Chapter 1
The American Tropics, a Forest Region

The American Tropics (neotropics) is that portion of the Western Hemisphere lying between the Tropic of Cancer and the Tropic of Capricorn, the parallels of latitude at the greatest north and south declinations of the Sun (23° 27′) from the Equator. It has a land area of about 16.5 million km^2, about 11 percent of the Earth's land area (Anon. 1990a, 1993a).

Within the Tropics worldwide, the land area is about equally divided between the equatorial (inner) Tropics (11° 43′ N. to 11° 43′ S.) and the outer Tropics. The Western Hemisphere contains less than a third of the tropical land. Of this amount, 70 percent is in the Southern Hemisphere and 61 percent is equatorial (fig. 1–1; table 1–1; Baumgartner and Reichel 1975).

Forests that are "physiognomically tropical" extend beyond the geographic Tropics of America, notably in northern Mexico, southern Florida, southeastern Brazil, and northeastern Argentina (Baur 1964b).

The climate and physiography of the American tropical region as well as the forests themselves are described in this chapter. Sources of the climate and regional features precede a discussion of climatic classifications of forests. Under physiology, the geological source of the present physiography and the characteristics and major classes of soil are described. The forest description begins with the genesis of the forests, their present extent and location, and their classifications, finishing with a description of the extensive forests of the Amazon basin, mangrove forests, and cerrado.

Climate

The climatic Tropics is a band of varying width on either side of the climatic Equator, a line that connects points relatively uniform in humidity and temperature. The climatic Equator deviates from the geographic Equator because of a lack of uniformity in the distribution of land, oceans, and orographic influences. Tropical climatic conditions, sometimes termed "subtropical," may be extended beyond the geographic Tropics by cyclone systems.

Climate is the greatest force affecting the natural distribution of vegetation. Thus climate similarities or differences are a key to explaining the degree to which forest productivity varies from place to place and the corresponding probability that measured results in one place may apply to another. The description of the climate of tropical America that follows draws on Trewartha (1968).

Solar Radiation. The greatest determinant of climate is solar energy. Each day, tropical America is bathed somewhere by the Sun's rays from vertically overhead. Some 30 percent of the radiation received at the upper edge of the Earth's atmosphere over the Tropics (fig. 1–2; Gentilli 1968, cited by Trewartha 1968) is lost through reflection, chiefly because of clouds. Of the radiation not reflected, about 30 percent is absorbed as it passes through the atmosphere before reaching the Earth's surface. The amount so lost is least where the Sun is directly overhead and more where the atmosphere is penetrated at an angle. Angularly incident radiation is also less effective because it is diffused over a larger area of ground surface. These losses are further increased by reductions in day-length as latitudinal distance from the position of the Sun increases. Daily insolation levels at the Earth's surface for the months of June and December are shown in table 1–2 and figures 1–3 and 1–4.

Solar radiation at the Earth's surface in the outer Tropics is greater than in the equatorial Tropics because of greater cloudiness near the Equator. The radiation at latitude 10° is about 6 percent greater than at the Equator; at latitude 20°, it is about 10 percent greater (Budyko 1962, Trewartha 1968). For example, inner Amazonia on the Equator receives less than 120 kcal/cm2 of solar radiation per day, whereas the eastern Sahara, at latitude 20° N., receives more than 220.

The reflective capacity of the Earth's surface, termed "albedo," varies with the nature of the land surface. For grasslands, it may be 15 to 30 percent; for bare ground, 7 to 20 percent; and for forests, 3 to 10 percent (Trewartha 1968).

If the annual vegetative period of the Tropics were only as long as that of the Temperate Zone, the Tropics would be at a disadvantage with respect to potential photosynthesis (Best 1962) because daylight in the summer is markedly shorter in the Tropics than in the Temperate Zone. The ratio of tropical to temperate average daily radiation is approximately 1:1.5 (Best 1962). Moreover, sufficient water to grow crops in the Tropics is generally available only during the monsoon season when radiation is less than in the growing season in the Temperate Zone.

Temperature. Normal temperatures in tropical America vary somewhat from summer to winter (fig. 1–5). More than half the region's land area experiences mean temperatures above 25 °C in the summer, and less than a

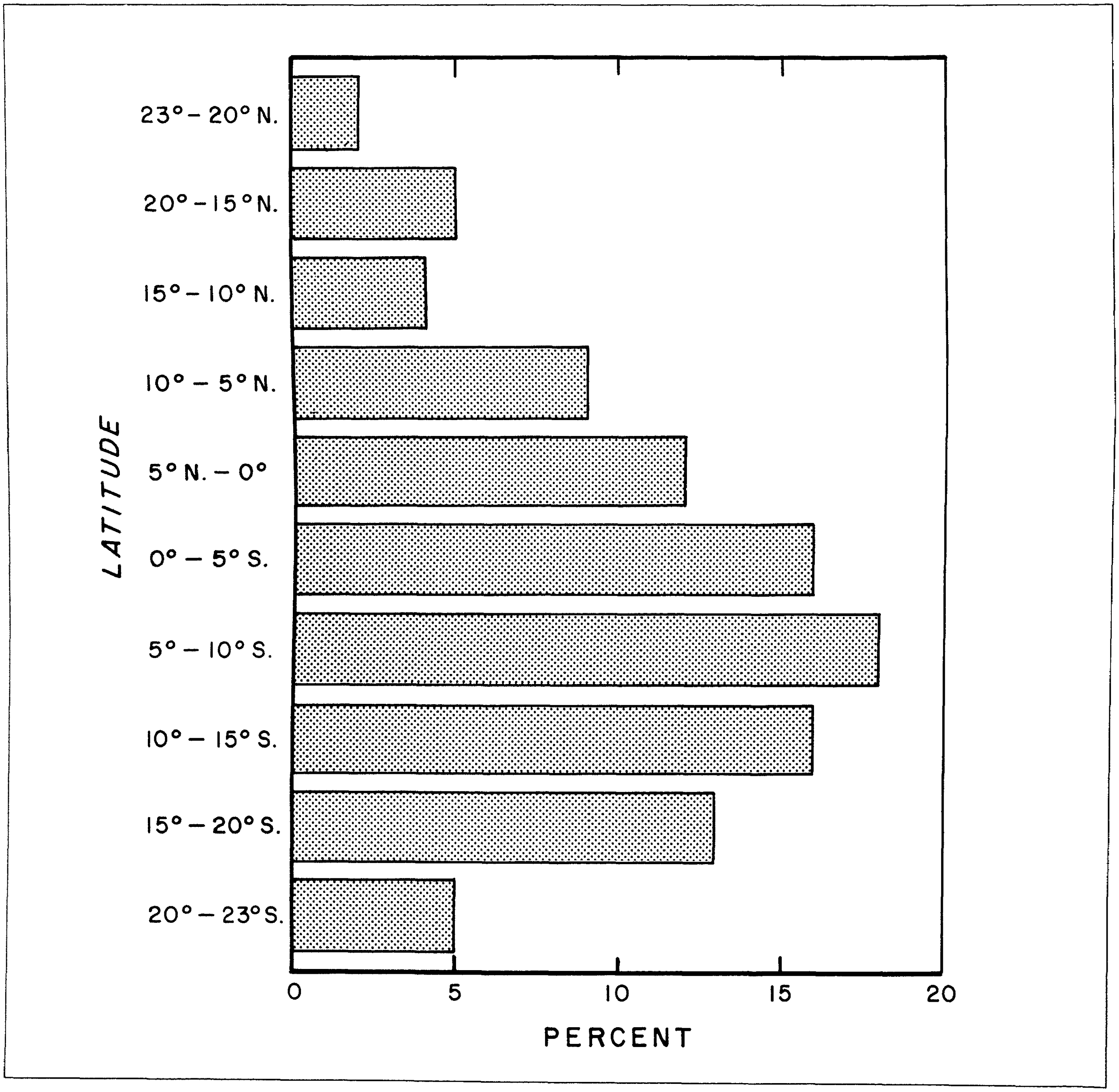

Figure 1–1.—*Percentage of land at different latitudes in the American Tropics (Baumgartner and Reichel 1975).*

Table 1–1.—Equatorial (inner) and outer tropical land areas

Location (latitude)	Tropical land areas (%)
Equatorial Tropics (0° to 11° 43′)	
North	22
South	39
Outer Tropics (11° 43′ to 23° 27′)	
North	10
South	29
Total	**100**

Source: Baumgartner and Reichel 1975.

fifth of the region is cooler than 15 °C all year (Anon. 1975b, 1979b).

Proximity to the sea produces maritime climates in part of tropical America. Since turbulence leads to slow warming and cooling of water surfaces, the climates of oceanic islands and exposed coasts are relatively uniform. Oceanic surfaces probably do not change in temperature more than 1 °C between day and night. Continental areas far from the sea experience much greater daily and seasonal extremes. Webb and others (1980), analyzing data from 319 weather stations in tropical and subtropical America, found that below 1,000 m in elevation, the lapse rate is a change of 1 °C for every 278-m change in altitude, whereas between 2,000 and 3,000 m, a change of 1 °C occurs every 189 m. They also concluded that the rate of change decreases with distance from the Equator. At latitude 0° a rise of 204 m in elevation reduces temperature 1 °C, whereas at latitude 25° N., it takes a 276-m change to reduce temperature 1 °C. Their findings are summarized in table 1–3; a few examples appear in table 1–4.

Nearly the entire region is free of frost. Major exceptions are the Sierra Madre in Mexico, the high Andes, and southern Brazil.

Wind. Winds in the Tropics are seasonally variable. Surface winds as a whole are easterly. The winds of tropical America generally blow from north of due east in the Northern Hemisphere and south of due east in the Southern Hemisphere throughout the year. The trade winds are strongest near 10° N. and S. latitudes (fig. 1–6). However, there are many exceptions to the seasonal uniformity of wind direction and much remains to be learned about tropical wind movements. Westerly winds are not rare, and the "doldrums"—prevailing calms and light, variable winds attributed to the zone of convergence of the easterly trade winds from the Northern and

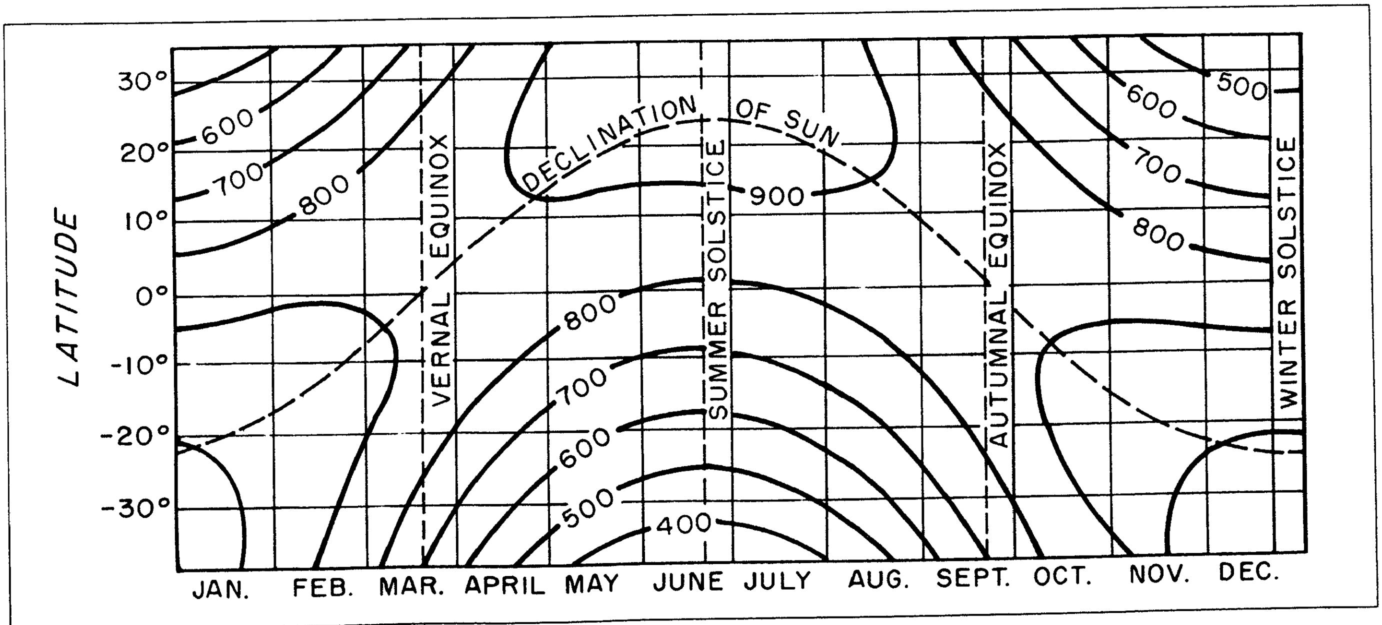

Figure 1–2.—*Mean surface solar radiation as affected by season and latitude in the Tropics (Gentilli 1968).*

Table 1–2.—Daily insolation losses at the Earth's surface for June and December by type of loss and latitude

Type of loss and resultant insolation	Equator	Tropic of Cancer	Tropic of Capricorn
Equinox			
(June—Sun over Equator)			
Loss due to angularity	0	8	8
Loss through atmosphere	39	39	39
Effect of day-length	0	0	0
Resultant surface insolation	61	53	53
Northern solstice			
(December—Sun at 23° 27′ N.)			
Loss due to angularity	8	0	33
Loss through atmosphere	39	39	33
Effect of day-length	0	49	-4
Resultant surface insolation	53	70	30

Source: Gentilli 1968.

Southern Hemispheres—are common. Weather in this region is extremely localized.

The seacoasts of tropical America are subject to land and sea breezes caused by seaward drift of air that has been cooled by more rapid night radiation over land than over sea and, conversely, landward drift during the day caused by the rise of more rapidly heated air over land. These sea breezes may reach storm intensity and are particularly strong on dry, tropical coasts adjacent to cool, ocean currents. Similar diurnal and nocturnal mountain and valley winds also occur due to these temperature differentials.

Violent cyclones or hurricanes enter tropical America each year. They usually approach from an easterly or southeasterly direction through (or just to the north of) the Caribbean Sea, affecting the West Indies and the Atlantic slope of Central America and Mexico. Tropical hurricanes may also reach the west coast of Central America and Mexico from the Pacific Ocean, entering from a northwesterly direction. These hurricanes develop wind speeds up to 250 km/h or more. Roughly circular in outline, they may attain 600 km in diameter and affect a single area for days. Precipitation totaling 1 m or more may accompany such storms.

