2. The natural resource base

Whether or not the measures for maintaining and improving soil fertility discussed in the following chapters of this book are successful depends primarily on the extent to which the potential (e.g. sunshine, water) and limiting factors (e.g. low nutrient storage capacity of the soil) are recognized and used or overcome (e.g. through a high turnover rate of the biomass and nutrients).

2.1 Climate

2.1.1 Climatic classifications of the tropics

Background. Agroclimatic classifications of the earth's agricultural land are based primarily on temperature and precipitation. With regard to the latter, a distinction is made between absolute rainfall and seasonal distribution. This distinction is of vital importance to the use of land for agriculture.

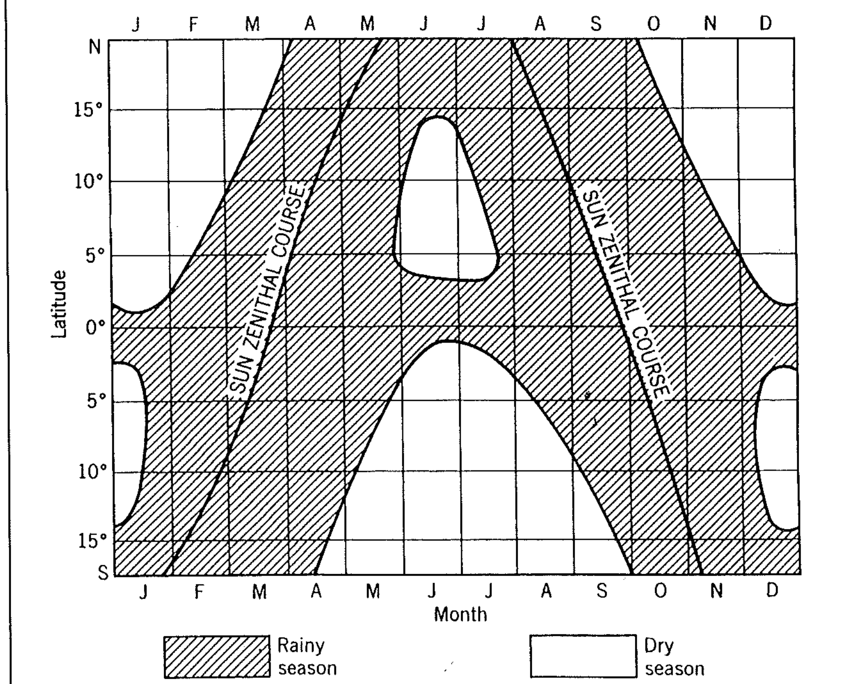
The tropics, defined as lying between the tropics of Cancer and Capricorn (23.5° North to 23.5° South), are divided into the permanently humid intertropics and the subhumid outer tropics. In the tropics, the changes in temperature between day and night are greater than those over the year (diurnal climate). Temperatures are particularly constant in the equatorial (inner) tropics, while fluctuations (day/night and seasonal) are greater in the subhumid outer tropics[1]. The factor that distinguishes the two, however, is not the differences in temperature, which are slight, but different rainfall conditions.

Figure 2.1 represents the "idealized" occurrence of rainy and dry periods in various tropical regions. Owing to differences in the distribution of land masses, conditions in the northern hemisphere are somewhat different from those in the southern (KÖPPEN and GEIGER 1936). For example, the thermal equator lies some 10° north of the geographic equator (WALTER 1979). Also deviating from idealized conditions

[1] This does not apply to higher tropical altitudes.

