Chapter 1

The Natural Environment of the Tropics

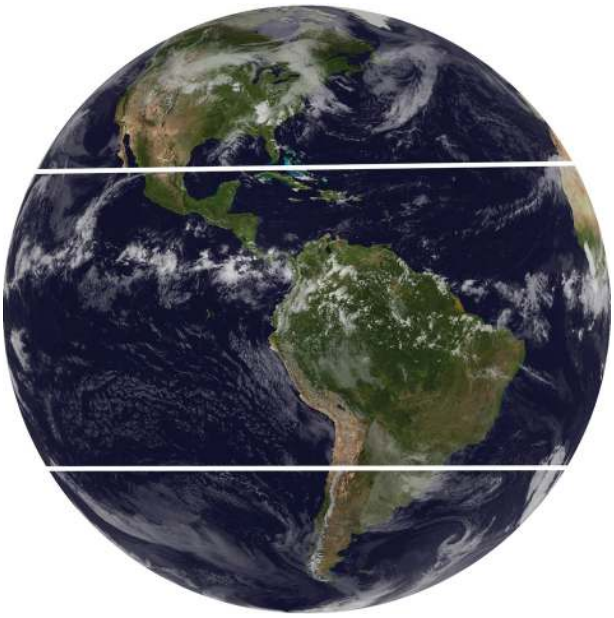

Fig. 1.1 The western hemisphere tropics. Heavy lines show the Tropic of Cancer (23.5° N) and the Tropic of Capricorn (23.5° S). Source: NOAA Environmental Visualization Lab (NOAA National Centers for Environmental Information 2016)

The purpose of this chapter is to provide a framework of the biophysical environment of the tropics. There have been major changes in emphasis since the first edition was published 40 years ago. At that time, I looked at the tropical environment almost exclusively in terms of increasing food production to feed a rapidly growing population. While doing my doctoral research in the Philippines in the late 1960s I never heard the terms climate change, biodiversity, or ecosystem services while working at the University of the Philippines at Los Baños, the International Rice Research Institute (IRRI) and Cornell University. Things have changed for the better. Soil science in the tropics has broadened to encompass tropical ecology as well as tropical agronomy.

1.1 The Tropics Defined

The geographic definition of the tropics includes that part of the world located between 23° 28′ north and south of the equator, that is between the tropic of Cancer and the tropic of Capricorn (Fig. 1.1). Because the tilt of the Earth's axis has the same angle, these latitudes are the limit of the Sun's apparent migration to the north or south of the zenith. The tropics are the only part of the world where the Sun passes directly overhead, receiving more energy than the temperate and boreal regions.

The tropics comprise 38 percent of the Earth's land surface (approximately 5 billion hectares) and half of the world's population, about 3.6 billion people in 2013 (according to the FAOSTAT statistics database [fao.org/faostat]). A total of 124 countries and territories lie wholly or mostly in the tropics. They include most of the "developing" countries except those in the Middle East, North Africa, the former Soviet Union, China, Mongolia, North Korea, Pakistan, Afghanistan, Bhutan and Nepal.

The literature is full of attempts to quantify precisely the tropical versus extra-tropical parts of the world. The concept used in this book is the strictly geographical one, which includes the cold tropical highlands as well as the hot lowlands. Like any quantitative geographical definition, it loses meaning at the boundaries because changes are gradual. The tabular data presented in this book follow the latitudinal definition but are based on entire countries. Thus, parts of northern India, northern Bangladesh, northern Mexico, southern Brazil, southern Australia and southern South Africa outside of the tropics are included, whereas parts of southern China and the Arabian Peninsula within the tropics are excluded.

1.2 Temperature and Solar Radiation

1.2.1 Temperature

The reason for choosing the latitudinal definition is its ease of quantification in terms of temperature. The tropics can be defined as that part of the world where the mean monthly surface air temperature variation is 6 °C or less between the average of the three warmest and the three coldest months (Table 1.1). The daily variation is generally within this range.

This definition includes the tropical highlands, the difference being their lower overall temperatures. Mean air temperatures generally decrease by 0.6 °C for every 100 m increase in elevation in the tropics. Local variation in topography, rainfall, wind direction, and other factors alters this relationship.

People unfamiliar with tropical regions generally consider them to be oppressively hot and humid. Although this condition certainly exists, it is as broad a generalization as considering the temperate region to be oppressively cold and dry. I have experienced more intense hot and humid conditions in Washington, DC during the summer than in the heart of the Amazon Basin, where one can almost always count on cool night breezes.

Near the equator, tropical climates are hot; averaging 26 °C at low elevations, pleasantly cool at 1000–2000 meters, and positively frigid at elevations above 3000 meters.

Table 1.1 Mean monthly air temperatures at sea level in January and July at different latitudes (°C).

Latitude	January	July	Mean annual
20° N	22	28	26
15° N	24	28	26
10° N	26	27	26
5° N	26	24	26
0	26	25	26
5° S	26	25	26
10° S	26	24	25
15° S	26	23	24
20° S	25	20	23

Travelling in Kenya from hot and humid Mombasa at sea level, through the eternal spring climate of Nairobi (1550 m), and to the top of Mount Kenya with glaciers (5200 m) illustrates this point, as these locations all lie within 3° from the equator. The main point to remember about temperatures in the tropics is their relative constancy rather than any absolute value.

The low but constant temperatures of the tropical highlands constitute one reason why certain temperate crops that require winter chilling for high yields and quality, such as pears, perform poorly in these areas. In addition, it takes longer to grow crops. For example, it takes 5 months to grow a crop of maize in temperate North Carolina and about the same time in the lowlands of Colombia, but in Bogotá, at an altitude of 2800 m, maize requires 11 months to mature. During the growing season in the temperate region, temperatures are higher than in the tropical highlands.

