India may be susceptible to any increased acid deposition.

Northern Africa would be less sensitive due to neutral or alkaline soils, while equatorial Africa could become acidified more easily due to the generally low pH and CEC in soils. Here too, areas around large, fast-growing population centers, such as parts of Nigeria, could be more sensitive to acidification (Isichei and Akeredolu, 1988).

South American lowland soils are in general the most acidic and lowest in CEC. When coupled with high present and projected emission rates as in southeastern Brazil (Moreira-Nordemann *et al*., 1988) and northern Venezuela (Sanhueza *et al*., 1988), future acidification problems may become severe. Despite their high population densities, Central America and Mexico would be less sensitive to acidification due to the high pH and CEC of soils that normally occur in these countries.

A more detailed assessment of the risks for future acidification problems in tropical regions requires more complete information about soil and vegetation characteristics. The future development of industrial activities is, of course, a decisive factor.

Figure 1.8 summarizes schematically areas where the soils are sensitive to acid deposition and areas where high emissions of acidifying pollutants occur today. Areas that combine sensitive soils with high current emissions represent today's problem regions: parts of eastern North America, northern and central Europe, and southern China. Potential problem regions are identified based on soil sensitivity and expected future emission rates, based mainly on current population density. We wish to emphasize that some of these areas may not actually experience acidification, at least not in the immediate future, even if anthropogenic emission were to increase. This is due to the ameliorating effect of sulfate adsorption in the soils (McDowell, 1988; Galloway, 1988).