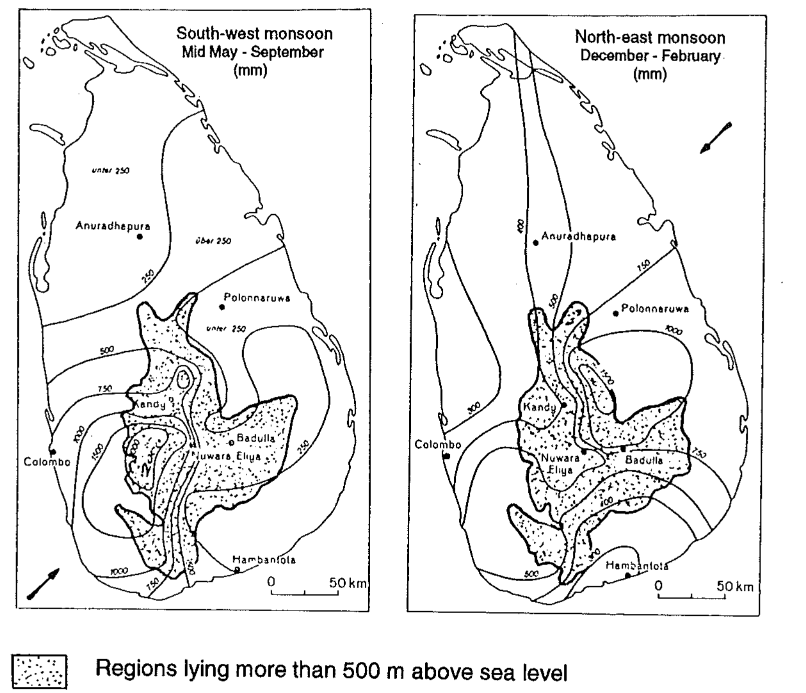
are climates which do not conform to that of any zone. Among these are the climates of South and South-East Asia, in which seasonal prevailing winds (the north-east trades in the northern hemisphere and the south-east trade winds in the southern) bring moist air from the ocean. When this meets a land mass, especially mountains, rainfall occurs. Leeward areas lie in the rainshadow.

Figure 2.1. Idealized diagram of the march of seasons in the intertropical regions



Source: Adapted from DE MARTONNE (1957), cited in SANCHEZ (1976)

Figure 2.2. Distribution of rainfall over Sri Lanka during different seasons and under different wind systems



Source: Adapted from DOMRÖS (1971)

A particularly clear example of a monsoon climate is Sri Lanka, where the southwest wind delivers the main portion of rainfall to the heavily settled, intensively cultivated southwestern part of the island during the summer months. The northeasterly brings somewhat less rain to the north of the island during the winter. A dry zone is found at the island's flat northern tip.

In some regions, such as the Caribbean or the Philippines, tropical cyclones frequently occur, leaving a trail of severe damage to agriculture in their wake.

Because the actual climate only rarely corresponds to the idealized character of a given latitude, classification systems have been developed which are "independent" of latitude and based primarily on rainfall characteristics and temperature. These allow us to compare areas with similar climates which do not fall geographically within the same latitudes. Before turning to classification systems, the factors governing climate in the tropics must be briefly examined.

Rainfall and evaporation. These essentially determine the water economy of a site. Table 2.1 shows typical values obtained under tropical conditions.

Table 2.1. Rainfall and potential evapotranspiration (ETP) per year at different tropical locations

	Rainfall (mm/yr)	ETP (mm/yr)	Average temperature (°C)
Yangambi (evergreen rainforest)	1828	1312	24.6
Bouaké (moist savanna)	1210	1547	26.6
Ouagadougou (dry savanna)	897	1770	28.8
Source: MÜLLER (1982)			

The subhumid tropics are characterized by considerable differences in evaporation rates. Thus for example, in Ouagadougou, values for potential evaporation range between 4.1 mm/day in the rainy season and 5.7 mm/day in the hot, dry season (MÜLLER 1982). When rainfall exceeds evaporation we speak of humidity; when it is less, of aridity. While rainfall measurements have been recorded for many years over a fairly dense network of stations, determining evaporation has been, and still is, problematic. The multiplicity of methods and theories has contributed to much uncertainty and a confusion in terminology. Here are a few brief definitions:

* **Potential evaporation (E_O)** represents the evaporation from a theoretically unlimited open water surface. It can be determined by means of an evaporimeter (e.g. a Class A pan) or a formula (e.g. PENMAN 1948), and often serves as a reference value.

* **Actual evapotranspiration (ET_a)** is the real amount of water evaporating from vegetation and the soil surface. This can be determined approximately using a non-irrigated lysimeter.