Moisture. For the Tropics as a whole, cloudiness is greatest near the Equator. The worldwide average for latitudes 0° to 10° is 52 to 56 percent (Brooks and Hunt 1930). Cloud cover is 40 to 46 percent for latitudes 10° to 20° and declines to 34 to 38 percent in the 20° to 30° latitudinal range.

Rainfall in tropical America is typically either convectional, caused by cooling of rising air above the warm land surface, or orographic, caused at least in part by upthrust effects of highlands. The generation of orographic rainfall is illustrated in figure 1–7.

Rainy "seasons" characterize most of the Tropics. These generally result from the unstable air common to the intertropical front, a zone of convergence between permanent cells of moist equatorial air in each hemisphere. This zone migrates northward and southward each year, generally being found in the hemisphere experiencing summer (figs. 1–8, 1–9). The saying that rainfall "follows the Sun" is illustrated well by de Martonne's chart (fig. 1–10).

Mean annual precipitation for all tropical land masses worldwide varies by latitude (Brooks and Hunt 1930, Meinardus 1934). The amounts are generally lower than those for America alone because vast tropical areas of the Eastern Hemisphere are relatively rainless. Precipitation over the oceans is much greater in the equatorial Tropics where large-scale lifting of warm, humid air is of major climatic significance.

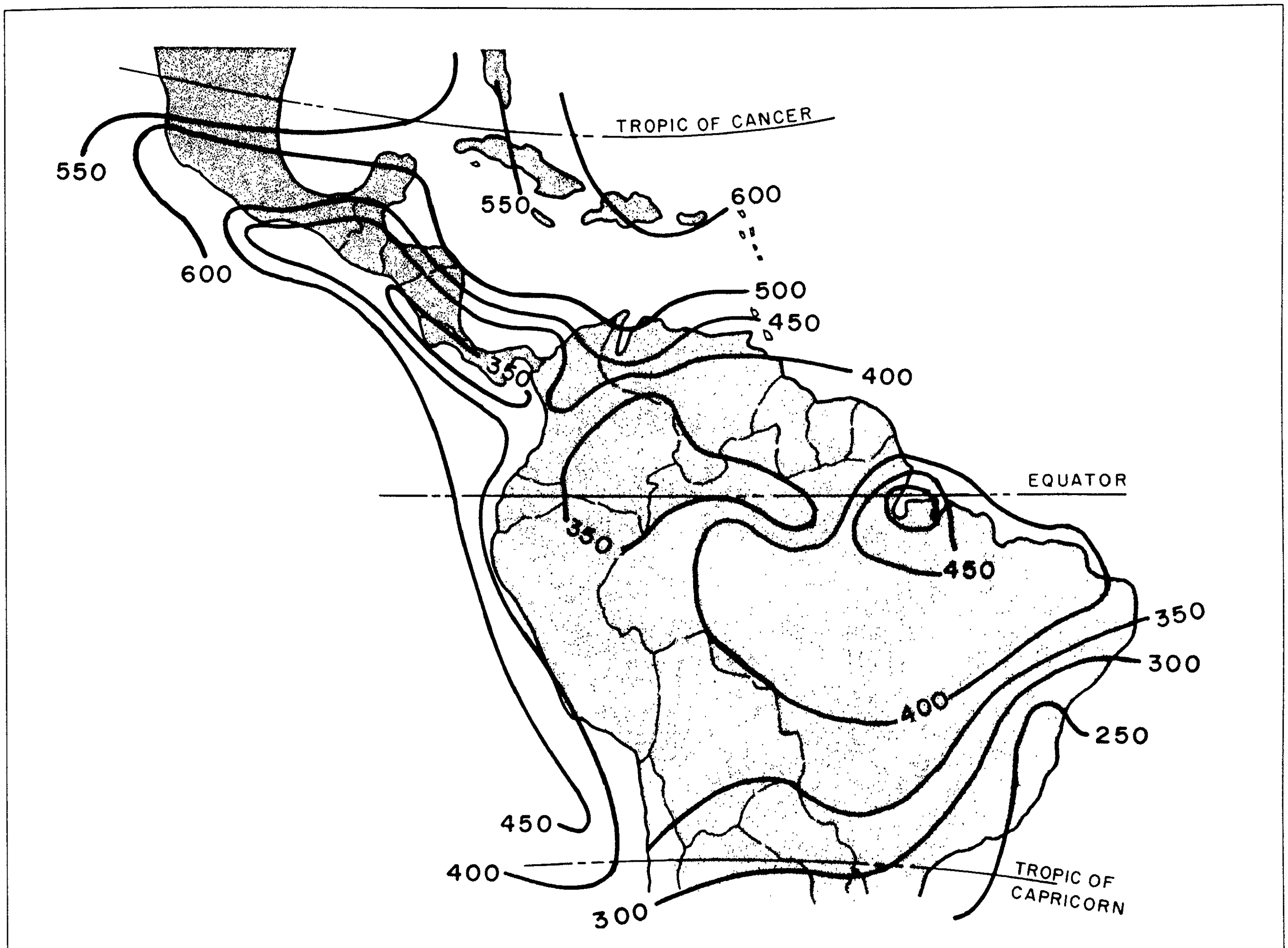

Figure 1–3.—*Mean daily solar radiation (calories/cm²) received at the Earth's surface in June (Landsberg 1961).*

The mean annual precipitation over the region ranges from less than 40 cm in a few isolated areas to more than 320 cm (figs. 1–11, 1–12; Anon. 1975f, 1979f). About 70 percent of the area receives 160 to 320 cm/yr. Monthly precipitation of 10 cm or less slows the biological activity of many plants. Much of the area in tropical America receives less than 10 cm during part of the year, between December and April north of the Equator and between May and September south of the Equator. About 64 percent of the region experiences dry months with less than 5 cm of precipitation (Anon. 1975a, 1979g).

Precipitation in the region may vary widely from year to year, especially in the dry climates of northwestern Mexico, northeastern Brazil, coastal Peru, western Bolivia, and northern Chile. In these areas annual rainfall in any specific year may average 40 percent below or above the mean. In the rest of tropical America, this variation ranges from 10 to 20 percent (Biel 1968). The seasonal rainfall patterns (fig. 1–13) affect the types of forest vegetation present and the adaptation of individual tree species to different regions.

The evaporation capability of the air is proportional to the atmospheric saturation deficit, which is a measure of the degrees that vapor pressure is below saturation. More commonly used for this purpose is relative humidity, a measure of the percentage of vapor pressure in the air. Actually, saturation deficit and vapor pressure are better indicators than relative humidity of moisture stresses on plants because they take into account current temperature and pressure (Longman and Jenik 1974). In the moist

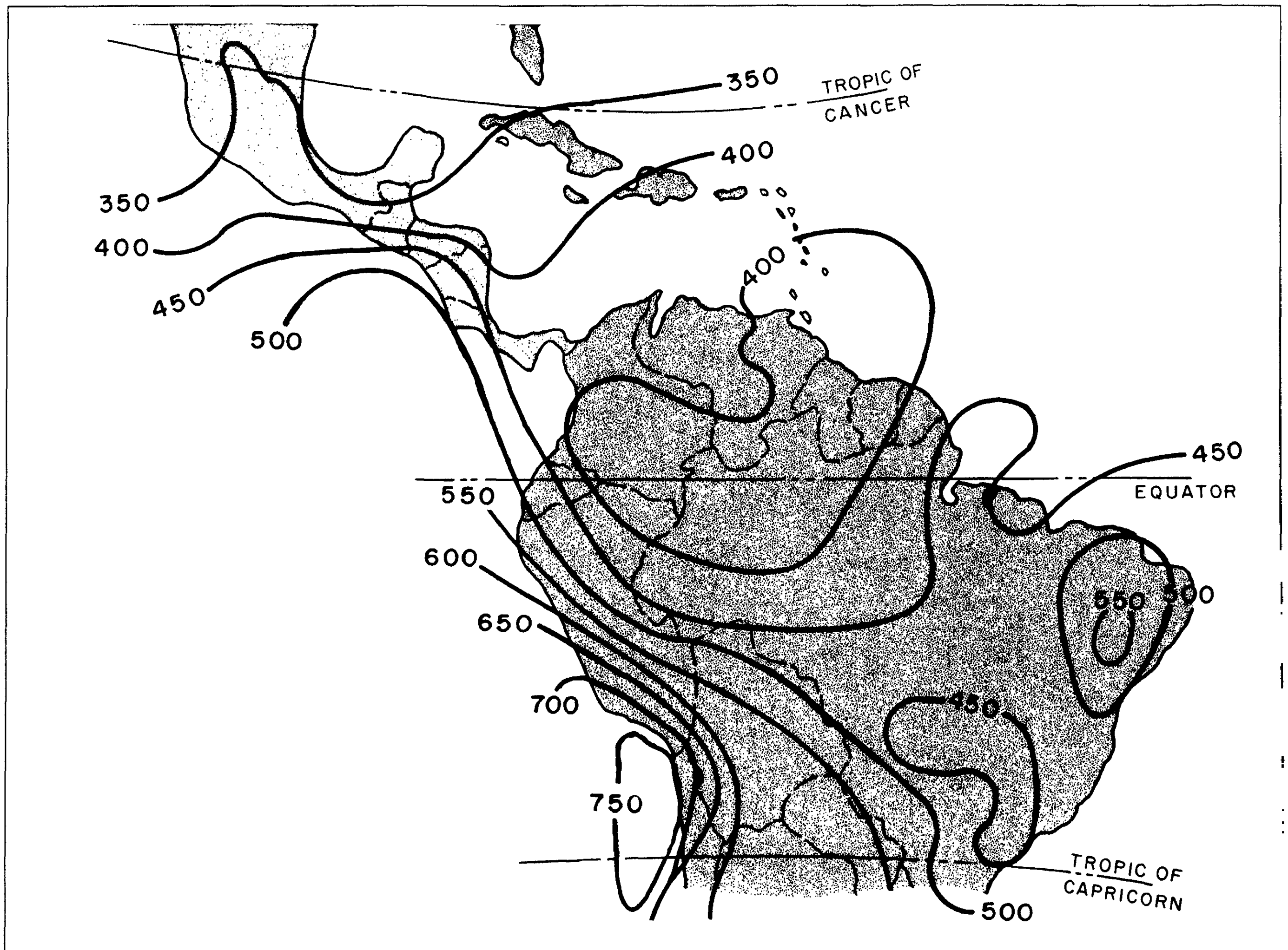

Figure 1–4.—*Mean daily solar radiation (calories/cm²) received at the Earth's surface in December (Landsberg 1961).*

Tropics, relative humidity may fall to 70 percent at midday in the forest canopy, but at the soil surface it is generally higher than 90 percent. At night, the humidity is generally higher than 95 percent (Longman and Jenik 1974). Twenty-four-hour means range between 70 and 85 percent.

Probably more than half the Earth's evaporation takes place within the Tropics (Trewartha 1968). Evaporation decreases slightly at the Equator due to heavy cloudiness there. Potential evaporation, or that which would take place with unlimited amounts of water, averages 120 cm/yr at latitudes 0° to 10° and 130 to 140 cm/yr for latitudes 10° to 20° (Schwerdtfeger 1976).

Regional Climatic Features. Tropical America is characterized by distinct subregional climatic features. Descriptions of these appear in appendix A and draw heavily on Garbell (1947) and Schwerdtfeger (1976).

The classification of climates of significance to vegetation is fundamental to the recognition of distant but similar climates to guide land use and forest practice. These classifications are particularly useful in interpreting the extent to which research results may be expected to apply in a distant area. Climatic classification has been undertaken since the mid-19th century, chiefly by biologists (Thornthwaite and Hare 1955). By 1875, the idea that climates might be classified according to vegetation

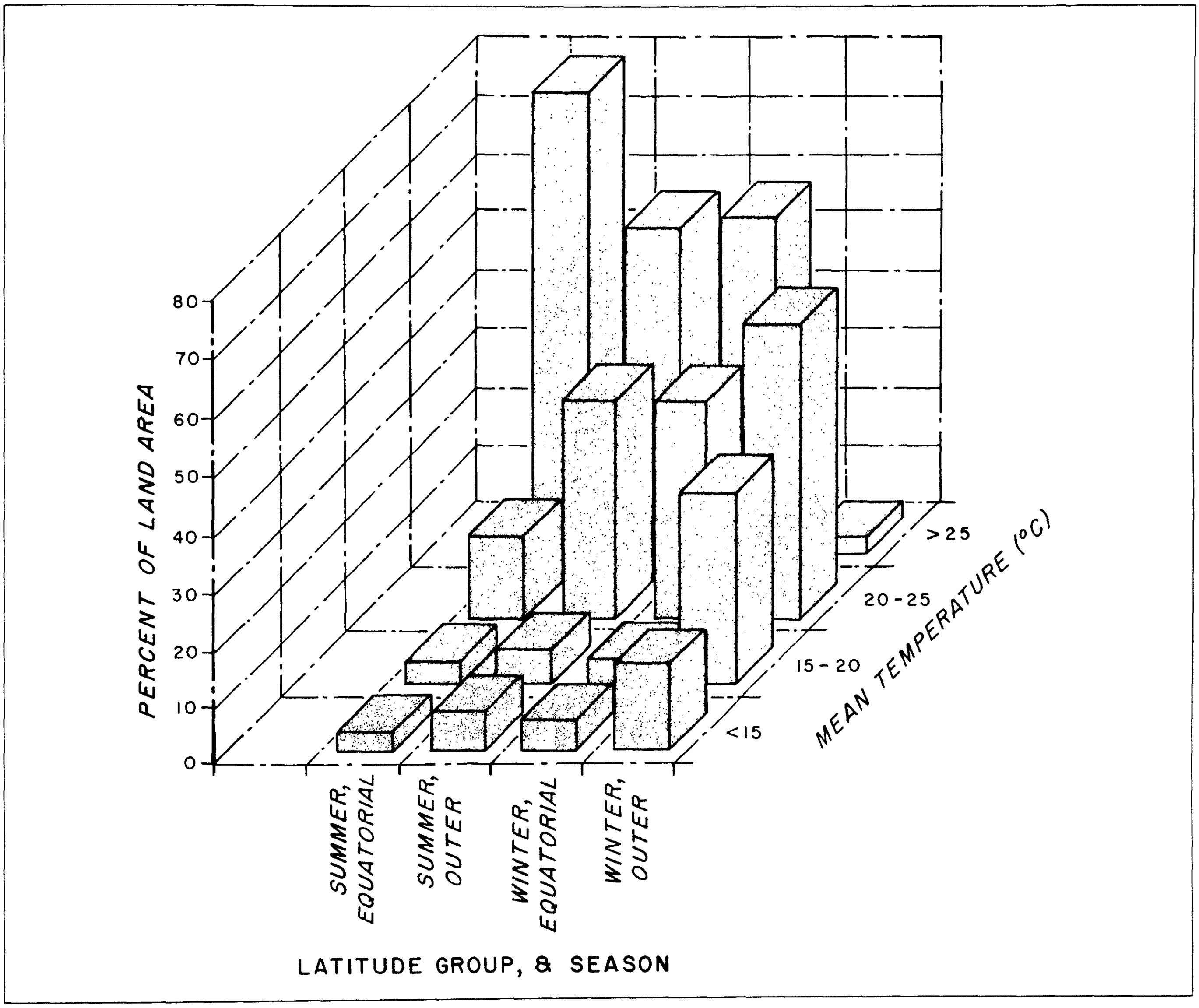

Figure 1–5.—*Land area of tropical America by latitude and mean temperature (Anon. 1975b, 1979b).*

type was well established. Yet today no one classification system is currently accepted worldwide, and new, local classifications continue to appear. A record of major classifications applicable to the Tropics is to be found in appendix B.