Tropical climates are also different from Mediterranean climates, which are characterized by hot, dry summers and cool, wet winters, with temperature variations higher than in the tropics. Typical Mediterranean crops like red-wine grapes and olives do not do well in the tropics. I have yet to find an excellent red wine produced in the tropics. The best are from the Mediterranean climates of California, Italy, southern France, the Cape region of South Africa, Chile and Argentina.

The least temperature variation occurs within 6° of the equator. As latitude increases, diurnal and seasonal air temperature variations also increase, reaching maximum values in the desert areas near the tropic of Cancer. The widest temperature variation is found in inland areas with the least rainfall, close to the tropic of Cancer, such as Tomboctou, Mali.

Soil temperatures in the tropics, as defined in the Soil Taxonomy system, fall in the "iso" temperature regimes, that is, those with "less than 6 °C difference between the average soil temperature of June, July and August and the average soil temperature of December, January and

Table 1.2 Soil temperature regimes as defined by the Soil Taxonomy system and their corresponding equivalents in terms of mean annual air temperature and elevation at the equator.

Regime	Soil temperature (°C)[a]	Mean annual air temperature (°C)	Elevation (m)
Isohyperthermic	> 22	> 20	0–900
Isothermic	15–22	13–20	900–2000
Isomesic	8–15	6–13	2000–3200
Isofrigid	< 8	< 6	> 3200

[a] In all cases the difference between mean soil temperature is < 6 °C between the three warmest and the three coldest months.

Table 1.3 Mean monthly soil temperature and daily variation in Jakarta, Indonesia (Mohr *et al.* 1972).

Soil depth (cm)	Highest month (°C)	Lowest month (°C)	Daily variation (°C)
Air	26.6	22.5	6.9
3	29.9	28.3	5.2
5	29.9	28.7	5.0
10	29.9	28.9	3.1
15	30.0	28.7	1.5
30	30.0	28.5	0.3
60	30.8	28.5	0.05
90	29.8	28.7	0.05
110	29.7	28.8	0.04

February at 50 cm depth or to a dense, lithic or paralithic contact" (Soil Survey Staff 1999, 2014). Soil temperatures can be estimated from air-temperature records by adding 2 °C to mean annual air temperatures in the lowland tropics (Murtha and Williams 1986). Table 1.2 presents the soil temperature regimes as defined by the Soil Taxonomy system along with their corresponding approximate equivalents of mean annual air temperature at the soil surface and elevation at the equator, using a change of 6 °C for each 1000 m increase in elevation.

The above definition excludes soil temperature variation in the topsoil. This is illustrated in Table 1.3, where the monthly air and soil temperature variations are shown for a soil in Indonesia. Very high soil temperatures have been registered on the surface of bare soils during dry periods. Mohr *et al.* (1972) reported a record of 86 °C at the surface of a bare soil in Congo. At a depth of 10 cm, the same bare soil had a nearly normal temperature of 30 °C. At the same site, the surface soil temperature was 34 °C under grassland and 25 °C under forest. Unless exposed, soil temperatures even at the surface do not seriously exceed air temperatures.

This buffering is due partly to the relatively low heat capacity of soils, about one-fifth of the heat capacity of water. Any excess heat is reradiated to the atmosphere. This is the reason why one cannot fry an egg even on the hottest soil, whereas it is possible to do so on asphalt because it has higher heat capacity.

1.2.2 Solar Radiation

The tropics receive more solar energy that is available for photosynthesis than the temperate and boreal regions. Because of the spherical shape of the Earth's atmosphere the Sun's rays strike almost at right angles near the equator but at increasingly acute angles towards the poles. This concentrates heat in the tropics. Also, as latitude increases, the Sun's rays have to pass through a thicker atmosphere and lose more energy through absorption, reflection and scattering (Osborne 2000). From 56 to 59 percent of the Sun's radiation at the rim of the atmosphere reaches the Earth's surface in the tropics; about 46 percent at 40° latitude (New York City); and only 33 percent at 60° latitude (Stockholm) (Landsberg 1961).

The average annual solar radiation in the tropics (20.3 MJ/m^2 per day) is twice that of the temperate region, and about 2.5 times that of the boreal region (Landsberg 1961, Reading *et al.* 1995). The annual solar radiation is lowest in the humid tropics (about 15 MJ/m^2 per day) due to high cloud cover, and highest (25 MJ/m^2 per day) in tropical deserts (Reading *et al.* 1995). In areas with even rainfall distribution, such as rainforests or deserts, there is little seasonality in solar radiation.

In areas with distinct rainy and dry seasons, cloudiness causes considerable seasonality. Table 1.4 shows some examples, with the tropical ones related to irrigated rice-growing areas. In Los Baños, the Philippines, the higher solar radiation during the dry season has a positive impact on irrigated rice yields and nitrogen fertilizer response. Rainy-season irrigated rice yields are almost identical in Yurimaguas, Peru and Los Baños, when solar radiation is relatively low, due primarily to cloudiness.

The highest crop yields in the tropics are in arid, irrigated valleys where solar radiation is very high. This is shown for Lambayeque, Peru, where some of the highest experimental rice yields have been recorded. The situation is similar in other arid, irrigated areas in Mexico, India, Mali and elsewhere.

Table 1.4 Average daily solar radiation reaching the Earth's surface during a 4-month growing season at different latitudes, all at low elevations.