* **Potential evapotranspiration (ETP)** is the hypothetical evaporation from vegetation, assuming a constant optimal water supply. It is closely correlated with E_O (e.g. ETP $\sim$ 0.75 E_O; from PENMAN 1948) and can be calculated using a special formula (e.g. THORNTHWAITE 1954; TURC 1961) or measured by means of an irrigated lysimeter.

Cloud cover, insolation, air temperature, relative humidity and wind speed are the climatic factors most influencing E_O and ETP.

Measurements of evaporation are scarce and often inexact, while calculations are generally cumbersome and require considerable data. Efforts have therefore been made to use hygrothermal indices based on temperature and precipitation to determine the humidity or aridity of a climate or a particular month. One of these is the aridity index based on DE MARTONNE (1926), which was used by LAUER (1952) in his pioneering work. According to this, a month is regarded as humid if

$$N \geq 5 \frac{(t + 10)}{3}$$

where: N = monthly rainfall in mm, t = mean monthly temperature. This method of determining humidity is scientifically outdated for many purposes today, but is still useful - even where there are insufficient data - for roughly estimating the number of humid months[2].

In addition to its absolute quantity, the character of rainfall (its distribution, reliability and intensity) plays an important role.

Character of rainfall. The distribution of rainfall over the year roughly determines the length of the growing period for annual crops. Climate diagrams (see Figure 2.3), which present the average monthly temperature and precipitation values on different scales[3], can be used to show the relatively humid and arid months at any location. In most cases the diagrams only roughly reflect real conditions. Nevertheless, they graphically convey the occurrence, the length (horizontal line), and the intensity (vertical line) of humid and arid periods of the year. Another advantage is that they can be made for any site using basic meteorological data (shown in bold in the legend of Figure 2.3). This type of diagram can be found in the World Atlas of Climate Diagrams (WALTER et al. 1975), which covers a large number of stations in the tropics.

Douala (Cameroon) is humid throughout the year. San José (Costa Rica), on the other hand, has a dry spell lasting from late December to mid-April, as is shown by the precipitation curve for this period, which is located below the temperature curve.

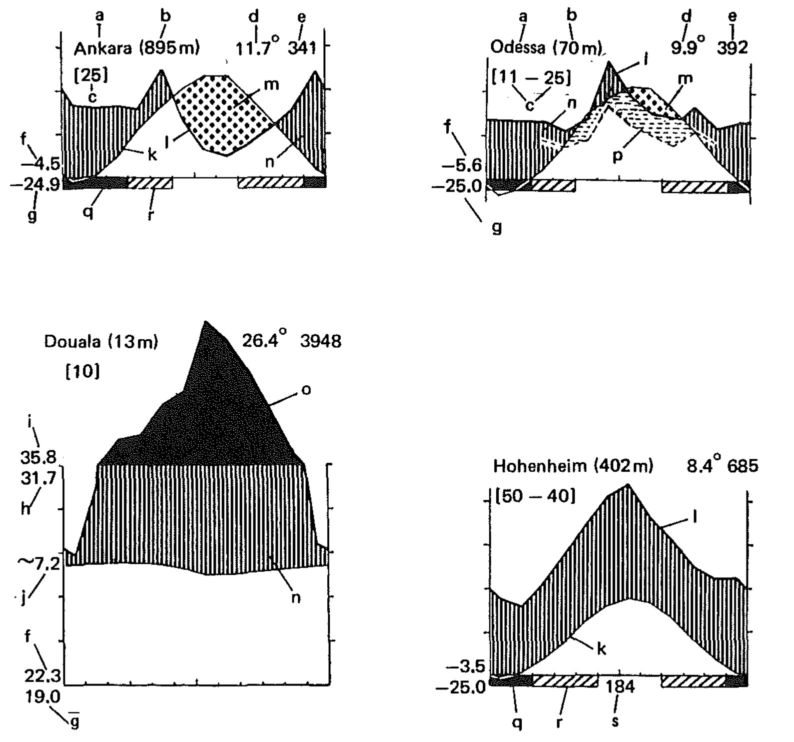
LAUER (1975) categorizes tropical climates according to the ratio of humid months to arid months as follows:

- Humid climate: 9.5 - 12 humid months (0 - 2.5 arid months)
- Semi-humid climate: 7 - 9.5 humid months (2.5 - 5 arid months)
- Semi-arid climate: 2 - 7 humid months (5 - 10 arid months)
- Arid climate: 0 - 2 humid months (10 - 12 arid months)

[2] A comparison of this method with that of LAUER indicates that the number of humid months calculated in this way is generally somewhat higher than that obtained from evaporation calculations.