The climatic classifications described in appendix B show different attempts to integrate temperature and moisture in terms significant to vegetation and thus lead to its broad classifications as well. At best these systems distinguish only widely different vegetation; additional sources of differences in forest structure and particularly composition are local soil, topography, and degree of isolation. Greater refinement for purposes of management calls for descriptions of forest associations and types.

Physiography

Three-fourths of the land in tropical America lies below a 500-m elevation (fig. 1–14; Anon. 1979f). In contrast,

Table 1–3.—Mean temperature relative to altitude and latitude (°C)

Altitude (m)	Latitude 20° N.	0°	20° S.
0	25.8	27.2	23.1
1,000	22.8	23.1	19.9
2,000	17.2	18.1	16.3
3,000	10.8	12.2	12.1

Source: Webb and others 1980.

nearly half the land in the eastern Tropics lies above 500 m. The following physiographic description draws heavily on Sanchez (1976).

The most outstanding physiographic feature of tropical America is the mountainous Cordillera near its western edge, extending throughout North, Central, and South America, including the Sierra Madre Oriental in Mexico and the Cordillera Oriental of Colombia and Venezuela. The highest peaks are Popocatepetl in Mexico (5,400 m), Huila in Colombia (5,800 m), Chimborazo in Ecuador (6,300 m), and Huascaran in Peru (6,800 m). In addition, extensive plateaus from 1,000 to more than 3,000 m characterize central Mexico, southeastern Venezuela, the southern half of the Guianas, and Brazil south of latitude 5° S. In contrast, extensive lowlands less than 500 m in elevation are found to the east of the Cordillera on Mexico's Yucatan Peninsula, in the Llanos of the Orinoco in Venezuela, and in the basins of the Amazon and the upper Rio Paraguay, extending southward from the southern Matto Grosso into Paraguay. Elevations in the West Indian islands range from the extensive lowlands of central Cuba to mountainous areas in eastern Cuba (2,000 m), Jamaica (2,300 m), and Hispaniola (3,200 m). The Lesser Antilles are nearly all mountainous, with many peaks higher than 1,000 m.

The Cordillera arose late in the Cretaceous period (65 to 135 million years ago) and has undergone subsequent modifications, including probably three periods of volcanism. The high peaks on the Mexican plateau (Popocatepetl, Ixtaccihuatl, etc.) arose during the Miocene epoch (10 to 25 million years ago), when volcanism affected all of Mexico. Volcanic activity resumed in this area and began in Central America in the Pliocene epoch (600,000 to 10 million years ago) and has continued to the present. The marine deposits of the Yucatan Peninsula were laid down during the Pleistocene epoch (12,000 to 600,000 years ago).

Most of western Mexico and the mountainous areas of Central America and central Hispaniola and Puerto Rico have been above sea level since the Cretaceous period (Schuchert 1935). Cuba and the Yucatan were largely submerged during the Pleistocene epoch. The central Lesser Antilles, which have the most active volcanoes at present, may have appeared as early as the Miocene epoch, but the islands to the north and south of these are of Pliocene and Pleistocene origin.

In the northern Andes, the Pliocene epoch was a time of vast volcanic eruptions and mountain construction. The plateaus to the north and south of the lower Amazon are of Mesozoic (65 to 230 million years ago) or Paleozoic

Table 1–4.—Mean temperature change with elevation at different locations in the Western Hemisphere

Location	Latitude	Difference[a] Elevation (m)	Mean temperature (°C)	Rate of change (m/°C)
Alvarado/Desierto de los Leones, Mexico	18° N.	3,190	13.6	235
Barinas/Mucuchies, Venezuela	9° N.	2,820	16.0	176
Cobija, Bolivia/ Cerro de Pasco, Peru	11° S.	4,200	17.8	236
Chaco Mission, Paraguay/ La Quiaca, Argentina	20–22° S.	3,340	14.7	227

Source: Webb and others 1980.
[a]Difference in elevation and mean temperature of the two locations listed in the first column.

Figure 1–6.—*The easterly trade winds prevailing throughout the region shape the crown of this sentinel standing on the windward coast of the island of Saint Lucia.*

(280 to 600 million years ago) origin and are the oldest structures of the region (Schuchert 1935). The extensive lowlands of South America are Tertiary and Quaternary deposits (within the past 65 million years).

The moist conditions and the limitations of agricultural productivity have left extensive forests on the steep slopes of the uplands of tropical America, local exceptions notwithstanding. At the other extreme, because of similar difficulties for successful agriculture, extensive lowlands in the Yucatan Peninsula, the coastal plains of Central America, and the Amazon Basin also remain largely forested.

No summaries of topography were found for the region as a whole but an Empresa Brasileira de Pesquisa Agropecuaria (EMBRAPA) study (Cochrane and Sanchez 1981) for the central lowlands of tropical South America showed the relations given in table 1–5.

Soils

Information given here draws heavily on descriptions of the formation, classification, and properties of the soils of the Tropics by Mohr (1944), Sanchez (1976), and Young (1976).

Formation. Seven factors significantly affect soil formation: climate, parent material, relief, drainage, organisms, time, and human activity (Young 1976). Profile depth, stoniness, and soil texture affect the properties of the soils that are formed. Climate helps determine the organic component, the reaction, and the base saturation; the parent material influences soil texture; relief influences soil depth and stoniness.

Young uses Koeppen's (1936) system of climatic classification for soil relationships because of its simplicity. Young contrasts soil formation processes in different climates. In a rain forest (Koeppen's Afl), weathering is intense, with complete breakdown of all minerals other than quartz. Leaching throughout the year produces acid soils with low base saturation. Dry seasons of up to 3 months duration do not retard these processes significantly.

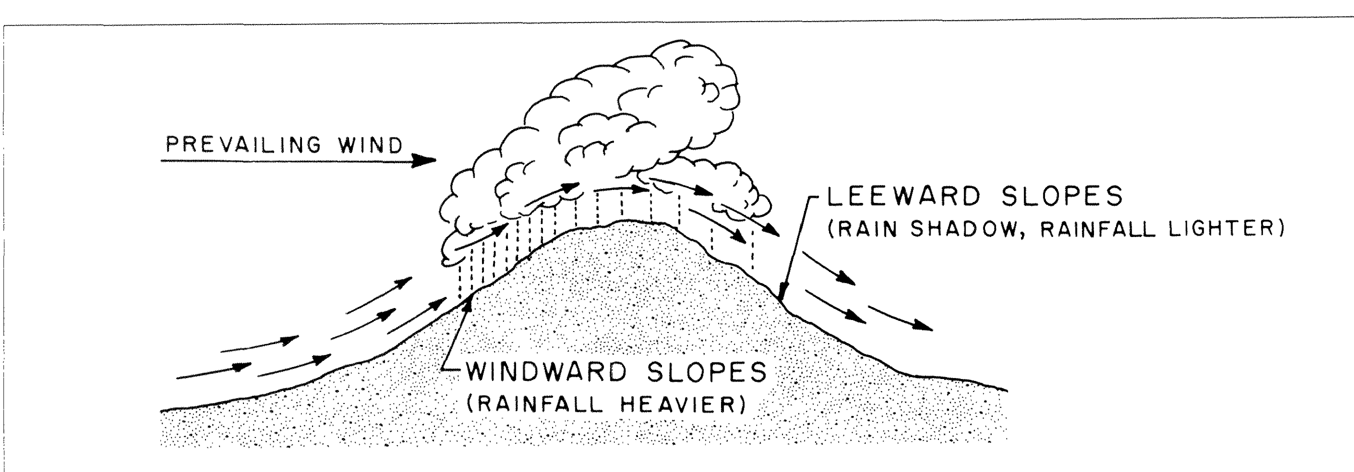

Figure 1–7.—*Rainfall contrasts on windward and leeward slopes (Beard 1949).*

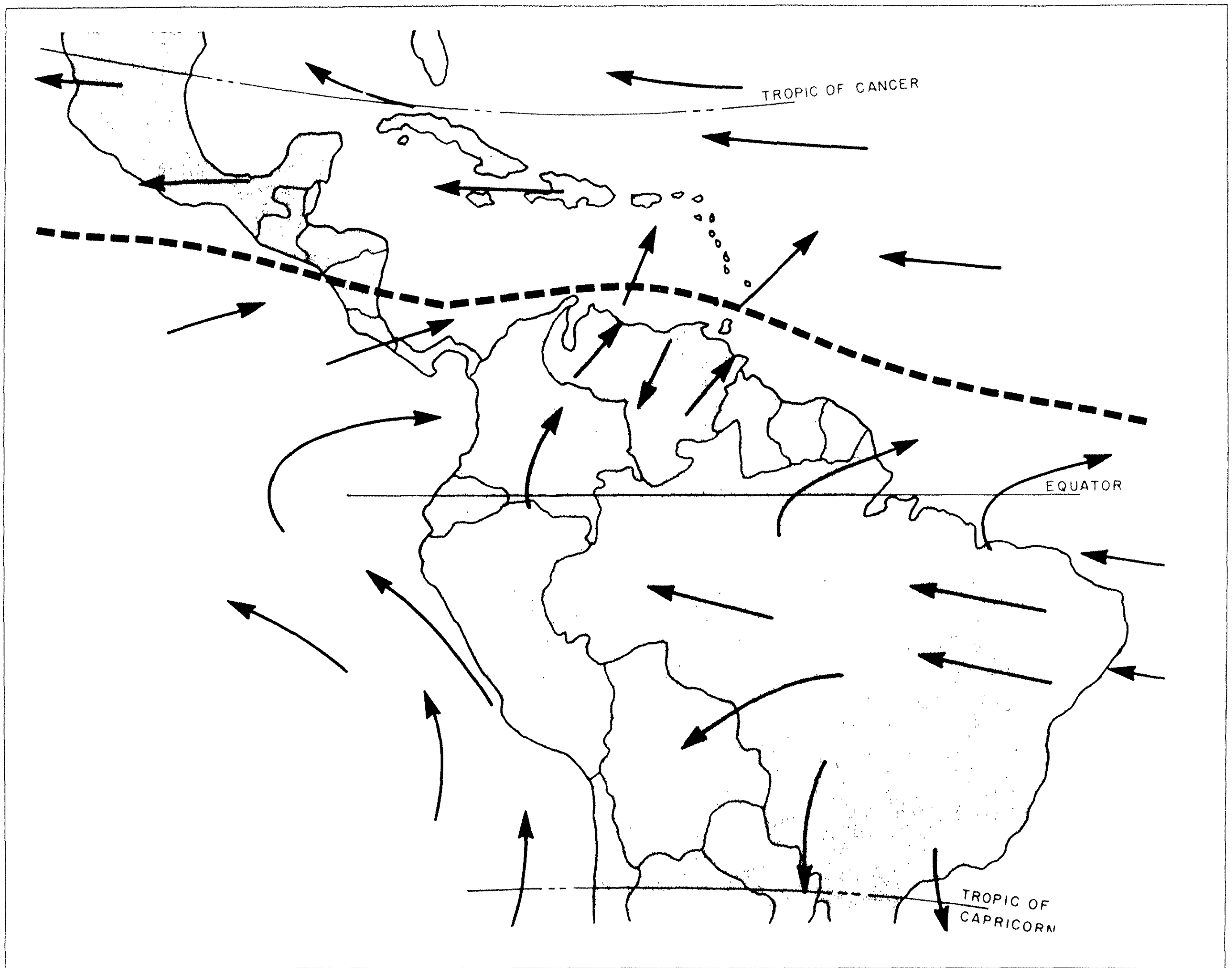

Figure 1–8.—*Surface windflow pattern during the northern solstice; dashed line equals the convergence zone (Garbell 1947).*

In the rain forest-savanna transition zone (Am), leaching is less intense; therefore, acidity is less and base saturation (content of calcium [Ca], magnesium [Mg], potassium [K], or sodium [Na]) is higher. The moist savanna (Aw) soils are leached but may dry to wilting point to a depth of more than 1 m. Acidity ranges from a pH of 5.0 to 6.0 and base saturation from 40 to 60 percent. In the dry savanna (CWa) where rainfall is concentrated within a 5-month period, the wilting point may reach a depth of 2 m. Base saturation rises to between 60 and 90 percent. Both fertile and infertile soils are widespread.

In the semiarid climates where mean annual rainfall is below 60 cm, calcium carbonate is not leached and accumulates in the lower soil horizons. A clearly developed humic topsoil may accumulate. Lithosols are common on slopes, and saline soils are common on low-lying sites.