Location	Months	Latitude	Solar radiation (MJ/m^2 per day)
Yurimaguas, Peru (humid tropics, Amazon Basin)	September–December	6° S	14.2
Lambayeque, Peru (tropical desert, irrigated)	September–December	6° S	20.2
Los Baños, Philippines (rainy season, subhumid tropics, irrigated)	September–December	14° N	14.3
Los Baños, Philippines (dry season, subhumid tropics, irrigated)	February–May	14° N	17.5
Ithaca, New York (summer, humid temperate)	June–September	42° N	18.5

In the temperate region, the annual solar radiation reaches high levels during the summer months because of longer days, as shown for Ithaca, New York in Table 1.4. The breadbaskets of the temperate region therefore receive more solar radiation during their cropping season than most tropical rainy seasons, giving these temperate regions the advantage on a per-crop basis. But most humid and many subhumid tropical areas can produce more than one crop per year.

1.2.3 Photoperiod

Days in the tropics are shorter throughout the year than days during the growing season in temperate regions. Day length changes during the year, ranging from almost zero at the equator to 2 hours and 50 minutes at 23.5° latitude. The variation in day length in the temperate region is much wider. Tropical plants are considered "short-day" plants, but many are very sensitive to changes in photoperiod. Some cultivars, for example, are so photoperiod sensitive that a 10-minute change in day length prevents flowering. This is why it is not feasible to transport "long-day" crop cultivars from the temperate region to the tropics where the days are short. Such plants would produce low yields.

1.3 Rainfall

Rainfall distribution – not annual rainfall – is the most important climatic parameter for plant growth in the tropics (Fig. 1.2), and it is the main criterion used to classify tropical climates. The seasons in the tropics are rainy or dry, not cold or hot. As a carryover of temperate influence, the term "summer" is often synonymous to dry season and "winter" to rainy season in many tropical countries.

Rainfall in the tropics is driven by complex circulation patterns and weather disturbances. The main pattern is the movement of the Intertropical Convergence Zone and the main disturbances are the El Niño Southern Oscillation and tropical cyclones.

1.3.1 Intertropical Convergence Zone

The concentration of radiant heat above the equator warms the air, which rises as it expands. When the warm air rises, it cools, and since cold air holds less water, rain falls. The resulting drier air spreads poleward and falls again at about 30° N and S, creating high atmospheric pressures, where many of the deserts are. The Coriolis force caused by the Earth's rotation deflects the winds, becoming northeasterly in the northern hemisphere and southeasterly in the southern hemisphere in the tropics. These two "trade winds" mix in an equatorial low-pressure trough known as the Intertropical Convergence Zone. The march of this low-pressure trough causes the rainy seasons. The periods of heaviest rain follow the apparent north–south migration of the Sun in the tropics (Figs. 1.3 and 1.4). Over much of the globe the Intertropical Convergence Zone position is influenced by the ocean, so there is a lag from the time when the Sun is directly overhead (Mark Cane, personal communication, 2016).

Fig. 1.2 Rainfall distribution is the most critical biophysical parameter in the tropics. Localized wet-season rains in Planaltina, Brazil.

The Intertropical Convergence Zone moves northwards from the equator during the northern-hemisphere summer (June–August) and southwards from the equator during the southern-hemisphere summer (November–January) following the apparent migration of the Sun. It is approximately over the Equator during the summer and winter solstices (21 June and 21 December) and at the tropics during