[3] The ratio of 10°C to 20 mm rainfall is based on empirical values, and the temperature curve thus takes the place of the potential evaporation curve. Together with the precipitation curve, they approximately express the water balance.

Figure 2.3. Climate diagrams



a) Station
b) Altitude above sea level
c) Number of observation years (where two figures are given, the first refers to temperature and the second to precipitation)
d) Mean annual temperature
e) Mean annual **precipitation**
f) Mean daily minimum of the coldest month
g) Lowest measured **temperature**
h) Mean daily maximum of the warmest month
i) Absolute maximum (highest measured temperature)
j) Mean daily T fluctuation
k) Curve of **mean monthly temperature** (1 scale section = 10°C)
l) Curve of **mean monthly precipitation** (1 scale section = 20 mm)
m) Dry period (dotted)
n) Humid season (hatched)
o) Mean monthly precipitation exceeding 100 mm (1 scale section = 100 mm), black area
* For the purpose of comparison, the year in the northern hemisphere begins in January and in the southern hemisphere in July.

Source: Adapted from WALTER (1964)

There are other systems of classifying humidity, only one of which we will describe here. For West Africa, the International Institute of Tropical Agriculture (IITA) uses an agroclimatic humidity classification with the following divisions (adapted from LAWSON 1979, cited in IITA 1981):

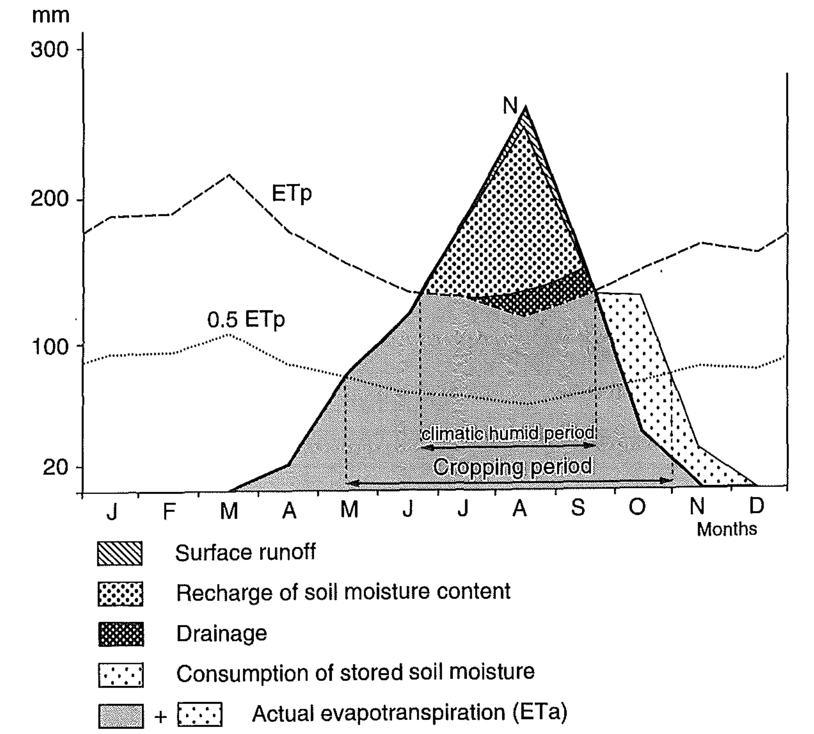
*	Perhumid:	> 8 humid months (ETP)
*	Humid:	6-8 humid months
*	Transition from humid to subhumid:	5-6 humid months
*	Subhumid:	4-5 humid months
*	Semi-arid:	2-4 humid months
*	Arid:	1-2 humid months
*	Desert:	≤ 1 humid month

Because annual crops only need about half of the potential evaporation during early growth, the beginning of the growing period is often assumed to have already started at N > 0.5 ETP rather than at N > ETP, the start of the humid period in climatic terms (see Figure 2.4). The water stored in the soil at the end of the growing period must also be taken into account, which is why the actual growing season is often longer than the climatic humid period.