In areas that are subtropical because of elevations of 900 to 1,600 m (as in central Africa), the zonal soils are humic Latosols. At higher elevations, organic matter increases substantially. In subtropical, humid areas

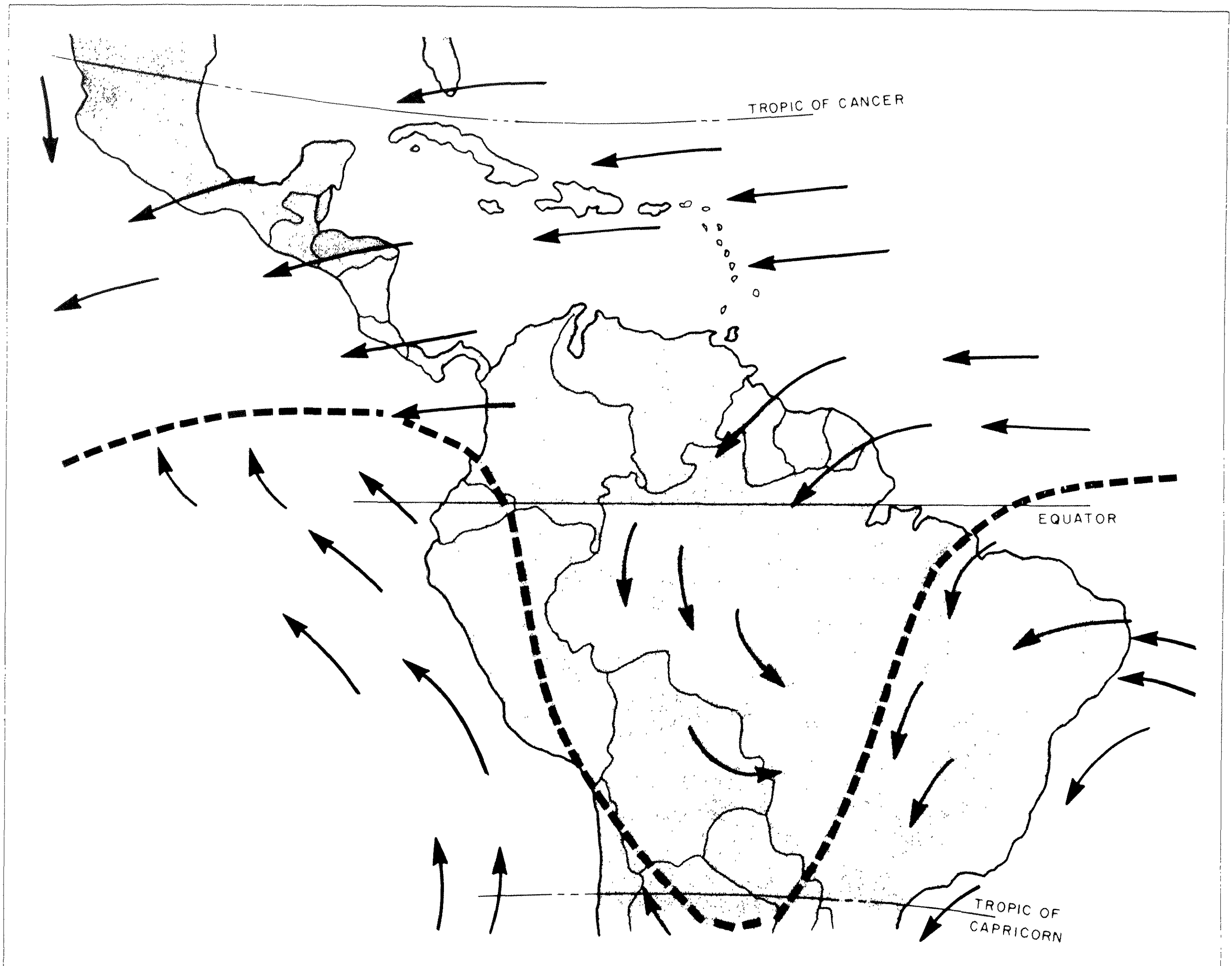

Figure 1–9.—*Surface windflow pattern during the southern solstice; dashed line equals the convergence zone (Garbell 1947).*

adjacent to the Tropics, leached red-yellow podzolic soils are common.

Soil formation in the Tropics is largely related to water and its amount, changes, and movements in the soil. Most weathering and leaching of tropical soils are a result of moisture combined with high temperature.

Rainwater dissolves carbon dioxide from the atmosphere and thus is already a weak solution of carbonic acid before it reaches the earth. Its acidity increases as it comes in contact with the carbon dioxide in the soil air and takes organic substances into solution. As soil acidity increases further, the soil solution becomes an increasingly more powerful leaching agent. Typical soil conditions in the Tropics described below are adapted from Young (1976).

- *Lowland rain forest, free drainage.* Rapid downflow of soil water throughout the year. High rates of weathering and leaching.

- *Lowland rain forest, impeded drainage.* Wet throughout the year. Subsurface has laterally, generally downward throughflow. Conditions conducive to reduction except for intermittent oxidation at the surface.

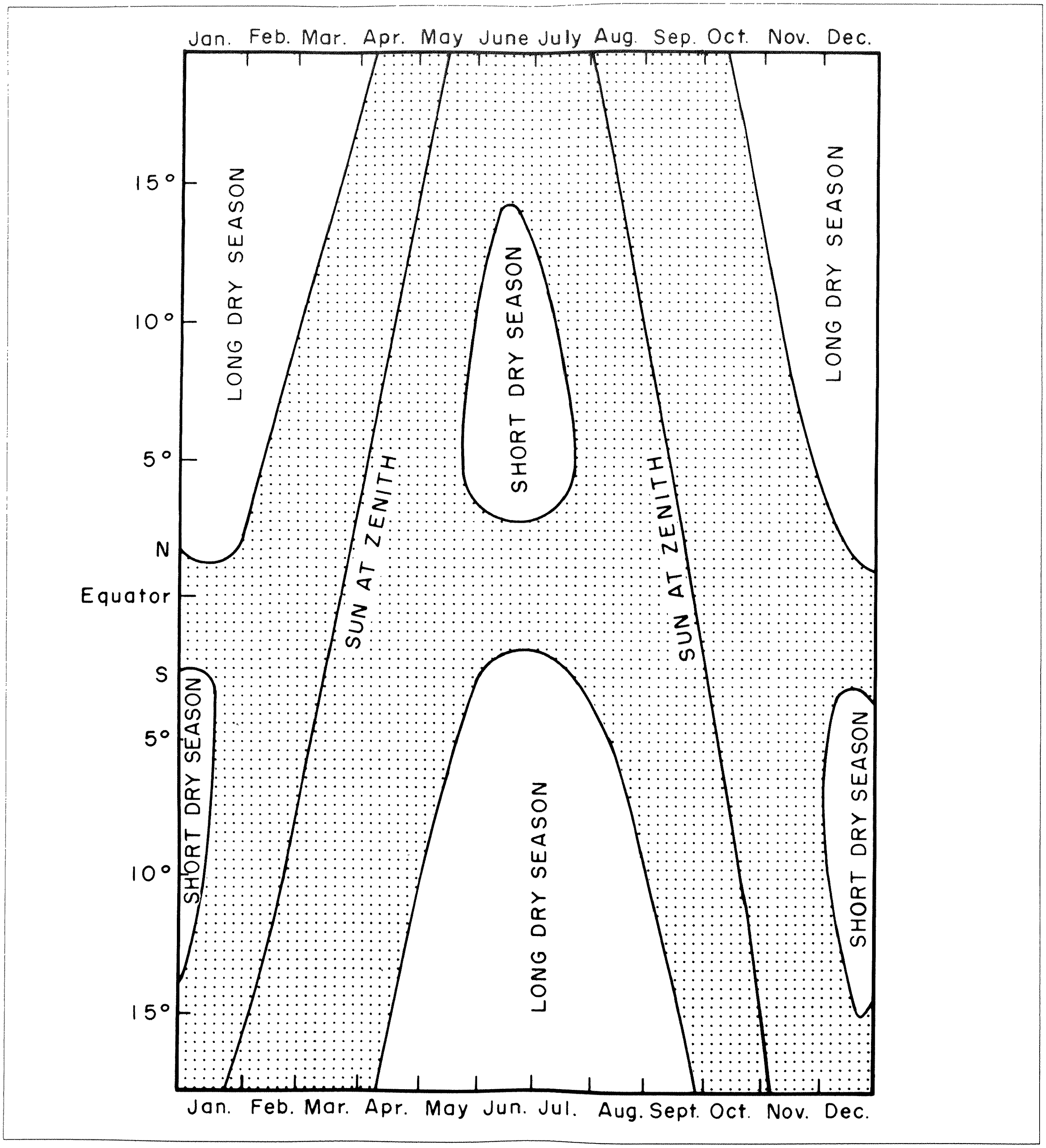

Figure 1–10.—*Wet and dry seasons in the Tropics in relation to latitude (adapted from E. de Martonne, cited by Richards 1952).*

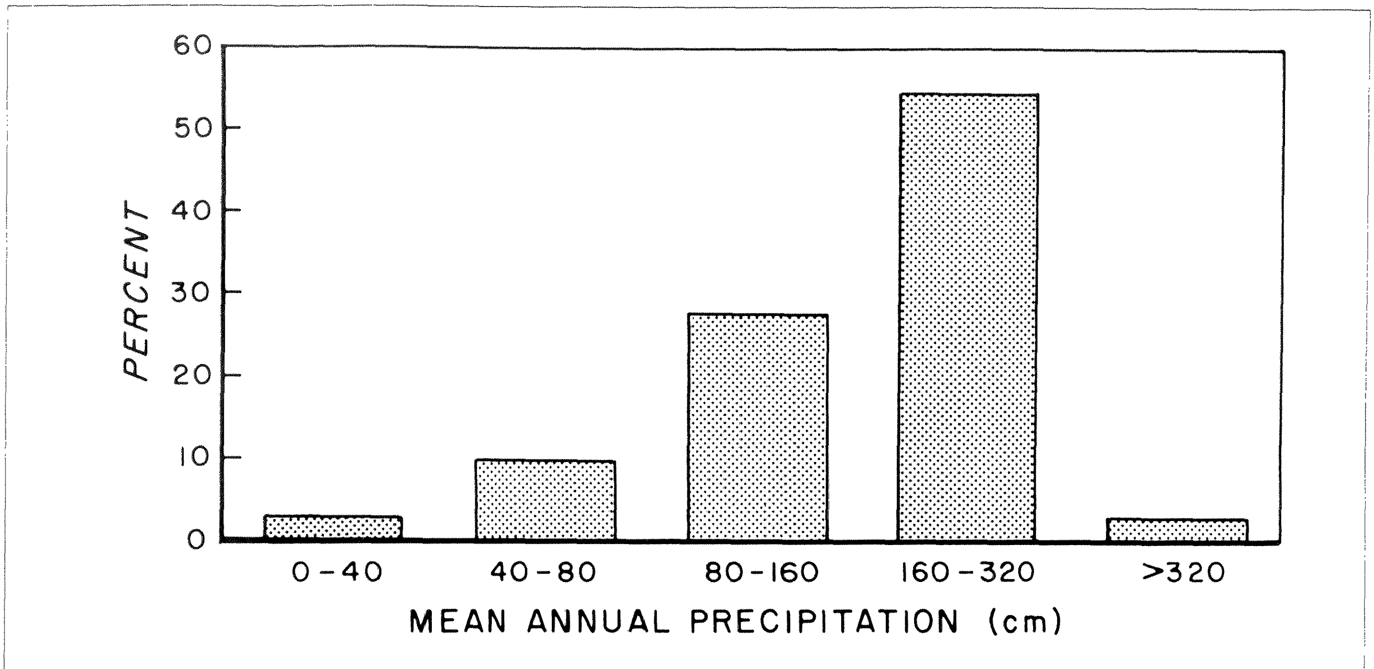

Figure 1–11.—*Land areas of tropical America by precipitation levels (Anon. 1975h, 1979f).*

- *Savanna, free drainage.* Moist during wet season with downward flow. Static in the early dry season and becoming dry 1 to 2 m in depth in the late dry season. Weathering of bedrock is rapid but slowed within the profile during the dry season. Leaching in the wet season alternates with precipitation of dissolved substances in the dry season.

- *Savanna, high water table.* Wet in the wet season and at depth throughout the year. Upper horizons alternately wet and dry. Reduction during the wet season alternating with dry-season precipitation of dissolved substances.

Little is known about absolute rates of soil formation. Both rock weathering and profile development are involved; the latter process is much more rapid than the former. Young (1969) estimated rock weathering sufficient to produce 1 m of regolith (unconsolidated material that overlies solid rock) generally would take 20,000 years but thought rates in the humid Tropics would be higher. Profile development in the Tropics may take place in 100 years or less.

Parent Material. Mineral soils originate from the three classes of rock: igneous, sedimentary, and metamorphic. Igneous rocks have solidified from a liquid state. Sedimentary rocks developed from materials transported and deposited by water or air. Metamorphic rocks are usually of igneous origin, but they have been subjected to such prolonged high pressure and temperature that their characteristics are altered.

Igneous rocks that solidified deep in the Earth are plutonic. Those that solidified en route to the surface are intrusive. Those that solidified after they reached the surface are volcanic. Because all igneous rocks may arise from the same magma (molten rock), their composition is generally similar: they commonly contain quartz (SiO_2) and feldspar (SiO_2, Al_2O_3, and K_2O or Na_2O). The quartz resists weathering as do those feldspars rich in SiO_2.

Sedimentary rocks differ in particle size from coarse sand to fine clay and in composition from calcareous to volcanic materials. Metamorphosis may produce a variety of new minerals. Based on soil parent material, Young distinguishes crystalline and sedimentary rocks and unconsolidated materials. Igneous and metamorphic rocks of similar composition are grouped together, because there is no clear difference in their effect on pedogenesis.