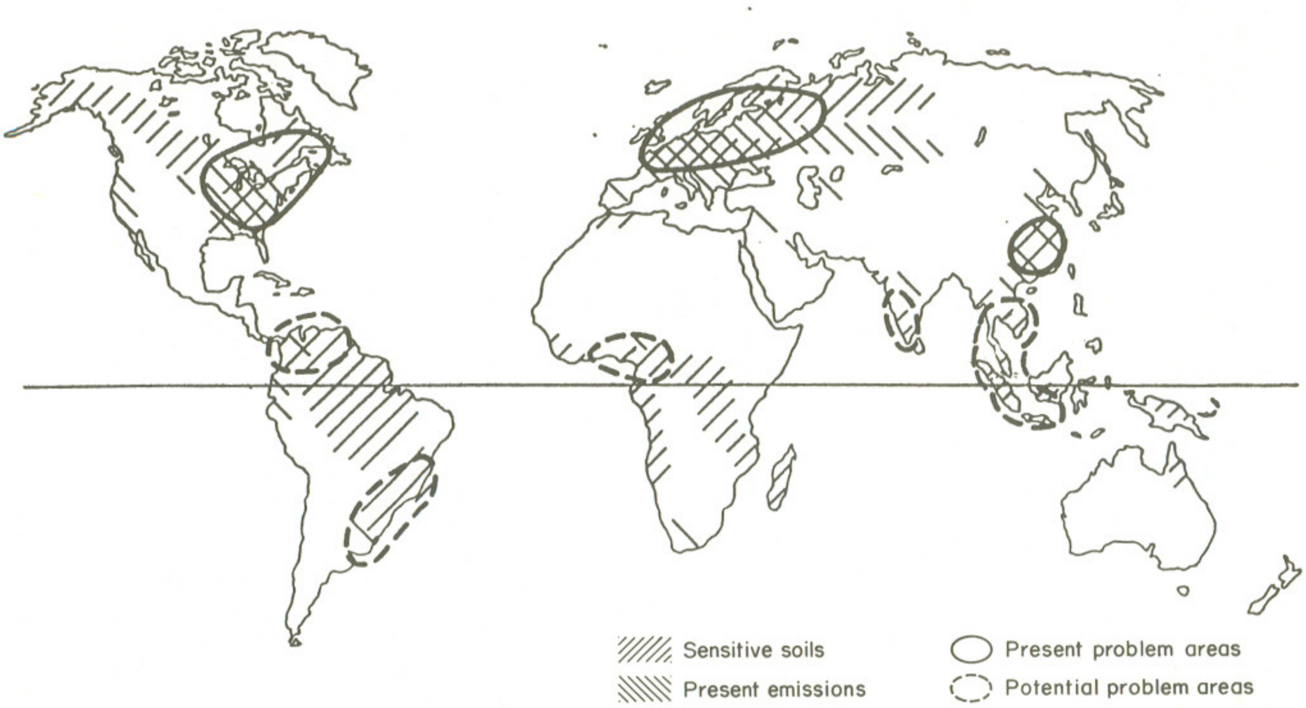

Figure 1.8 Schematic map showing regions that currently have acidification problems, and regions where, based on soil sensitivity, expected future emissions and population density, acidification might become severe in the future

1.5.2 Effects on Aquatic Ecosystems

Acidification of aquatic ecosystems is both a natural and an anthropogenic phenomenon. In tropical areas with high rainfall, natural acidification of soils and surface waters is common, but aquatic ecosystems are especially sensitive to further acidification by increased atmospheric deposition of sulfate and nitrate ions.

According to Galloway (1988), generally three conditions must be met before aquatic ecosystems will be acidified by atmospheric deposition:

1. Atmospheric deposition of sulfate or nitrate or some other anion must increase.
2. The soils adjacent to the aquatic ecosystem must not retain the anion that is increased in deposition.
3. The aquatic ecosystem must have low alkalinity for acidification to result in biological damage. Aquatic ecosystems of this type are typically associated with acid soils.

Aquatic ecosystems will acidify only if the additional sulfate or nitrate ions are not retained by soils. Therefore, information must be available on the anion retention capacity of the soils in question (Reuss and Johnson, 1986).

Certain highly weathered tropical soils have large anion adsorption capacities (Galloway, 1988; Jordan, 1985). Very little information is available on the spatial variability of the anion adsorption capacity of tropical soils. Most general soil maps lack the necessary detail on the magnitude of anion adsorption capacity.

The third condition is that the aquatic ecosystem must have an alkalinity low enough so that increased acidity will result in pH reductions sufficient to cause biological damage. Information on the average alkalinities over large regions indicates that vast areas of some tropical regions (e.g. South America) have aquatic ecosystems with low alkalinities (cf. Table 7.5 in Sanhueza *et al*., 1988). The information on biological populations of potentially sensitive areas is sparse. In many areas the taxonomy of the populations is not known, nor is their sensitivity to pH reductions.

Husar and Husar (1985) published a global survey of sulfur run-off to river water. Whereas large parts of North America and Europe exhibit a specific run-off of more than 2 g S/m^2/year, clearly influenced by human activities, most tropical regions have values below 1 g S/m^2/year. The run-off of sulfur in tropical regions will likely increase in the future as a result of increased circulation of pollution-derived sulfur and from mining activities.

1.5.3 Effects on Monuments and Construction Materials

Deterioration of engineering material and monuments is a serious problem in several countries, both economically and from a cultural point of view. Such deterioration is particularly rapid in coastal areas, exposed to seasalt aerosols, and in polluted cities and industrial areas where dry deposition of sulfur dioxide is a major factor. The corrosive effect of NO_x alone seems to be low. Combinations of sulfur and nitrogen oxides greatly intensify corrosion rates of copper and calcareous stone materials.

The influence of acid rain on corrosion is complex. On one hand it brings dissolved acids in contact with surfaces, and on the other hand it may wash away corrosive agents that were dry deposited in rain-free periods.

Whereas most corrosion damage caused by air pollutants occurs in cities and close to pollution sources, corrosion of metals used in contact with soil and surface water can occur several hundred kilometers away from major emission sources (Kucera, 1988).

Only limited data exist on corrosion rates of different materials in tropical environments. Severe corrosion problems affecting, for example, sandstone and carbon steel, have been reported from southern China (Zhao and Xiong, 1988) and Brazil (Moreira-Nordemann *et al*., 1988). In general, corrosion rates of metals exposed above ground or water sites are comparable with those in temperate climatic zones.