The reliability of rainfall must be taken into account when recommending crops and developing agricultural systems for a specific location, especially when one of the aims is to reduce farmers' risk. Annual averages alone are of little use.

Dry periods often occur during the growing season in many locations. These can last several weeks and markedly reduce yields. Yet their occurrence does not show up at all in averages taken over several years (SANCHEZ 1976).

Figure 2.4. Example of an average water balance from the Ouagadougou area (dry savanna)



The reliability of rainfall (see below) is also an important factor in determining the period utilizable for agriculture. Hence in many cases the actual utilizable period will be shorter than the simplified representation here.

Source: Adapted from ROOSE (1981)

This is also true of deviations from the average seasonal, monthly or annual rainfall. As absolute rainfall decreases, so also does the reliability of rainfall. Fluctuations, both upwards and downwards, increase in number and extent, resulting in higher risk (Table 2.2). In dry locations it is therefore especially important that optimal use be made of all the precipitation received. This can be achieved, for example, by minimizing surface runoff and aiding infiltration through good soil structure.

Table 2.2. Average deviation of rainfall from the annual mean, viewed by zone

Zone	Mean annual deviation of rainfall from average (%)
Rainforest	15
Semi-evergreen rainforest	15-20
Moist savanna region	20-25
Dry savanna region	ca. 30
Source: Compiled from data by WEISCHET (1979)	

The maximum variations may be considerably larger. It is possible for two sites each to receive a seasonal average of 750 mm - one with values ranging between 500 and 1000 mm, and the other between 625 and 875 mm. The land use suitable for each differs, yet on the strength of their averages they would be classified as similar.

Where climate data have been gathered over many years, the probability of a certain amount of rain can easily be calculated statistically. GLOVER and ROBINSON (1953) describe a simple method that is accurate enough for practical purposes.

Simpler still, and quite practicable, is a method by which precipitation values recorded over several years (at best 20 or more) are ordered according to quantity, with the highest values at the top and the lowest at the bottom. To find the rainfall level which was (or will be) reached or surpassed in 80% of years, the user counts down 16 positions from the top of the list if there are 20 values (20 years). If there is an even number of years, the value for 80% will be the average of the values shown at the sixteenth and seventeenth position. If the number of years is uneven

(e.g. 21) the value will be the seventeenth from the top. Thus it can be stated that in the past 21 years there has been an 80% probability that x mm or more of rain fell in a given period (year, month or decade). Assuming that no climatic change has taken place, this can be expected to recur in the future.

Table 2.3. Calculating rainfall probability

No.	Year	Annual rainfall (mm)	
1	1952	950	**Rainfall level that**
2	1963	940	
3	1958	910	a) was (will be) reached or surpassed in 80% of years = average of 16th and 17th values:
4	1969	890	
5	1953	860	$\frac{690\ \text{mm} + 660\ \text{mm}}{2} = 675\ \text{mm}$
6	1970	850	
7	1964	800	
8	1954	780	
9	1955	780	b) was (will be) reached or surpassed in 60% of years = average of 12th and 13th values:
10	1962	770	
11	1965	750	$\frac{720\ \text{mm} + 710\ \text{mm}}{2} = 715\ \text{mm}$
12	1959	720	
13	1960	710	
14	1966	700	
15	1956	700	
16	1971	690	
17	1961	660	
18	1968	570	
19	1967	500	
20	1957	480	

Depending on the degree of accuracy required, probabilities[4] can be calculated for any time interval (year, month, week); but for agronomic purposes it is best to break rainfall periods down into 10-day intervals. Plotting the resulting probabilities on a graph permits several probability curves to be compared at the same time.

Calculation techniques have constantly improved in recent years, and rainfall probability maps now exist for many regions. These are a valuable aid in planning agricultural land use.

By calculating rainfall data in relation to the water requirements of crop plants, JAETZOLD and SCHMIDT (1982) have been able to construct yield probability charts. These are of great value in land use planning.