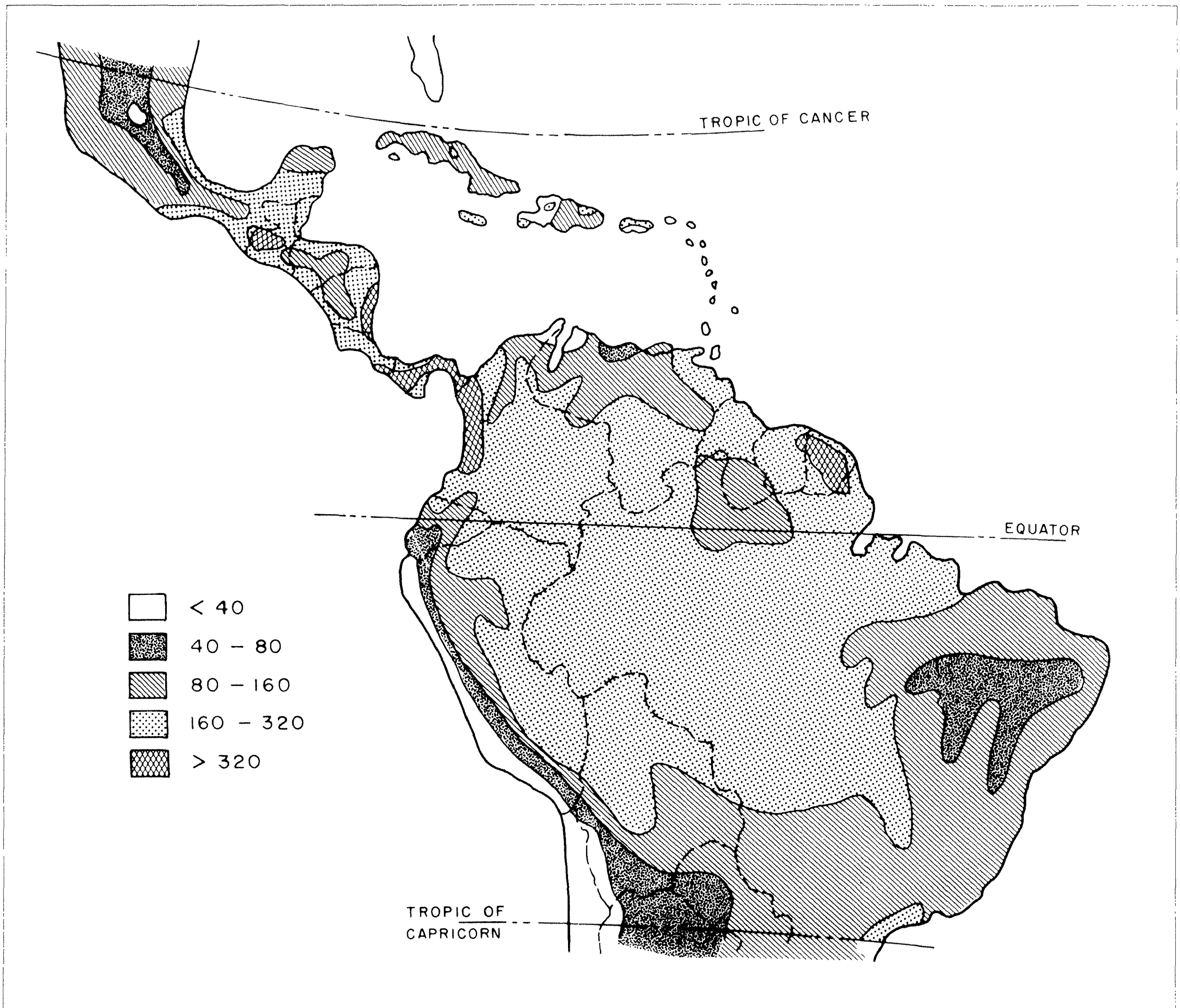

Figure 1–12.—*Mean annual rainfall (cm) in the neotropics (Anon. 1975h, 1979f).*

Rock composition ranks with rainfall as one of the two main causes of soil differentiation in the Tropics. The main variable in the composition of parent material is silica; felsic rocks contain 66 percent or more, intermediate rocks contain 55 to 66 percent, and basic rocks less than 55 percent. Rock composition determines which products are supplied to the soil solution through weathering.

Felsic rocks are a poor source of Ca, Mg, K, iron (Fe), and manganese (Mn). Residues of weathering include quartz and kaolinite; all weatherable minerals are readily dissolved. Basic rocks, in contrast, retain weatherable minerals in the lower parts of the profile, thus providing a continuous source of new weathering products, such as Ca, Mg, and K, to the soil solution. Soils developed from rocks of felsic or intermediate composition are so extensive as to be termed zonal soils.

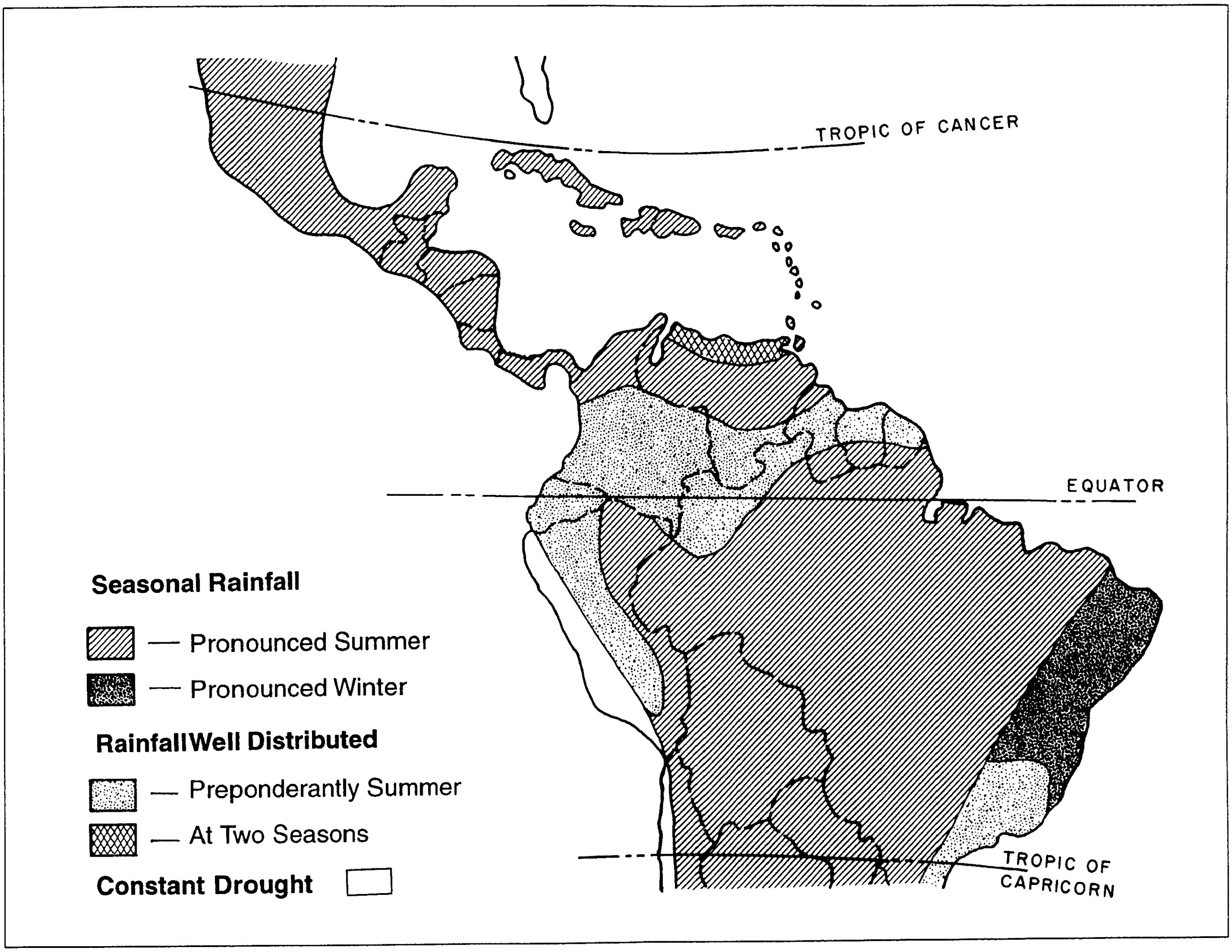

Figure 1–13.—*Seasonal rainfall patterns in tropical America (Biel 1968).*

Limestone soils in the Tropics are intermediate in fertility between the felsic and basic soils. In humid areas, they are generally acid Latosols, whereas in the semiarid zones they generally are Vertisols.

Felsic crystalline rocks are mainly granites and gneisses, the most extensive types of parent material in the Tropics. The resulting soil is either sand or sandy clay. In humid climates, these rocks are low in weatherable materials and high in permeability and are thus subject to strong leaching, which produces an acid reaction and low base saturation. Fertility is low. At the other extreme, basic igneous rocks yield clay soils that retain weatherable minerals. Fertility is adequate to sustain continuous cropping.

Sedimentary rocks weather more slowly than felsic crystalline rocks. Sandstones may give rise to sandy soils. Fine-grained sedimentaries, except shales, weather more deeply. Soils derived from shale have poorer physical but better chemical properties than those from sandstone. They also have higher available water capacity and higher nutrient levels.

Topography not only directly affects soil formation but also influences climate and drainage, which in turn

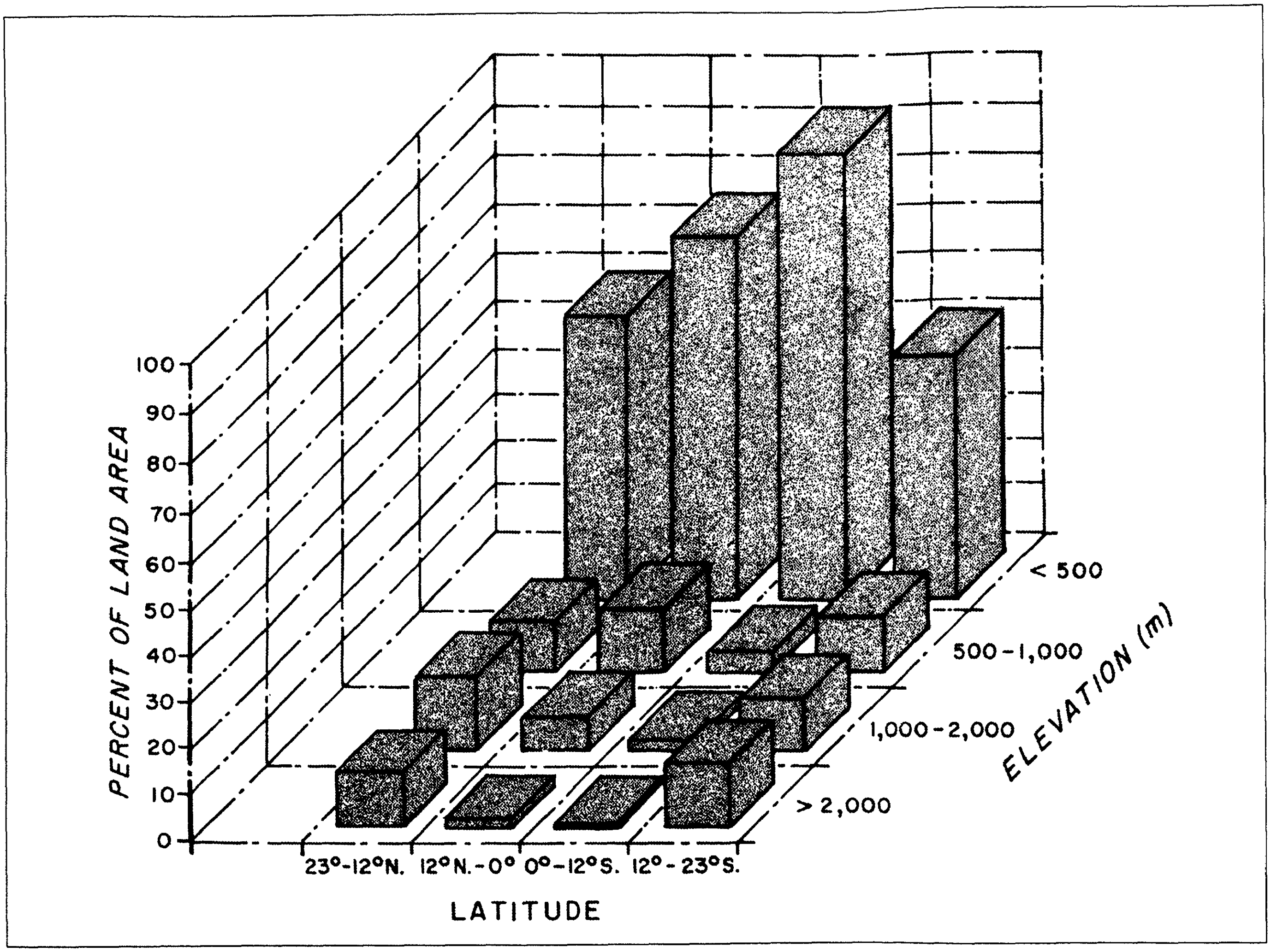

Figure 1–14.—*Percentage of land area of tropical America by latitude and elevation (Anon. 1979b).*

affect soil formation. Temperature change with elevation produces elevational soil zones that differ particularly in organic matter content. Elevation affects rainfall, especially on windward slopes. Relief also has a great effect on soil drainage.

Steepness of slope affects soil formation both directly and indirectly. The steeper the slope the greater the erosive power of water. Apparently the weathering rate is not affected by slope, so the imbalance of weathering and erosion on steep slopes results in thinner soil there than elsewhere. On the other hand, on gentle slopes the longer residence time of the soil may lead to a highly weathered (and thus infertile) surface soil, whereas, on

Table 1–5.—Topography of tropical South America

Topographical type	Area: Millions of hectares	Area: Percent of total land area
Flat, poorly drained	170	21
Well drained		
Slope 0–8 percent	497	61
Slope 8–30 percent	116	14
Slope >30 percent	36	4
Total	**819**	**100**

Source: Cochrane and Sanchez 1981.

the steep slopes, the shorter residence time of the soil means it is less weathered and may contain more minerals. These differences are common knowledge among shifting cultivators, who may get their best yields on steep slopes.

Drainage. Drainage is critical to soil properties. Poor drainage commonly results in the reduction of Fe compounds in the absence of oxygen (O) and their partial reoxidation and precipitation.

Soil water may be free in soil cavities, adhering to soil particles, hygroscopically combined, chemically combined, or in vapor. It enters mostly from above in the form of rainfall and dew, from the side on the surface, or from below by ascent of ground water. Soil water leaves by evaporation, transpiration, or lateral or gravitational flow. Evaporation and transpiration increase generally with rainfall and with saturation deficit of the atmosphere. Under forests, soil moisture 1 m deep or more may be less than on bare land because of draft by the vegetation (Henry 1931, cited by Mohr 1944).

Young (1976) quotes the Food and Agriculture Organization (FAO) Manual on soil drainage classes as follows:

- *Very poorly drained.* The water table remains at the surface for most of the year, and frequently there is standing water. Applied to swamps.

- *Poorly drained.* The water table is at or near the surface for much of the year. Soils exhibit gleying in the topsoil. Applied to sites that, although not swamps, suffer from poor drainage.

- *Imperfectly drained.* Waterlogged for significant periods. Applied to soils with a clearly mottled B horizon. Crops sensitive to drainage impedance cannot be grown.

- *Moderately well drained.* The profile is wet for short periods, and the soil is mottled to some depth. These soils are freely drained for most purposes but show slight indications of temporary impedance.