1.6 CONCLUSIONS

In concluding this chapter, we return to the six questions posed in the introduction. Existing knowledge is inadequate to formulate precise answers in many cases, thus this chapter offers recommendations for future studies aimed at filling some of the most important gaps in our knowledge.

1. What are the fluxes of sulfur and nitrogen compounds to and from the atmosphere in tropical areas? Estimates of sulfur- and nitrogen-oxide emissions are summarized in Tables 1.2 and 1.3. An important feature is the role of soil emissions and biomass burning. Deposition occurs through rainfall, direct uptake of gases, impaction of fine aerosols, and gravitational settling of coarse particulate matter (Figures 1.4 and 1.5).

2. To what extent do human activities affect the cycles of sulfur and nitrogen? In the tropics, emissions associated with human activities (i.e. industrial processes, fossil fuel combustion, biomass burning, and volatilization of livestock and human wastes) already match, or possibly even outweigh, emissions from natural processes. This implies that the wet and dry deposition of sulfate and nitrate are expected to be significantly elevated over large areas. A corresponding influence on rainwater pH is expected, although a quantitative assessment is difficult to make at present. Nitrogen oxide emissions from biomass burning have been shown to induce a significant increase in concentration of ozone in large areas of Brazil. Increased concentrations

of ozone are expected in other tropical countries with significant biomass burning.

3. What is the acidity of precipitation in areas not directly influenced by industrial emissions? Pure water in equilibrium with atmospheric CO_2 has a pH close to 5.6, but due to the presence of other soluble constituents of natural and anthropogenic origins, rainwater acidity often deviates significantly from this value (Charlson and Rodhe, 1981). Although good-quality data are limited, rainwater pH in many tropical forest regions seems to be consistently quite low, ranging from 4.5 to 5.0. There are indications that naturally occurring organic acids contribute significantly to this additional acidity. In regions with basic soil material exposed to wind erosion, for example in northern China and parts of India, pH values regularly exceed 6.

4. Do air pollutants from industrialized areas in northern temperate regions reach the tropics in significant amounts? Oxides of sulfur and nitrogen, ozone and aerosol particles have atmospheric lifetimes in the lower troposphere of less than one week. Since it usually takes at least several weeks for air in middle and high latitudes to reach the tropics, very little of this pollution would remain airborne long enough to reach tropical areas. Emissions in, for instance, the southern parts of North America, might influence neighboring areas in Central America, and a similar situation might exist between southern China and countries further south. Due to efficient vertical mixing in the tropics coupled with longer chemical lifetimes in the upper troposphere, pollutants emitted or formed in the tropics may be transported to higher latitudes in significant quantities.

5. How susceptible are vegetation, soils, and surface waters in the tropics to deposition of acidic compounds and associated air pollution? Direct toxicity of SO_2, NO_x, and O_3 to tropical vegetation has been studied almost entirely in the immediate vicinity of metal smelters, and major urban industrial centers. Almost nothing is known about the direct toxicity effects of regionally dispersed airborne pollutants in the tropics. Naturally acidic soils in large parts of South America, Africa, and Southeast Asia are expected to be susceptible to a high additional input of acid deposition, although the degree of susceptibility is not well established. Other areas, e.g. Central America, India, and northern China with more alkaline soils are probably substantially less susceptible.

6. What parts of the world contain both susceptible ecosystems and a substantial likelihood of rapid industrialization in the not too distant future? Areas of probable sensitivity to soil acidification include southern China and other areas of Southeast Asia, southwestern India, equatorial Africa including Nigeria, southeastern Brazil, and northern Venezuela. These areas include surface waters that are likely to be sensitive to acidification by atmospheric deposition of acidic and acidifying compounds.

APPENDIX: A SIMPLE PROCEDURE FOR REGIONAL ACIDIFICATION STUDIES

The previous discussion clearly shows a fundamental lack of knowledge about the occurrence of acidic and acidifying compounds, and many basic processes relevant to assessing present and potential acidification and air pollution problems in tropical regions. The fact that some emerging problems have already been identified, e.g. regionally acidified precipitation in southwest China, increased ozone concentration over the Brazilian savanna, and a rapidly deteriorating situation with regard to air pollutants in and around many large cities, make it important to fill these knowledge gaps.