Statements by farmers about climate and rainfall are a source of further valuable information. Only they can provide detailed information on local conditions, which cannot be picked up by the weather station's broad network. In addition, subjective accounts of weather events offer insights into important site factors and farming practices[5].

The violence of rains is a problem for farmers in the tropics where, as a result special measures are required to protect soil fertility. Cloudbursts and heavy showers of up to 80 mm per hour are common. In Uganda (Namulonge) these make up some 25% of the total annual rainfall; 9.4% of rains achieve an intensity of over 140 mm per hour, lasting between 5 and 40 minutes (WEBSTER and WILSON 1966).

Light. With regard to light, the tropics lie in the most favored region in the world. Factors such as the tilt of the earth's axis, "thinner" atmosphere and temperatures that permit a potential year-round growing season contribute to greater photosynthetic production in the tropics than anywhere else on earth. In the tropics, up to 56% of the

[4] According to WEBSTER and WILSON (1966), the probability that a sufficient quantity of rain is available to a crop should be at least 80% (a lower value may be acceptable if the farmer's financial risk is low).

[5] In this connection see also MANNING (1950), YNIGUEZ and SANDOVAL (1966), and JACKSON (1982).

sun's radiation reaches the earth's surface, a figure that compares with 46% at 40° north and 33% at 60°. Even in the tropics, however, cloud cover can reduce insolation, seasonally in the subhumid outer tropics and continuously in the humid inner tropics. Table 2.4 shows the solar radiation conditions of three tropical locations and one temperate one.

Seasonal variations in solar radiation have a pronounced impact on crop yields in the tropics. DE WITT (1967), calculating potential crop yields for a number of locations based on temperature values (duration of growing period) and amount of sunshine, found that tropical areas have approximately twice the yield-producing potential of temperate climates (Table 2.5).

Despite other critical factors (water, etc), this advantage is of such magnitude as to challenge agriculture to make full use of it. Practices such as mixed or multi-story cropping (see Chapter 3 on agroforestry), or improvements in the soil-water economy can mitigate the limiting factors and make it possible to exploit the one and only resource that is free of charge and inexhaustible: sunlight.

Table 2.4. Mean monthly solar radiation at several stations (in langleys/day)

Month	Yurimaguas, Peru 2087 mm/yr (trop.rain forest)	Los Baños, Philippines 1847 mm/yr (monsoon climate)	Lambayeque, Peru 19 mm/yr (desert)	Ithaka, N.Y., USA 766 mm/yr (temperate climate)
January	308	295	487	136
February	309	361	498	214
March	232	379	482	273
April	283	492	456	359
May	249	439	405	470
June	265	377	355	515
July	342	383	321	492
August	324	403	378	412
September	345	333	435	345
October	379	355	481	242
November	326	312	484	107
December	309	253	503	106
Annual daily mean	306	366	440	306

1 langley = 1 gram calorie/cm^2

Source: Adapted from SANCHEZ (1976)

Table 2.5. Potential productivity at various latitudes, derived from temperature and solar radiation

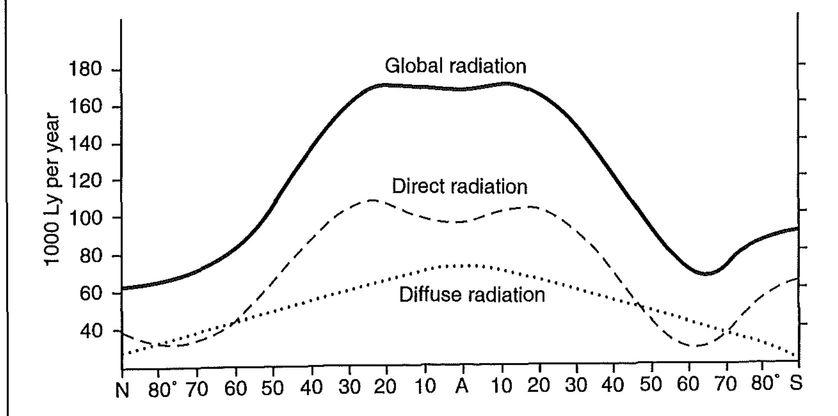
Northern latitude (°C)	Months with mean temperature over 10°C	Carbohydrate production (t/ha/year)
70	1	12
60	2	21
50	6	59
40	9	91
30	11	113
20	12	124
10	12	124
0	12	116
-10	12	117
-20	12	123
-30	12	121
-40	8	89
-50	1	12

Source: DE WITT (1967), cited in SAN PIETRO et al. (1967)

Special climate characteristics. Climatic parameters such as annual precipitation, duration of sunshine and so on provide valuable data for general guidance, but a more detailed analysis of climatic factors (rainfall intensity, amount of diffuse radiation, etc) is usually necessary for identifying an optimal cropping system.