- *Well drained.* Excess water is removed from the profile freely but not rapidly. No mottling is present.

- *Somewhat excessively drained.* Water drains through the profile as rapidly as added. Applied to sandy soils.

- *Excessively drained.* Water is removed from the profile very rapidly. Applied to stony soils on steep slopes.

Soil Organic Matter. Differences between weathered rock and the soil derived from it (and, in fact, much of soil fertility) may be considered largely biological (Jacks 1963). Organic matter in tropical soils increases erosion resistance and root penetration, augments cation exchange capacity, and constitutes a store of nutrients. The nutrient content and exchange capacities of most tropical soils are largely held in the organic complex within the top 20 cm of mineral soil.

The plant-soil system contains four stores of organic materials: living vegetation, dead vegetation, soil humus, and soil organisms. Carbon (C) is commonly used as a measure of organic matter. About half of oven-dry dead vegetation is C.

Organic-matter content of the soil may remain relatively constant beneath forests, but it is potentially unstable because the rates of humidification of litter and root exudations and of humus oxidation are both rapid relative to net storage in the soil. Nye and Greenland (1960) show that annual cycling rates for humidification and oxidation are each equal to about 2.5 percent of soil humus storage in lowland rain forests.

Young (1976) states that soil organic matter generally varies directly with rainfall and inversely with temperature. He estimates that a topsoil 10 to 20 cm deep contains 3 to 5 percent organic matter in zonal soils under lowland rain forests. Under moist savannas, the organic matter content averages 2 percent and under dry savannas, about 1 percent. Under rain forests, the layer of leaf litter may range in thickness from two leaves to 5 cm. At elevations of 1,500 to 3,000 m, the humic horizon is thicker and may contain 5 to 10 percent organic matter. Organic matter levels of the principal tropical soils compare favorably with those of the same general classes in the Temperate Zone. In many instances, the nitrogen (N) content of tropical soils is greater than that of Temperate Zone soils (Sanchez and others 1982).

Soil organic matter (humus) is supplied from rainwater and the resultant humidification of vegetative litter and root exudations. It is lost through oxidation to the atmosphere, erosion, leaching, and root uptake.

Lowland rain forest soils have topsoil C contents of 1 to 3 percent, or 3 to 9 kg/m^2. The turnover period for soil humus under rain forests is 20 to 50 years. The turnover period for dead litter is less than 1 year, decomposition being 1 to 3 percent per day. Once litter is humidified, however, the loss may be only 2 to 4 percent per year (Nye 1963). For savannas, the turnover period for soil humus is 40 to 50 years.

Both animals and plants affect the soil, but the major impact is from vegetation, primarily dead plant material. Biomass may be 300 to 900 or more tonnes per hectare in tropical rain forests, 60 to 100 t/ha in moist savanna woodlands, and 30 t/ha in dry savannas. Wood may make up 92 to 96 percent of this biomass in rain forests and about 88 percent in savannas. The overall productivity of the vegetation, reflected by turnover rates, is significant to the supply of soil organic matter. Rates range from 30 t/ha/yr in rain forests to 10 t/ha/yr in moist savannas and 5 t/ha/yr in dry savannas. For lowland tropical environments, topsoil organic matter is directly related to these productivity rates. Typical organic matter contents are 2 to 5 percent under rain forests and 1 to 2 percent in the savannas, levels not much different from those of the Temperate Zone (Kanehiro 1978).

Vegetation strongly affects soil moisture. In rain forest climates, leaf litter maintains a stable microclimate at the soil surface favorable to evergreen species. Under savannas and steppes, this cover decreases greatly during the dry season, accentuating the seasonal contrast.

Weathering. Vegetation also increases the weathering rate, modifies N mineralization, and increases fertility as a result of N fixation. Plant remains also increase the activity of soil fauna, which, in turn, affects soil formation.

Soil formation is a slow process, so time is critical. Mohr (1944) recognized five stages of soil weathering:

- Beginning—unweathered parent material
- Juvenile—weathering begun but still much unweathered material
- Virile—weathering more advanced but still much unweathered material
- Senile—unweathered material occurs only sporadically
- End—soil weathered out.

Mohr differentiates chemical from physical soil weathering. The former can occur only in the presence of water. What is dissolved in the water is very important. In nature, water never occurs in pure form. The purest water is rainwater that falls after the initial part of a shower has washed the atmosphere of its acidity. Water containing carbon dioxide is generally acidic; water containing calcium bicarbonate is alkaline. Water emanating from forests in which detritus (loose material such as rock fragments or organic particles) is being decomposed on the surface is generally acidic.

Soil formation is further affected by the predominant direction and velocity of water movement. Three general conditions have been cited (Mohr 1944): (1) continuous downward movement, (2) alternating upward and downward movement, and (3) upward movement. The first two are the most common. One result of such movements is the development of horizons within the soil. Some horizons lose constituents through leaching, whereas others may be correspondingly enriched.

Erosion significantly affects soil formation. The erosive power of water is a function of its speed and volume. Erosion resistance is determined by the weight of soil particles and their cohesiveness. These two factors are inversely related to particle size. Thus, coarse, sandy soils are loose and erosive; clay soils (composed of small, light particles) are cohesive, but once detached, the particles are easily transported by water.

Past human influences on the soils have been less evident in tropical America than in the Eastern Hemisphere. Some of the consequences of exploitation and culture of soil resources have been changes in organic matter content, nutrient levels, reaction, and moisture regime, and increases in runoff, erosion, sedimentation, compaction, salinization, and pollution.

Soil weathering in the Tropics is chiefly chemical and consists of the breakdown of primary minerals and the synthesis of secondary ones. Chemical weathering is inseparably related to leaching because elements released by weathering are subject to leaching and the intensity of leaching affects the types of secondary minerals found.

The ubiquitous presence of organic acids in the soil solution affects the susceptibility of different minerals to weathering (fig. 1–15). At any pH level, leaching tends to be selective (Lucas and Davies 1961). According to

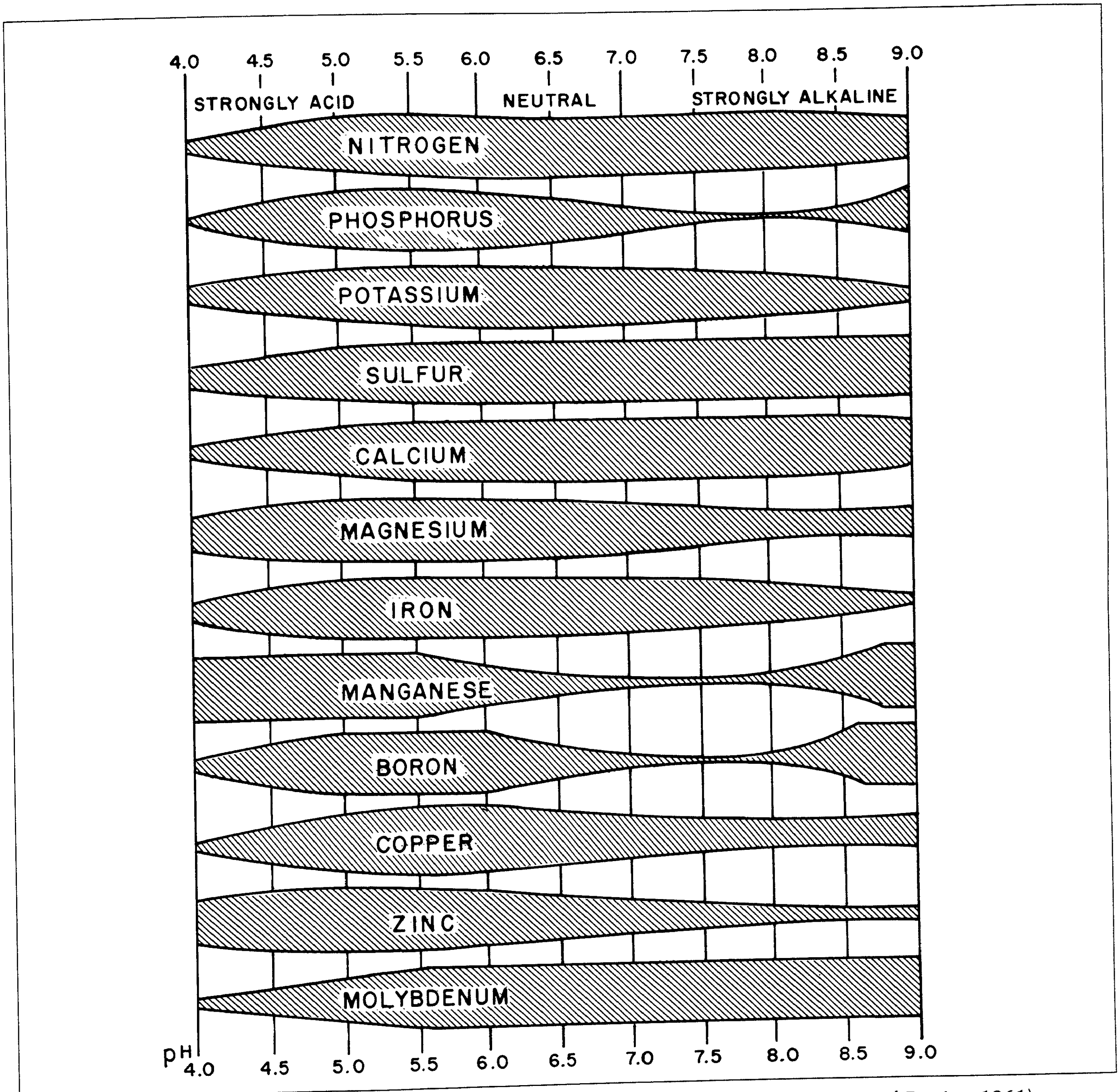

Figure 1–15.—*Influence of soil acidity and alkalinity on availability of plant nutrients (Lucas and Davies, 1961).*

Young (1976), soluble salts (chlorides and sulfates) are 30 to 100 times more mobile than the exchangeable bases (Ca^{2+}, Mg^{2+}, Na^{+}, and K^{+}), which, in turn, are 5 to 10 times more mobile than silica in forms other than quartz, and these are 5 to 10 times more soluble than quartz and sesquioxides.

The soils of the Tropics are predominantly reddish brown or yellowish red. In lowland humid areas, they are high in clay content and low in silt, and the B horizon is blocky in structure. In the rain forest zone, soils are very friable, due to clays consisting almost entirely of kaolinite and sesquioxides. The A horizon of many tropical soils is darker than other horizons because of the presence of humus. Dark soils, however, should not generally be considered rich in humus. Mottled coloring is a common result of drainage impedance. Generally, clay content decreases with elevation and dryness of climate. Savanna areas commonly have a sandy topsoil.

Soil Classifications. The variation in geological history and climate in tropical America has produced a wide variety of soils. The only valid generalization about these soils, other than their common location, is a lack of marked seasonal soil temperature variation.

The following descriptions of the major soil orders of tropical America are taken largely from Aubert and Tavernier (1972) and Sanchez (1976) and are related to groups already described by Young (1976). The percentage of tropical America covered by each soil group is cited by Sanchez (1976) from Drosdoff, based on a map by Aubert and Tavernier (1972).

Oxisols. Oxisols are principally mixtures of kaolin, hydrated oxides, and quartz and are low in weatherable minerals. They are usually deep-red or yellow soils of excellent granular structure and have uniform properties throughout their depth. They are well drained, but low in fertility.

Oxisols occur in humid areas on very old tablelands where weathering products have been protected against erosion for long periods. Oxisols depend mostly on the amount and quality of organic matter for retention of cations. Without added fertilizer, they can support only tree crops, shifting cultivation, or extensive grazing.

Mountain Soils. These soils can vary greatly within short distances because of changes in elevation, relief, parent material, temperature, and moisture.

Inceptisols. Inceptisols are young soils without accumulations of translocated materials other than carbonates and silica. Some Inceptisols are in river floodplains and in areas of rock outcrops. An important subgroup of these soils evolved from volcanic ash into an amorphous clay. When combined with organic matter, they have a high waterholding capacity. At a low pH, these soils may have a low cation exchange capacity. Their potential productivity varies widely; at best, they may be excellent agricultural soils.

Ultisols. Ultisols are soils with subsurface horizons of clay and a low base supply. They are usually deep red or yellow, well drained, with less desirable physical properties than Oxisols but with more weatherable minerals (and thus slightly better fertility, although still low).

Ultisols characteristically form under forest vegetation in climates with slight or pronounced seasonal variations in moisture supply. In the humid Tropics, they have a low cation exchange capacity. Bases not held in the plant tissue are depleted. A few Ultisols contain plinthite, a soft, clayey material that hardens into ironstone if exposed to wetting and drying.

Alfisols. Alfisols have subsurface horizons of clay and a medium-to-high base supply. They are similar to Ultisols except for greater fertility. Alfisols characteristically form under forest or savanna vegetation in climates subject to seasonal droughts when evapotranspiration exceeds precipitation and stored soil moisture is depleted.

Entisols. These recently developed soils have no pedogenic horizons. Included in this classification are rock outcrops, dunes, and alluvial sediments. Entisols range from unproductive sands to periodically flooded alluvial sediments that are among the most productive soils in the world.

Aridisols. As the name implies, these soils are common to dry regions. They are never moist for as long as 90 consecutive days.

Mollisols. Mollisols have nearly black, humus-rich surface horizons and a high base supply. Some are usually moist, others usually dry.

Fertility of Tropical American Soils. According to Sanchez (1976), citing the President's Science Advisory Committee, 51 percent of the soil types in the Tropics are Oxisols, Ultisols, and Alfisols, highly weathered and leached. Another 17 percent are dry sands and shallow soils. Fourteen percent are Aridosols; other soils make up the remaining 18 percent.

The FAO/Unesco soil survey of 1971 showed that more than 8 million km^2 (about 56 percent) of tropical America have soils that may be too poor for farming or grazing but are capable of producing forests. Oxisols are stable aggregates that drain gravitational water as sands do and resist compaction and erosion. However, they may be droughty and highly leached. Ultisols and Alfisols may have a sandy topsoil that is subject to compaction, runoff, and erosion; thus tillage is seriously detrimental, especially on steep slopes.

Organic matter content of tropical Oxisols is higher than the red color suggests. In moist tropical climates, organic C is added and decomposed five times faster than in the Temperate Zone. Organic matter benefits the soil by recycling most of the N and sulfur (S), maintaining cation exchange capacity, blocking phosphorus (P) fixation, improving structure, and forming complexes with micronutrients.