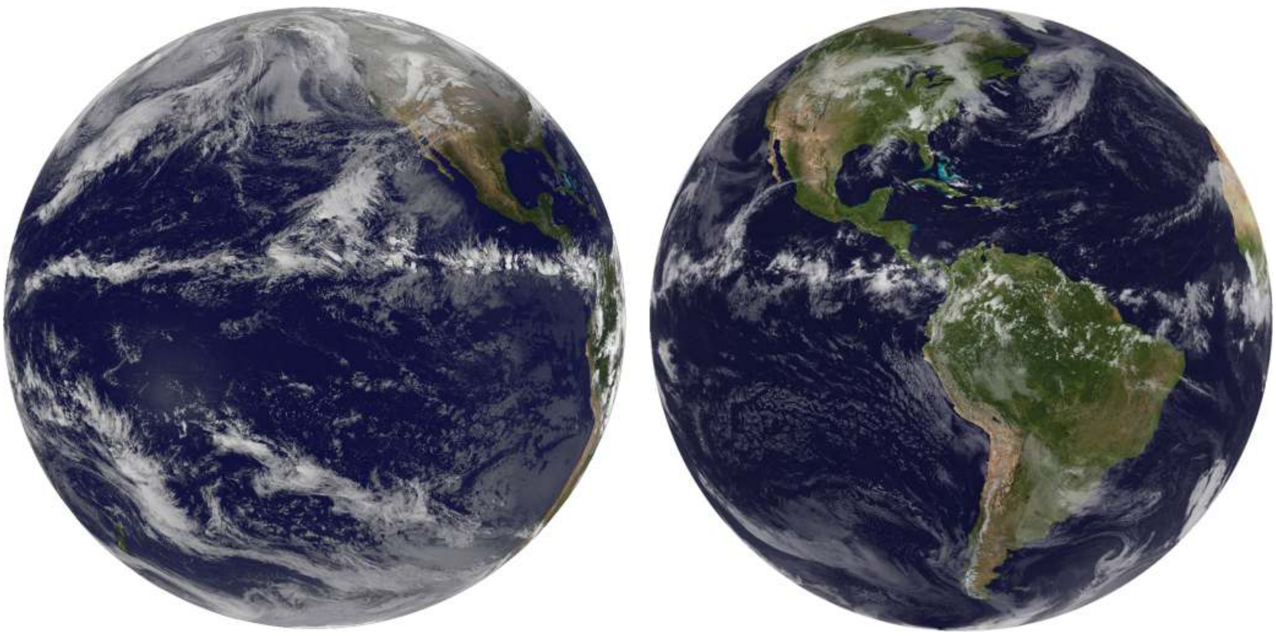

Fig. 1.3 The Intertropical Convergence Zone over the Pacific Ocean and Latin America as it moves north towards the equator. Images were taken May 19, 2013, about 1 month before the northern-hemisphere summer solstice (21 June), the longest day of the year in the northern hemisphere. Source: NOAA Environmental Visualization Lab (NOAA National Centers for Environmental Information 2016)

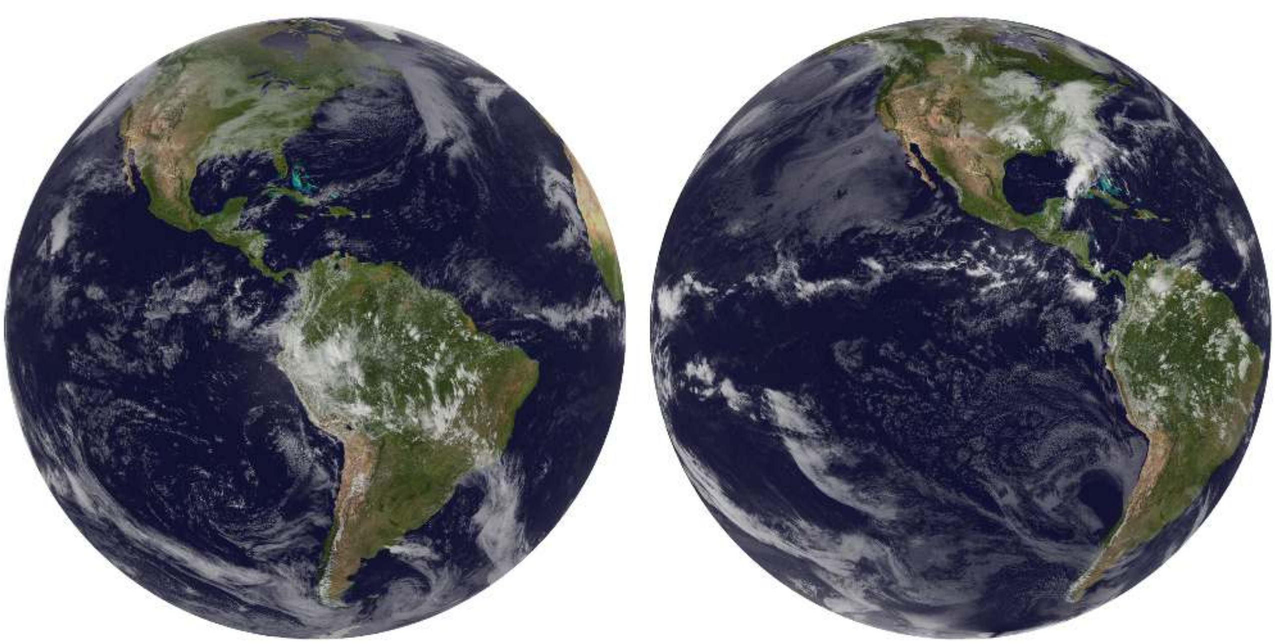

Fig. 1.4 The Intertropical Convergence Zone at the tropics of Capricorn and Cancer. Left image shows the zone on November 24, 2010, having crossed the equator and approaching the tropic of Capricorn, which it will reach 3 weeks after, on the summer solstice (21 December), the longest day in the southern hemisphere. Right image, taken May 17, 2016, shows the return northwards of the Intertropical Convergence Zone, approaching the tropic of Cancer on 21 June. Source: NOAA Environmental Visualization Lab (NOAA National Centers for Environmental Information 2016)

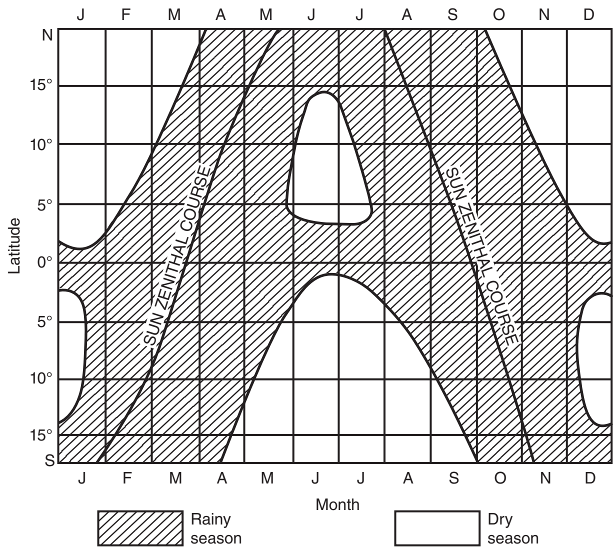

Fig. 1.5 The march of rainy and dry seasons in the tropics (De Martonne 1957).

the equinoxes (21 March and 21 September). Although such global generalizations are of limited local value, they correlate well with the timing and length of dry seasons, including the bimodal pattern of two dry seasons and two rainy seasons within 5° of the equator (Fig. 1.5). These equatorial regions receive periods of maximum rainfall when the Intertropical Convergence Zone crosses the equator.