A major research program on the biogeochemical cycling of sulfur, nitrogen, other nutrient elements, ozone, and other photochemical oxidants in tropical environments would yield a better understanding of the present situation with regard both to undisturbed ecosystems and to human-induced perturbation of them. It would also help to identify potential problem areas and thus provide a scientific basis for actions to remedy or avoid such problems in the future.

In addition, monitoring programs provide an early warning system for detecting changes in the environment before they become serious. Specific steps in such a research and monitoring program may include the following:

1. The current and projected anthropogenic emissions of acidifying and alkaline substances (e.g. SO_2, NO_x, NH_3) must be evaluated for the region under consideration. If information for a particular region is incomplete, comparable data derived elsewhere can give a preliminary estimate.
2. Local effects such as plant damage, health effects, and corrosion can be evaluated from atmospheric concentration distributions calculated with simple dispersion formulae, emission estimates, and some local meteorology. Plant damage effects should be studied as described later. This procedure should be sufficient to determine whether or not local undesirable effects are likely to occur.
3. It is more difficult to estimate the concentrations and rates of deposition of acidifying substances further afield. As a rough estimate one could assume that on a yearly basis all material emitted is deposited by wet and dry processes within 2,000 km. Then the deposition can be calculated for sectors from any given source. Meteorological observations of wind direction must be used to obtain the fraction of time during the year when large-scale winds blow from the source to within a given sector. This calculated deposition can then be compared with expected natural deposition rates and its acidifying effect on terrestrial and aquatic ecosystems evaluated. The results obtained should be weighted according to the annual precipitation over the sector. If one part of the region, e.g. a mountain range, receives larger than average rainfall, then the deposi-

tion should be scaled up according to the ratio of the rainfall rate over the special area to the rainfall rate over the whole sector.

4. If an area is identified as a region of potential concern then the next activity should be to set up a program at a few locations for measuring the acidity of rainfall events. The equipment, though simple and inexpensive, should conform to currently accepted standards; proper siting, use of plastic collectors that are rinsed in distilled water before each rainfall collection, and rainwater pH measurements taken with a calibrated pH meter within several hours of the rainwater collection. One site should be located upwind or away from the polluted area as a benchmark station for comparison with the polluted stations.
5. If significant acidity is encountered, or expected to occur in the future, terrestrial and aquatic ecosystems could be affected. More comprehensive studies are then required to properly assess the environmental impact of the acidification (steps 6–9).
6. Use of topographic, soil, and geologic bedrock maps to identify areas within countries with well-drained acid soils.
7. Determine alkalinity of perennial streams in these areas to assess the degree of sensitivity of the aquatic ecosystem.
8. Analyze representative soil samples associated with sensitive streams and vegetation to determine their pH, cation exchange capacity (CEC), percentage base saturation, labile aluminum concentration, and anion adsorption capacity.
9. In areas with sensitive streams and vegetation begin a baseline measurement program of the chemical composition of precipitation and streams.

Air pollution effects on agricultural crops and forests have been studied in both industrial and urban areas in many parts of the world. Most proven effects of air pollutants are caused by the toxicity of locally dispersed sulfur dioxide or fluoride in the vicinity of strong point sources, and to the toxicity of regionally dispersed tropospheric ozone (and possibly other photochemical oxidants) at a distance from major urban and industrial centers. Injurious effects of acid deposition *per se* on crops and forests are widely suspected but have yet to be rigorously proven even in temperate regions (Woodman and Cowling, 1987). Most of the postulated effects of acid deposition are suspected to occur by one or more of the following mechanisms: (1) leaching of nutrients from foliage especially after damage to cell membranes by ozone, sulfur dioxide, or fluoride; (2) leaching of calcium, potassium, magnesium and other cationic nutrients from forest soils; (3) increased concentration of aluminum in soils; (4) decreasing phosphorus availability in soils; (5) erosion of surface waxes from leaf surfaces leading to increased susceptibility to droughts; (6) inhibition of mycorrhizae; and (7) predisposition of plants to biotic pathogens (Cowling, 1985).