The total P content of a soil reflects the intensity of weathering. In highly weathered soils, organic P may account for more than half the total soil P. Most tropical Oxisols and Ultisols are too deficient in P for cropping. Phosphorus management is complex in soils with a high fixation rate. Sulfur deficiencies are also widespread throughout the Tropics, especially in Oxisols, Ultisols, and Alfisols, and in young volcanic and sandy soils.

In forested areas, the soil and forest may have a remarkably closed nutrient cycle, producing lush vegetation even on soils of low native fertility. In Mexico, Central America, and the Caribbean, soils of fair-to-good natural fertility were found to outnumber soils of low natural fertility (Anon. 1971c, d). The main limitation to productivity in this region is steepness. However, many lowland areas are grossly underutilized. With minor adjustments in traditional practices, these soils can be much more productive.

In South America, soil is generally low in natural fertility (Anon. 1971a). More than 90 percent is too poor for farming. Approximately 50 percent of the continent's soil is Ferralsols (Oxisols), Acrisols (Ultisols), and Arenosols that are low in cation exchange capacity and exchangeable bases. About 20 percent of the continent is so dry that farming without irrigation is risky or impossible. Ten percent is poorly drained, and another 10 percent is composed predominantly of Lithosols on steep slopes.

Forests

Tropical America's climate and soils are conducive to the natural development of forests. Ford-Robertson (1971) defines forests as "plant communities predominantly of trees and other woody vegetation, growing more or less closely together." The definition of trees from the same source excludes shrubs, which, although perennial and woody, generally lack "a single well defined main stem." Lesser classes of forests include scrub—areas of "small or stunted trees and/or shrubs, generally of unmerchantable species," woodland—areas where trees are characteristically short-boled relative to the depth of their crowns and form only an open canopy, tropical savanna woodland—areas with an undergrowth mainly of grasses, and tree savanna—areas where the trees are only irregularly scattered (Ford-Robertson 1971).

Vegetation Genesis. The origin of forests in tropical America is a response to the geological changes that formed the region. These are described in appendix C.

During the glacial period (21,000 to 13,000 years ago), the vegetational belt of the Andes was lowered by as much as 1,500 m because of cool, dry conditions, when the mean temperature was possibly 6 to 7 °C lower and precipitation less than half that of the present day. By 10,000 years ago, however, forests had ascended to at least 2,850 m in elevation. By 6,000 years ago, the temperature had risen to possibly 2 °C higher than it is today, so species of *Cecropia* and *Acalypha* grew several hundred meters above their present upper limit. About 3,000 years ago, the temperature fell to the present level, and the forests again receded below 2,850 m in elevation.

Concurrent with the cooling that began 3,000 years ago, grasslands in the western Llanos of Colombia were apparently being invaded by *Byrsonima spp.* and other forest plants (Wijmstra and van der Hammen 1966). Studies in the lower Magdalena Basin (Wijmstra 1967) indicate significant changes in precipitation in the upper or lower watershed during the past 2,000 years. From 1100 to 1500 A.D., forests and marshes were being replaced by savannas with *Byrsonima, Cecropia, Ficus,* and genera of Ulmaceae. Precipitation cycles may have been as short as 250 years.

Evidence of significant vegetational change during glacial periods has also been found in Central America

(Graham 1973, Martin 1964). Some 36,000 years ago, the forests in Costa Rica were 650 m lower, and paramo (moor) was found at 2,400 m instead of *Quercus* and *Alnus*. Some of the tree species now growing in the uplands were apparently then near sea level.

Glacial-period recession and interglacial advances of the Guiana coastline also were significant in the development of present-day forests of that region. Pollen diagrams from near Georgetown, Guyana, (van der Hammen 1963; van der Hammen and Wijmstra 1964; Wijmstra 1969, 1971) show sequences of *Rhizophora*, a seacoast mangrove genus; *Avicennia*, a landward mangrove genus; fresh water swamp trees; and upland vegetation such as species of *Byrsonima* and *Curatella*.

Fragmentary evidence from the southern Amazon Basin (van der Hammen 1972, 1974) indicates that an area of Rondonia now densely forested was open savanna some time during the past 10,000 years. All current equatorial rain forest areas seem to have been strikingly different 14,000 to 20,000 years ago (Flenley 1979). Mountain vegetation was of types now found at higher elevations, and lowland vegetation was of types typical of areas with a pronounced dry season.

Past hypotheses to explain the richness of the biota of the Tropics have leaned heavily on a presupposed constancy of a warm, moist, favorable climate. Current knowledge, however, suggests that, in terms of microclimate at any one location, such constancy must have been the exception. Pollen findings in the region show no evidence that forest communities have been stable for as long as 500 years, which is, indeed, no longer than the lifespan of some of the present-day trees.

The rain forest, therefore, has not been a paragon of stability. Its great diversity cannot be explained by long-term stability because these forests have existed in a state of equilibrium with their environment at most only a few tree generations (Flenley 1979). So the wealth of species is now explained as a result of—rather than in spite of—past environmental changes (Vuilleumier 1971).

Amazon biota illustrate this point. Although the Amazon flora were derived from families and genera that occur outside the region, most species are confined to Amazonia (Prance 1978). This internal speciation is attributed mainly to the succession of environments during the glacial period. As recently as 15,000 years ago, there was a significant climate difference between the uplands and the valleys of the region during warm periods. Savannas that are now discontinuous but have common genera (such as *Byrsonima* and *Curatella*) bear witness to widespread savannas of recent origin (Prance 1978). Speciation is believed to have been favored by the isolation of humid mountain forests and dry valley savannas.

Forest Extent and Location. The distribution of forests in tropical America has been changing continually over long periods in the past, but the rate of change has been almost imperceptible since the "discovery" of America. So, the extent and location of areas that, without human interference, would be forested can be determined from current climatic and edaphic conditions. The extent and location of natural forests also indicate the geographic limits within which forest growth continues to be suitable ecologically and, consequently, where forests would appear to be one rational land use.

Nonforested areas of the region (fig. 1–16) include the Mexican highlands, grassland savannas and marshes, the Llanos of the Orinoco, the Guiana highlands, the campos, the Matto Grosso swamps, the Andean uplands, and the Pacific coast of South America (Hueck 1972). These areas have not borne forests in recent years and do not appear capable of doing so, at least not without the environment being "made over" at great expense.

At least 70 percent of tropical America is environmentally suited for some type of forest. The largest consolidated natural forested area of the American Tropics is the Amazon Basin, an area of 6 million km^2, 98 percent of which was forested when European explorers arrived (Pires 1974).

The FAO forest inventory (Anon. 1993b) recognizes six forest formations: rain forest, moist deciduous, dry deciduous, dry, desert, and montane. Table 1–6 presents the 1990 inventory in these categories. The two deciduous zones and the dry and desert areas have been combined. It is seen that the forests of tropical America make up slightly more than half the tropical forests of the world. About a third are in Africa, and less than 20 percent are in the Asia-Pacific region. Of the tropical rain forests of the world, 63 percent are in America. Within tropical America, 87 percent of the forests are in South America. About half are classified as rain forests; these and deciduous forests making up 86 percent of the total. Forests in 1990 covered only 56 percent of the zones

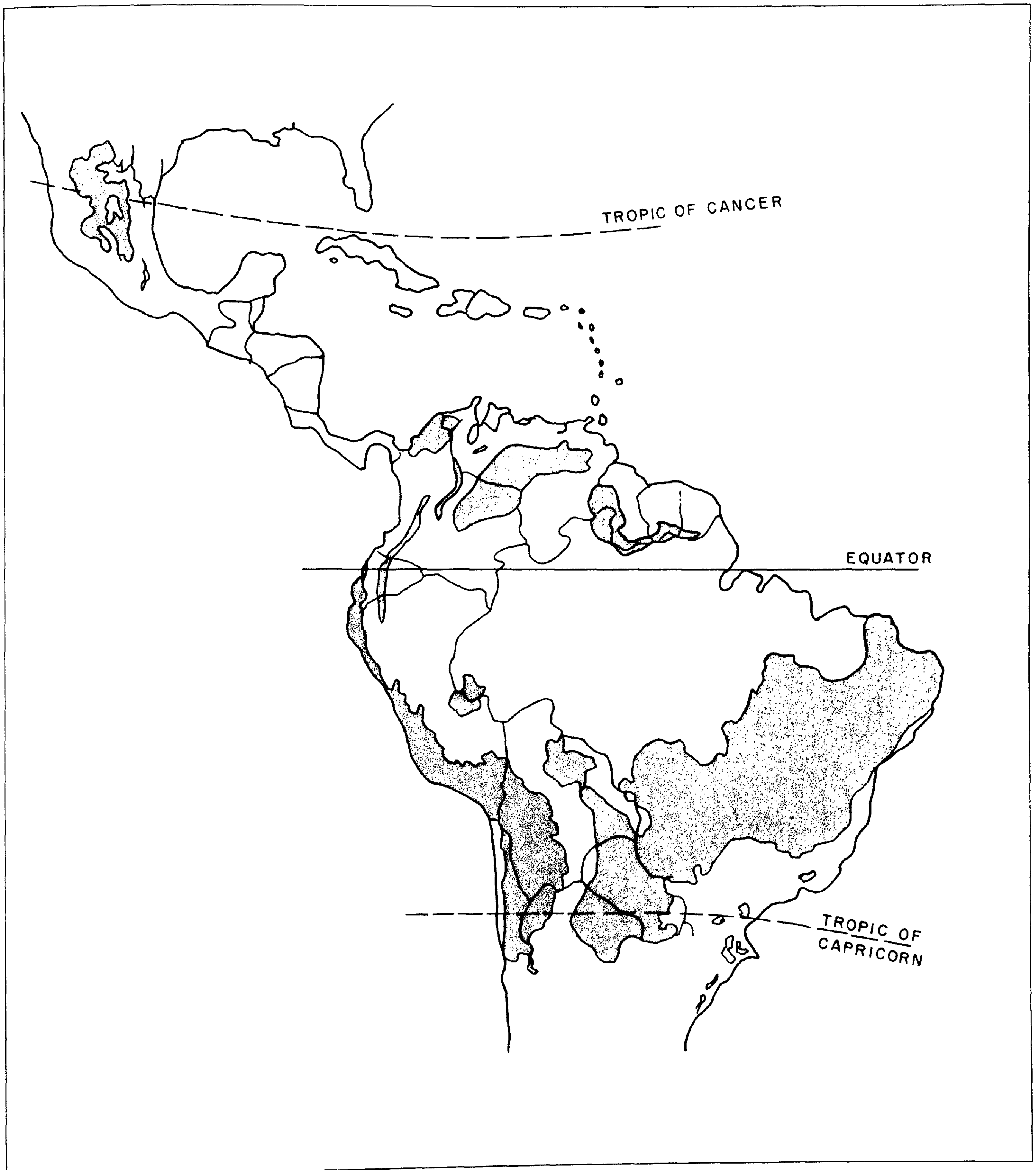

Figure 1–16.—*Shaded areas on map indicate portions of tropical America, including savannas, that are naturally without forests.*

Table 1–6.—Tropical forest formations by zones (thousand km²)

Zone	Rain forest	Moist and dry	Dry/desert	Montane	Total
Central America	124	152	22	383	681
Caribbean	357	85	0	29	471
South America	4,062	3,155	5	807	8,029
Tropical America (total)	**4,543**	**3,392**	**27**	**1,219**	**9,181**
Africa	866	3,437	620	353	5,276
Asia/Pacific	1,774	829	31	472	3,106
Tropics (total)	**7,183**	**7,658**	**678**	**2,044**	**17,563**

Source: Anon. 1993a, 1993c.

listed by FAO (table 1–6), suggesting that at one time the rain forests and deciduous forests together covered 92 percent of the land.

The present forest area of the region reflects centuries of human occupancy, beginning possibly as early as 20,000 years ago. In 1492, the region was at least partially settled, ranging from a population of more than 20 million in Mexico to a sparse population (which may have been denser earlier) in the Amazon Basin (Bennett 1975). Shifting cultivators temporarily removed wild vegetation from vast areas of tropical America, creating grasslands and vegetation mosaics. However, the native population decreased drastically in the 150 years following arrival of the Europeans, allowing forests to reclaim many areas. More recently, the trend reversed again and deforestation has accelerated due to increasing numbers of landless rural people and the expansion of beef production.

The FAO forest inventory (Anon. 1993b) shows one impact of past human intervention into tropical forests, that of deforestation (table 1–7). It is seen that 44 percent of the former forests have been removed. Of the former montane forests only 28 percent remains. Forest loss has been even greater in Africa and the Asia-Pacific region. The forest areas remaining in 1990 (Anon. 1993b) are listed in table 1–8.

Lanly and Clement (1979) inventoried "operable" forests, those containing commercially desirable wood accessible enough to be harvested. They estimated that 5.13 million km², or 78 percent of the region's closed forests fit this definition in 1975. Of this amount, 85 percent is in South America, and 5 percent is coniferous.

Environmental Influences of Forests. Tropical forests produce more water vapor and carbon dioxide than forests outside the Tropics because infrared emission, saturation vapor pressure, and plant productivity increase with temperature. In contrast, albedo and emission of some pollutants from tropical forests are less than the global mean. Of all these, the emission of carbon dioxide, which persists in the atmosphere, probably has the most influence outside the Tropics. However, the radiation that vaporizes water in the Tropics is also transported outside the region in the form of latent heat, becoming part of the global thermal balance after the water vapor condenses.

The water vapor produced within the humid Tropics contributes greatly to the global hydrological balance. The hydrological cycle is the disposal of rainfall through vegetation to the soil, streams, lakes, and the ocean and the return to the atmosphere of the moisture through evaporation and transpiration (fig. 1–17; Holzman 1941).

Some 58 percent of the global water vapor comes from the 37 percent of the Earth's surface within the Tropics (Baumgartner and Reichel 1975). Of the water vapor from the region, 15 percent arises from the 30 percent of the surface that is land and 85 percent from tropical seas. Tropical land surfaces supply about 9 percent of the world's water vapor (Baumgartner and Reichel 1975).

The moist Tropics receives three times the global average annual precipitation of 75 cm. Similarly, evapotranspiration from tropical vegetation is nearly three times the global average (120 cm versus 46 cm). Annual runoff from tropical land averages 88 cm as compared to 27 cm for the world as a whole.