1.3.2 Monsoons

Monsoon is the Arabic word for season and it's used in the context of change in the direction of winds. Monsoons are an actual manifestation of the movement of the Intertropical Convergence Zone northward in India (Gadgil 2003). Their consequences extend beyond the tropics, to 35° N on the Indian subcontinent. Here land masses heat more rapidly than the Indian Ocean during the hotter months, drawing humid air from it. A similar situation takes place in West Africa and in northern Australia (Osborne 2000). The variability of monsoon rains under the Intertropical Convergence Zone is a critical feature of the Indian subcontinent, affecting hundreds of millions of people. The East African coast is also affected by the Indian monsoon. The *kazkazi* north to northeasterly winds provide rains during the hot season from October to May, while the *kusai*, the cooler and stronger winds from the southern Indian Ocean, take place during the dry season. It is important to remember that monsoon wind and rainfall changes are produced by the Intertropical Convergence Zone, not by a separate phenomenon.

An idealized diagram of the march of the seasons in tropical regions appears in Fig. 1.5.

1.3.3 El Niño Southern Oscillation

The El Niño Southern Oscillation (sometimes abbreviated to ENSO) is an irregular low-frequency oscillation between a warm (El Niño) and a cold (La Niña) stage in the tropical Pacific Ocean (Cane 2005). The normal tropical eastern Pacific high pressure is associated with southerly winds. The winds create strong coastal upwelling and drive the cold Humboldt Current northwards, resulting in coastal deserts in Peru and Chile. Starting at about 6° S the southeasterly trade winds normally move the cold waters westwards. Surface water is gradually warmed under the tropical Sun as it crosses the equatorial Pacific Ocean, creating a pool of very warm water in the western equatorial Pacific that produces low atmospheric pressures and high rainfall as it reaches equatorial Southeast Asia. The western equatorial Pacific Ocean around Indonesia becomes 30 cm higher than the eastern Pacific Ocean.

When the trade winds collapse this mountain of water spreads east, bringing warmer sea surface temperatures and rains to the coastal desert around Christmas time. Peruvian fishermen of the nineteenth century called these events "El Niño" (for baby Jesus).

El Niño affects the entire tropics and beyond (Fig. 1.6). The main disturbances are droughts in Southeast Asia and Australia, the weakening of the monsoon rain-bearing winds on the Indian subcontinent, droughts in southern Africa (south of and including Malawi), and droughts in the Sahel and in parts of Central America, the Caribbean, and the northern Amazon. Wetter and warmer than normal weather takes place in East Africa, parts of Central Asia, across the southern half of the United States from California to Georgia, and in parts of the US Midwest and the La Plata basin of South America. Forest fires in Alberta, Canada are affected by El Niño, and two recent winter Olympics were too warm for snow to fall during El Niño years (Mark Cane, personal communication, 2016). There seems to be less hurricane activity in the Atlantic during El Niño years.

The larger the increase in seawater temperature under the Intertropical Convergence Zone, the more intense the El Niño events are, but the global impacts also depend on the timing of the El Niño with respect to the seasonal pattern of sea-surface-temperature changes in the tropical Pacific and whatever opposing or reinforcing effects the rest of the climate system imposes. Nevertheless, there will be more intense rainfall during El Niño events because there will be more available moisture (Mark Cane, personal communication, 2016).

La Niña events produce colder sea surface temperatures and less rainfall. The effects are also felt widely as the opposite of El Niños.

I experienced my first El Niño in 1971 when living in Chiclayo, a coastal desert city of Peru, while working on irrigated rice. What a terrible thing rain is in a desert that normally gets none! Adobe houses melted and irrigation and sewage systems were disrupted, spreading mud and filth all over.