Three general approaches are recommended for determining the impact of airborne pollutant chemicals on tropical terrestrial ecosystems:

Approach 1

Conduct surveys of the condition of native vegetation and planted crops along gradients of air concentration and/or atmospheric deposition of airborne chemicals near strong point sources of pollutants in the tropics.

The general objective of these surveys should be to establish possible correlations between gradients in forest or crop condition and gradients in exposure to airborne pollutant chemicals.

Transects should be established with sampling plots extending outward at various distances from local emission sources in cities and industrial centers. Transects should be established across the more important types of biomes in the tropics: savannas, tropical rainforests, cloud forests, deciduous forests, swamps, etc., as well as across crop land areas. Measurements along each transect should include environmental factors (such as concentrations of sulfur dioxide, ozone, and nitrogen oxides; major cations and anions in aerosols and precipitation; temperature variations; and soil chemical and physical characteristics) and various measures of crop or forest condition (such as rates of root, shoot, and diameter growth; visible symptoms of injury, including leaf spots, color changes, and premature loss of leaves, yield of produce, etc.).

Visual inspections from aircraft, aerial photographs, or even satellite images can be used to assess gradients in ecosystem condition along the transects. Ideally transects can be established before a new pollution source is started and then continued for some years after start-up.

Approach 2

Conduct exposure experiments in the tropics by measuring the growth and development of native vegetation or crop plants grown in ambient air or rain, and compare them with similar native vegetation or crop plants grown in charcoal-filtered air or rain of normal chemical composition.

The general objective of these experiments is to determine if ambient air or precipitation induce a decrease or other changes in the growth or development of natural vegetation or crop plants selected for study. Open-top chambers equipped with charcoal filters for removing airborne pollutant gases and aerosols in ambient air and for excluding ambient precipitation should be placed over natural vegetation or planted crops, as should similar chambers without charcoal-filters or rain exclusion devices. Ambient rain in the exclusion chambers should be replaced with similar amounts of irrigation water containing only the major anions and cations believed to occur in natural rain.

Ideally, measurements should be made of the concentration of airborne pollutant gases and aerosols in both the ambient air and charcoal-filtered air, and the major cations and anions in the ambient precipitation and irrigation water. Changes in the growth and development of vegetation in all four types of chambers (ambient air with ambient precipitation, ambient air with natural precipitation, charcoal-filtered air with ambient precipitation, charcoal-filtered air with natural precipitation) should then be compared.

Approach 3

Conduct controlled-exposure experiments to determine the growth and development of selected tropical plants in air and rain containing various amounts of airborne chemicals that are suspected to cause injury in tropical ecosystems.

Open-top chambers, constantly stirred tank reactors, or small cuvettes should be used to expose small seedling plants, foliage and shoots of mature plants, or soils and roots of mature plants, to various known concentrations of specific gases, aerosols, and dissolved and suspended substances in simulated rain over a period of weeks, months, or years. The amounts of specific airborne pollutant chemicals should be controlled (for example to include 0, 1×, 2×, 5×, and 10× the concentration or deposition of the particular substance in ambient air.

Rate of root and shoot growth and development, as well as any visible symptoms of injury, should be measured after various periods of exposure. Graphs of plant response to concentration and deposition of specific airborne pollutant chemicals should then be used to determine if, when, to what extent, and under what conditions the specific chemicals were injurious (or beneficial) for plant growth and development.

There is a great scientific challenge in understanding nutrient cycling, acidification, and regional pollution in tropical ecosystems. The researchers involved in this project found the interdisciplinary work necessary for better understanding to be exciting and rewarding. In addition to interdisciplinary work, the new approach involves examining the problem on a larger scale than previously addressed; that is, combining sources, regional transport, and ecological impacts over regions only slightly smaller than continental scale. Further international cooperation may be achieved through existing UNEP programs and the emerging ICSU International Geosphere Biosphere Program.

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