Table 1-7.—Annual tropical deforestation, 1981–90

Region	Rain forest	Deciduous	Dry/ desert	Montane	Total	Area per 1,000 people
	Thousands of hectares					
Central America	240	277	51	544	1,112	10.6
Caribbean	59	43	0	23	125	3.8
South America	1,639	3,463	12	1,055	5,172	27.9
Tropical America (total)	**1,938**	**3,786**	**63**	**1,622**	**7,409**	**20.6**
Africa	471	3,103	327	289	4,100	9.7
Asia/Pacific	2,162	1,122	32	584	3,900	2.8
Tropics (total)	**4,541**	**7,921**	**422**	**2,525**	**15,409**	**7.0**
	Percentage of deforestation in 1985					
Tropical America	0.3	0.3	2.1	1.2	0.8	
Global Tropics	0.6	1.0	0.6	0.9	0.8	

Source: Anon. 1993a.

The major rivers of the region, the Amazon and the Orinoco, carry 20 percent of all surface water discharge of the Earth (Anon. 1978a). Some parts of the uplands of tropical America receive as much as 600 cm of rainfall annually, 500 cm of which runs off; the rest is dissipated through evapotranspiration. The Amazon Basin receives an average of about 350 cm of precipitation, discharges 200 cm, and evapotranspires 150 cm (Anon. 1978a).

Tropical forests are also significant in the world's carbon balance. The natural forests of the Tropics were estimated in 1990 to average 169 t of biomass per hectare (Anon. 1993b). For tropical America the average is 185 t/ha. Tropical forests contain 30 percent or more of the carbon dioxide contained in the world's atmosphere and about a sixth of the world's organically bound C (Anon. 1978a). The carbon balance in the biosphere is a product of (1) assimilation and fixation of carbon dioxide by plants and (2) release of carbon dioxide by respiration of living organisms and oxidation (burning) of inflammable organic remains. Tropical forests fix some 15 to 20 billion tonnes of C annually (Lieth and Box 1972, Woodwell 1970), at least 25 percent of the Earth's total (Bolin 1970). Through photosynthesis they release some 55 million tonnes of O per year, an amount presumably equaled by respiratory consumption (Brunig 1971).

The influence of tropical forests on climate cannot be reliably measured yet because changes in atmospheric composition cannot be predicted and forest influences cannot be correlated with structural or site properties or the productivity of various forest types (Anon. 1978a). Far-reaching global influences of tropical forests on climate have been suggested in simulation studies by Potter and others (1975). Between latitudes 5° N. and 5° S., forest land produces much lower albedo (0.07 versus 0.25), less runoff, more evaporation, slightly higher surface temperature and precipitation, greater absorption of solar energy, greater convective activity, more warming of the middle and upper tropical troposphere, lower tropical lapse rates, and higher global temperatures than deforested land. Also, tropical forests induce part of the precipitation that falls as far away as latitude 85° N. and 60° S. (Anon. 1978a).

What effect deforestation of the Amazon Basin would have on the atmosphere is not clear (Newell 1971). It might reduce the available potential energy and heating at middle atmospheric levels at low latitudes. This could counteract the "greenhouse effect" expected if the carbon dioxide content of the atmosphere rises and constrains radiation outward from the earth.

The climatic effects of forests are chiefly local. Forests efficiently absorb visible and infrared radiation. Their reflectivity is 5 to 10 percent lower than that of other soil covers. The high energy intake of forests is expended primarily in evapotranspiration. Water vapor cools the

Table 1–8.—Natural forest cover in the Tropics, 1990

Country or continent	Total forest area (thousand ha)	Percentage of land area	Forest land per capita (ha)
Central America			
Costa Rica	1,428	28	0.5
El Salvador	123	6	—[a]
Guatemala	4,225	39	.5
Honduras	4,605	41	.9
Mexico	48,586	26	.5
Nicaragua	6,013	51	1.6
Panama	3,117	41	1.3
Total	**68,097**	**28**	**.6**
Caribbean			
Antigua and Barbuda	10	22	0.1
Bahamas	186	19	.7
Belize	1,996	88	11.0
Cuba	1,715	16	.2
Dominica	44	59	.5
Dominican Republic	1,077	22	.2
French Guyana	7,997	91	86.9
Grenada	6	16	.1
Guadeloupe	93	55	.3
Guyana	18,416	94	17.7
Haiti	23	1	—[a]
Jamaica	239	22	.1
Martinique	43	40	.1
Puerto Rico	321	36	.1
St. Kitts and Nevis	13	37	.3
St. Lucia	5	7	—[a]
St. Vincent	11	27	.1
Suriname	14,768	95	36.6
Trinidad and Tobago	155	30	.1
Total	**47,118**	**68**	**1.4**
South America			
Bolivia	49,317	46	6.7
Brazil	561,107	66	3.7
Colombia	54,064	52	1.7
Ecuador	11,962	43	1.1
Paraguay	12,859	32	3.0
Peru	67,906	53	3.0
Venezuela	45,690	52	2.3
Total	**802,905**	**60**	**3.3**
America	918,120	56	2.3
Africa	527,586	27	1.3
Asia/Pacific	310,597	35	.2
Total (continents)	**1,756,303**	**37**	**.7**

Source: Anon. 1993a.

[a]Less than 0.05 ha per capita.

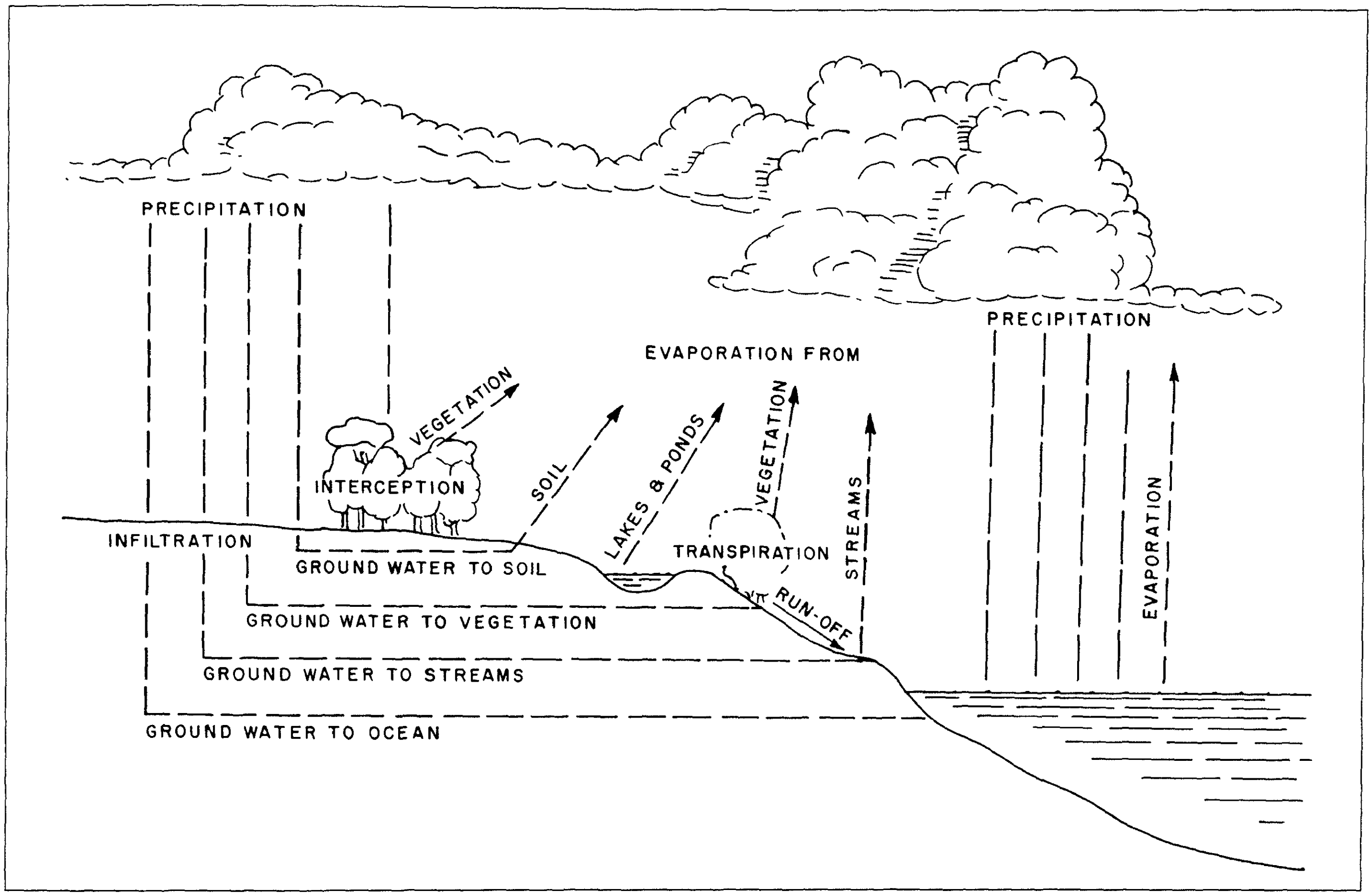

Figure 1–17.—*The hydrological cycle (adapted from Holzman 1941).*

air above forests, thus reducing convection. The water balance of the Tropics is sensitive to latitude. For the outer Tropics, annual evapotranspiration averages 65 cm, or 76 percent of the precipitation. For the equatorial Tropics, annual evapotranspiration averages 109 cm, or 62 percent of the precipitation.

At least as important to plant life as the amount of precipitation is its seasonal distribution. In most of the Tropics, the dry season coincides with the cooler months. The difference between rainy and dry seasons is more pronounced inland, especially on plains, than it is along the coasts and on the mountains. Most deserts within the Tropics occur at the borders and are tropical continuations of extensive subtropical deserts. The existence in the Tropics of both ombrophilous plants (requiring continuous moisture) and ombrophobious plants (not requiring continuous moisture) is significant to the selection of species for forest production. Ombrophobious species may survive in constantly moist climates, but they generally grow slowly except in open, sunny situations. Many of these species have delicate, pinnate leaves.

Insolation (solar radiation received) is as important as atmospheric temperature to living organisms, particularly in continental dry areas. However, the effects of insolation are especially important in humid areas because stomata remain open, through which moisture continues to be released. The high insolation in the Tropics results in shade flora that are distinct from flora that grow in direct sunlight.

Ferns (Polypodiaceae) are most abundant in humid tropical forests, especially in mild, cool, mountain climates. Conifers are also generally found on high mountains outside lowland tropical climates.

Monocotyledons are prominent in tropical vegetation. In dry areas, palms (Palmae) may be widely scattered, but in swampy areas they may grow in dense groves.

Bamboos (Gramineae) are common, growing in pure stands, scattered among other trees, or comprising part of the undergrowth. The Araceae, including fleshy vines such as *Philodendron*, are common in wet forests, as are the Scitamineae, including *Musa* and *Heliconias*. Other plants showing great diversity from place to place are the orchids (Orchidaceae) and bromeliads (Bromeliaceae).

The occurrence of several orders of dicotyledons reflects variations in the vegetation within the Tropics. The Amentaceae are mostly in the higher mountain regions. The Polygoninae, including the Piperaceae, are limited to the warmer and wetter parts of the Tropics. The Magnoliaceae of the order Polygoninae, important in the Temperate Zone, are limited in the Tropics to high mountains. The Citiflorae, including families such as Clusiaceae, Ochnaceae, and Dipterocarpaceae, are limited to the warm Tropics. Other groups exclusively warm-tropical are the Columniferae, with the Bombacaceae and Sterculiaceae, and the Terebinthinae, with prominent families such as the Meliaceae, Burseraceae, and Anarcardiaceae. Among the Aesculinae, the Malpighiaceae are limited to the warm Tropics. Of the Umbelliflorae, some families, such as Umbelliferae and Cornaceae, occur only in the highlands, whereas the Araliaceae also grow in the lowlands. Of the Saxifraginae, the Cactaceae are prominent in dry regions but occur also in wet areas as epiphytes or lianas. The Myrtiflorae are exclusively warm-tropical but include species of the uplands (Melastomataceae) and some in tidal swamps (Combretaceae and Rhizophoraceae). Of the Rosiflorae, some families, such as Chrysobalanaceae, are exclusively warm-tropical in distribution, whereas others (Rosaceae) are limited to the mountains. The Leguminosae include trees, shrubs, herbs, and climbers, some in humid and others in dry regions. Other orders preeminently warm-tropical are Diospyrinae (Ebenaceae and Sapotaceae), Tubiflorae (Cordieae), Personatae (Bignoniaceae), Labiatiflorae (Verbenaceae), and Companulinae (Rubiaceae).

Schimper (1903) recognized not only a general tendency of plant groups to segregate by broad climatic zones within the Tropics but also the effect of seasonal climatic changes on plant growth. He noted that plants experience alternating periods of repose and activity relative to certain functions. Where the climate is not seasonal, the alternation of rest and activity results from internal causes. Even evergreen woody plants in continuously wet climates exhibit alternative periods of rest and activity.

Where seasonal climatic differences are marked, flowering coincides less with the season of the year than with the climatic season. During most of the flowering period, vegetative development is retarded. Where there are dry seasons, woody plants blossom most abundantly during or immediately after the dry spell.

Leaf fall among woody plants is extremely variable, even in seasonal climates. Some plants lose their foliage before the end of the rainy season. Some shed their leaves at the beginning of the dry season. Others do so gradually during several months. Still others remain in full leaf until the new leaf buds open. And mixed among these may be evergreen trees never totally out of leaf.

Schimper (1903) observed that the influence of soil character on the differentiation of flora is much more pronounced in periodically dry regions than in constantly humid ones. He recognized that paucity of alkali, lime, P, Mn, and S—all essential to vegetation—is widespread in tropical soils. He further noted that in seasonal climates the most drought-resistant forest types—thorn-forest, thorn-bush, and thorn-scrub—develop on calcareous soils.

Schimper also pointed out that hygrophilous evergreen forests develop along the shores of lakes and rivers in regions that elsewhere are grasslands or xerophilous forests. He distinguished between open vegetative growth along rocky and sandy shores and littoral woodlands (mangroves) above and below high tide.

Appendix D presents the development of a number of attempts to classify and describe tropical vegetation. Each classification has some limitations. Each is an attempt to quantify differences between forest types in mathematical or physiognomic terms. None reflects significant differences with precision. For purposes of forest management, a classification framework at the formation level, within which edaphic and compositional variants exist, is precise enough to predict more widespread applicability of results from place to place. Until something better is derived, Holdridge's life zones (1967) may be as precise as is needed, provided edaphic variants are recognized and described.