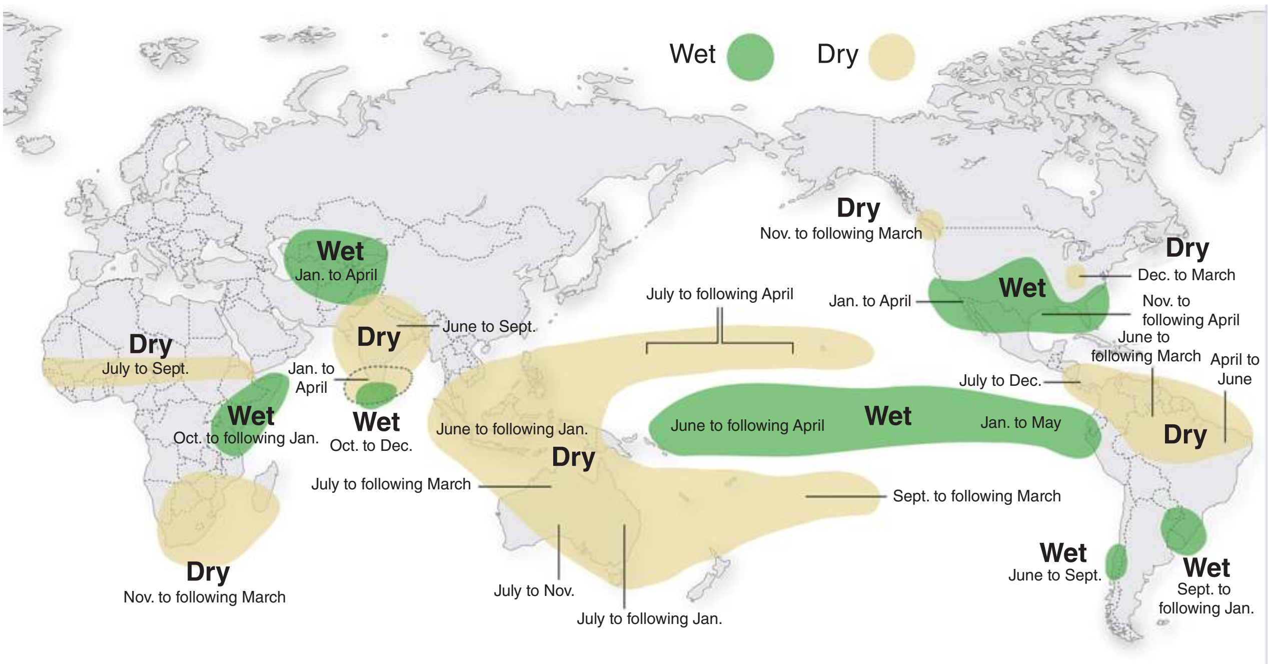

Fig. 1.6 The main consequences of El Niño events across the world. Source: International Research Institute for Climate and Society, Columbia University

My second El Niño was in 1992, this time in Africa, when many agroforestry experiments were wiped out by drought in Malawi, Zambia and Zimbabwe, while floods disrupted crops and infrastructure in Kenya. Similar "oscillations" are now beginning to be recognized in other oceans, but not to the magnitude of El Niño. In effect, most of the world is affected by El Niño. Because of this global effect, climatologists assert that "the tropics rule the world's climate" (Cane and Evans 2000).

1.3.4 Moisture Availability Index

As indicated before, rainfall distribution, rather than the total amount, is the most important climatic parameter for tropical plant growth. The number of consecutive months when soil moisture is limiting plant growth is used to differentiate tropical climates for agriculture as well as delineate natural systems. A dry month is traditionally and arbitrarily defined as one with less than 100 mm of rainfall.

A more detailed definition used by the Food and Agriculture Organization of the United Nations (FAO) Agroecological Zones project is that of the growing period, defined as the number of days during the year where the average precipitation exceeds half the potential evapotranspiration plus the days required to evaporate 100 mm of stored soil moisture (FAO 1981).

Reliance on average values has led to disastrous results. One of most notorious examples of such was the British Groundnut Scheme in Tanzania during the late 1940s (Wood 1950). The area had an average rainfall of about 700 mm during the rainy season, which is sufficient in quantity and length to grow peanuts. On this basis, several thousand hectares were planted to peanuts. They received 250 mm of rain during the first year and 300 mm the second, resulting in massive crop failures costing about 100 million dollars (in 1950 dollars).

Given the high variability, it is better to use a probability statement in rainfall data. An example of weekly rainfall probabilities is presented in Fig. 1.7 for Muguga, Kenya. Rainfall probabilities have been used to develop the Moisture Availability Index (MAI) concept (Hargreaves 1977). MAI is the ratio of the monthly dependable precipitation (75% probability level) divided by the potential evapotranspiration, in effect predicting the intensity of drought stress. MAI values > 1.00 predict no stress; from 0.67 to 1.00, slight probability; from 0.67 to 0.33, moderate; and < 0.33, highly probable drought stress.

The dry season is then defined as consecutive months with MAI values lower than 0.33, which reflects a high probability of serious drought stress to crops. Whenever more than 20 years of rainfall records are available this procedure, or a similar one, should be used in favor of

Cambridge University Press
978-1-107-17605-8 — Properties and Management of Soils in the Tropics
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average rainfall values. The MAI concept has been used effectively in Latin America (Cochrane *et al.* 1985).

1.3.5 Rainfall Intensity

Rainfall intensity (mm H_2O/hour) is also variable, largely depending on whether the rains are advective or convective. Advective rains are caused by air masses moving inland from the ocean or up a mountain range, causing drizzle, fog, high humidity and low-intensity rains for several days. I have endured this several times in the Amazon as well as in New York State. Most tropical rainfall, however, is convective (Kellman and Tackaberry 1997). Convective rains, caused by localized warming and rising air, develop into localized thunderstorms, which cause high-intensity rainfall for short periods. Such intense rains may result in direct crop damage and runoff, even in flat areas. It has been estimated in Surinam that 80 percent of a 10 mm/hour rain is retained by the soil, whereas only 32 percent is retained during a 50 mm/hour rain (Mohr *et al.* 1972).

1.3.6 Soil Moisture

Many attempts have been made to classify rainfall quantitatively in tropical climates. Since all of these are based on rather arbitrary assumptions and since our interest in rainfall lies in its role as a source of soil moisture to plants, the soil moisture terminology of the Soil Taxonomy system (Soil Survey Staff 1999, 2014) is used in this text.

The soil moisture regime is defined according to Table 1.5, based on the moisture control section. The moisture control section is defined as that part of the soil between the following two depths: (1) the upper boundary is the depth to which a dry soil will be moistened by 2.5 cm of water in 24 hours and (2) the lower boundary is that reached by 7.5 cm of water in 48 hours (Soil Survey Staff 1999). Roughly, this corresponds to depths of 10–30 cm for fine loamy, silty and clayey soils, 20–60 cm for coarse loamy soils, and 30–90 cm for sandy soils. The term "dry" refers to soil moisture tensions of at least –1.5 MPa (megapascals, or 15 atmospheres), that is, at or above the wilting point of

Table 1.5 Simplified definitions of soil moisture regimes in the Soil Taxonomy system as applied to the tropics ("iso" temperature regimes), with subdivisions by Armand van Wambeke. Adapted from Soil Survey Staff (1999), van Wambeke (1981, 1982, 1987), van Wambeke and Newhall (1985) and personal observations.

Soil moisture regime	Consecutive months per year when control section is dry
Udic	< 3
Ustic:	3–9
Typic tropustic	3–6
Aridic tropustic	6–9
Aridic	> 9
Aquic	Evidence of chemical reduction due to waterlogging

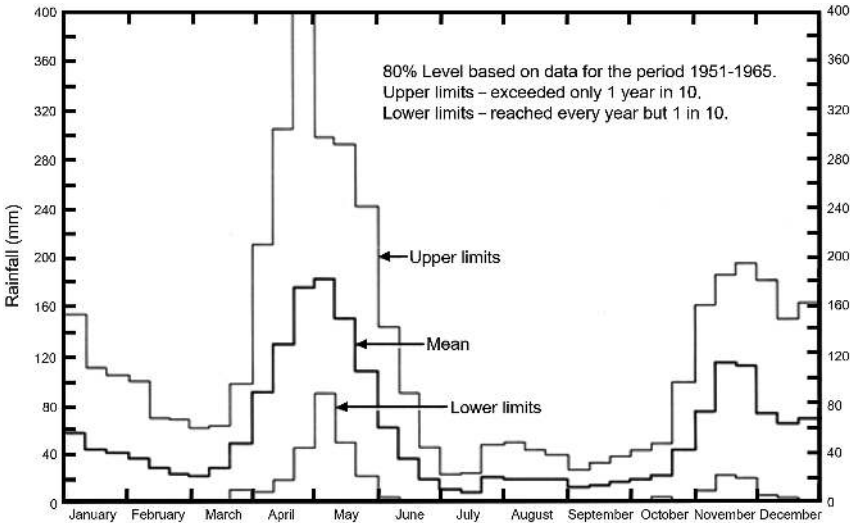

Fig. 1.7 Confidence limits of expected rainfall in Muguga, Kenya. Source: Lawes (1969)

Table 1.6 Example locations where different soil moisture regimes predominate in the tropics. Adapted from van Wambeke (1981, 1982, 1987) and van Wambeke and Newhall (1985) .

Soil moisture regime	Tropical Africa	Tropical America	Tropical Asia
Udic	Nairobi, Kenya	Yurimaguas, Peru	Kuala Lumpur, Malaysia
Ustic:			
Typic tropustic	Tamale, Ghana	Brasília, Brazil	Hyderabad, India
Aridic tropustic	Ouagadougou, Burkina Faso	Santiago de Cuba	Mysore, India
Aridic	Khartoum, Sudan	Lambayeque, Peru	Dadiangas, Philippines
Aquic	Maun, Botswana	Pantanal of Brazil	Banjarmasin, Indonesia

most plants. A normal year or a normal month is one within plus or minus one standard deviation from the long-term mean (at least 30 years of data). Additional caveats are described in the latest editions of *Soil Taxonomy*, such as the 12th edition (Soil Survey Staff 2014).

The intent of this definition is to facilitate the estimation of soil moisture regimes from climatic data. The **udic** soil moisture regime is defined as when the control section is dry for less than 3 consecutive months, implying that water stress will be absent during most of the year. It is roughly equivalent to the humid climate for most tropical soils. The **ustic** soil moisture regime indicates one rainy season of three months or more, which encompasses both subhumid and semiarid tropical climates. The **aridic** soil moisture regime implies a very short rainy season, insufficient for most crops to grow, and it is well correlated with desert climates. The **aquic** regime is typical of poorly drained sites and occurs even in deserts. Four soil moisture regimes are recognized in the tropics (Table 1.5) with sample locations listed in Table 1.6.

The proposed subdivision of the ustic by van Wambeke (1982) helps soil moisture regimes fit better with tropical ecosystems. Although not officially part of the Soil Taxonomy system (Soil Survey Staff 2014) I use two subdivisions because they make eminent sense. The typic tropustic is roughly correlated with the subhumid tropics and savanna vegetation. The aridic tropustic is roughly correlated with the semiarid tropics and semiarid vegetation.

Variation in soil properties and topography permit the existence of different soil moisture regimes under the same rainfall regime. A deep sandy soil may be ustic in a humid tropical climate because of rapid drainage.

1.4 Tropical Climates

Many approaches have also been used to classify tropical climates, basically how to distinguish a rainfall/natural vegetation continuum between rainforests and deserts. Basically, all are based on the original classification of Wladimir Köppen and Rudolf Geiger in 1936, updated by Rodenwaldt and Jusatz (1963) and Kotteck *et al.* (2006). I have chosen four main tropical climates that are most relevant to this book, the rainy climates (Af, Am), the seasonal climates (Aw), the dry climates (Bsh) and the deserts (BW). They are based on the length of the rainy seasons. Their associated natural vegetation and main soil moisture regimes are indicated in Table 1.7. The geographical distribution of such climates is shown in Fig. 1.8. About 24 percent of the tropics are humid, 49 percent subhumid, 16 percent semiarid and 11 percent arid. Such climates occur at all elevations in the tropics and are interspersed with natural wetlands and irrigated agriculture. Three examples of each tropical climate type are shown in Fig. 1.9.

1.4.1 Subhumid Tropics

The subhumid climate covers about half of the tropics. It is characterized by distinct seasonality of rainfall, with 4.5 to 9.5 humid months per year. Close to the equator the subhumid tropics have a bimodal distribution, with two short rainy seasons and two short dry seasons, making it possible to grow two crops per year. At latitudes higher than 5° the subhumid tropics have one long dry season and one long rainy season, permitting one crop a year without irrigation.

The subhumid tropics include the Cerrado of Brazil, the Llanos of Colombia and Venezuela, eastern Amazonia, the Pacific coast of Central America and Mexico, and most of Cuba in Tropical America. In Africa, they include most of the continent south of the Sahel and north of the Kalahari Desert (except the humid Congo Basin), and are flanked by semiarid areas in East and southern Africa. In Asia, the seasonal, subhumid climates cover most of India, mainland Southeast Asia and a belt in northern Australia. These are the most agriculturally productive tropical climates where the breadbaskets of Asia, Latin America and West Africa are located. One of its main assets is that the dry season breaks many biological cycles of pests, acting in a similar way to the

Table 1.7 Distribution of major tropical climates, relationships with tropical vegetation and main soil moisture regime. Source: Adapted from Köppen and Geiger (1936), Rodenwaldt and Jusatz (1963) and my interpretations.

Tropical climate	Köppen–Geiger termino-logy	Humid months (> 100 mm)	Natural vegetation	Million ha	Percent of tropics	Main soil moisture regime
Subhumid tropics	Seasonal climates (Aw)	4.5–9.5	Savannas, deciduous forests or woodlands	2430	49	Typic tropustic
Humid tropics	Rainy climates (Af, Am)	9.5–12	Humid tropical forests	1191	24	Udic
Semiarid tropics	Dry climates (Bsh)	3–4.5	Shrubs and trees with discontinuous grass cover	771	16	Aridic tropustic
Arid tropics	Desert (BW)	0–2	Deserts	558	11	Aridic
Total				**4950**	**100**	

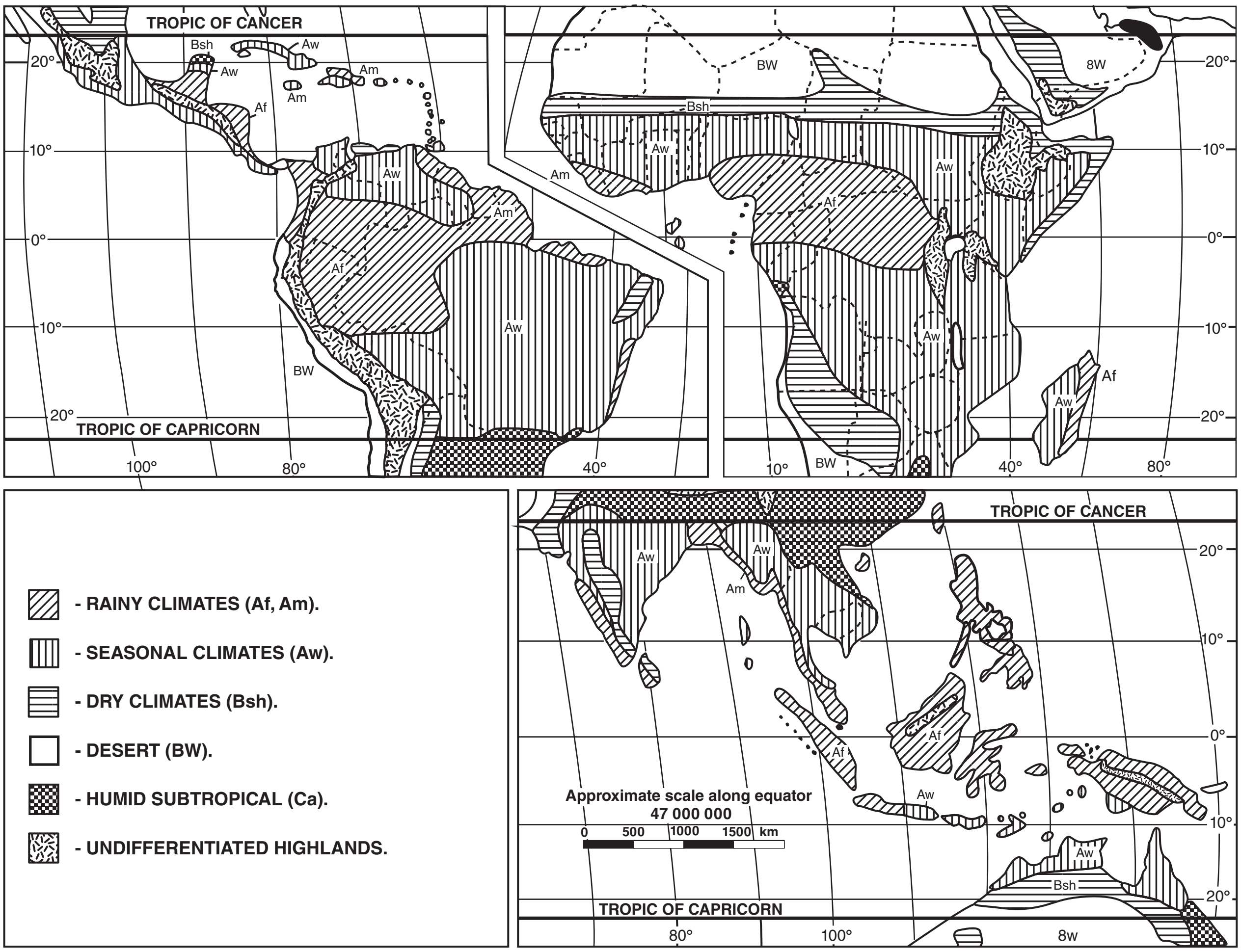

Fig. 1.8 Geographical distribution of tropical climates. Adapted from Rodenwaldt and Jusatz 1963