Mixed cropping, for example, is better suited than single-crop stands not only to the extreme rainfall conditions of the tropics (by virtue of its ground coverage), but also to the special sunlight conditions: the high level of diffuse radiation reduces light-shadow contrast and hence exposure differences within the plant habitat (Figure 2.5).

Figure 2.5. Total annual global radiation and its components at midday at different latitudes

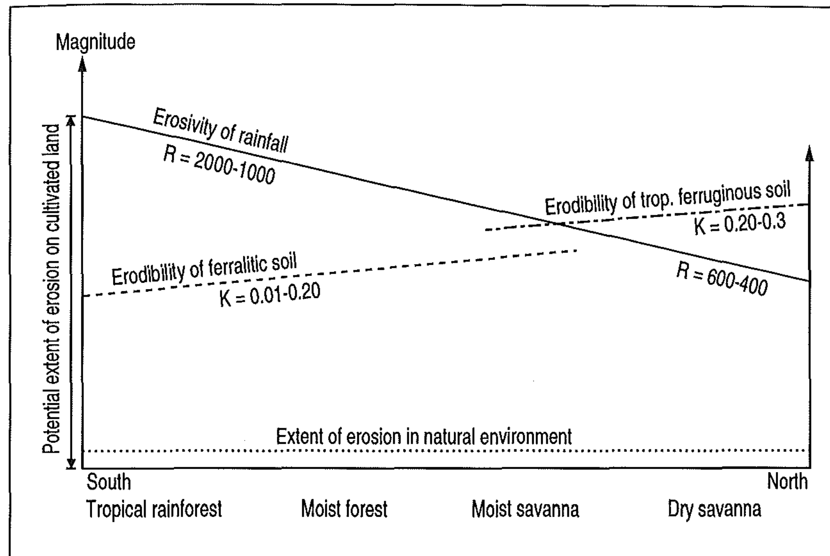


Source: Adapted from SELLERS (1965), cited in WEISCHET (1979)

The intensity of rains, represented in Figure 2.6, also varies widely within the tropics. The example in the figure is based on a gradient from Abidjan in Côte d'Ivoire northwards into Burkina Faso.

In the natural environment, erosion remains almost consistently low. While the intensity of rainfall declines with increasing aridity, soil erodibility increases. The potential extent of erosion on cropland therefore varies greatly and can, under some circumstances, be many times higher than in a natural environment (arrow in left margin, Figure 2.6).

Figure 2.6. Diagram of the response of experimental plots to rainfall intensity, correlated to climate, soil and vegetation



* The values R and K are index values, that represent the erosion-inducing characteristics of rain (rainfall and runoff factor R) and soil erodibility factor K. They are components of the universal soil loss equation from WISCHMEIER and SMITH (1978), in which mean annual soil loss (A) is the product of the factors R x K x L (slope length) x S (gradient) x C (soil use) x P (effect of applied protection measures).

Source: Adapted from ROOSE (1981)

2.1.2 KÖPPEN's Classification

KÖPPEN's Classification (KÖPPEN 1936) was one of the first climatic classification systems ever devised. It came to be used throughout the world and, in principle, is still in use today. Its geographic division is based on homologous climates, generally adjoining, in lowland regions. This system as well as its subsequent adaptations , is based primarily on the influence of climate on (natural) vegetation. It describes five broad climatic zones, of which only the first two - tropical climates A and B - are discussed here.

Tropical humid climates (A). In A climates, all mean monthly temperatures equal or exceed 18°C. KÖPPEN uses moisture conditions to further differentiate tropical humid climates, taking into consideration both the absolute rainfall and its distribution. He identifies (see Table 2.6):

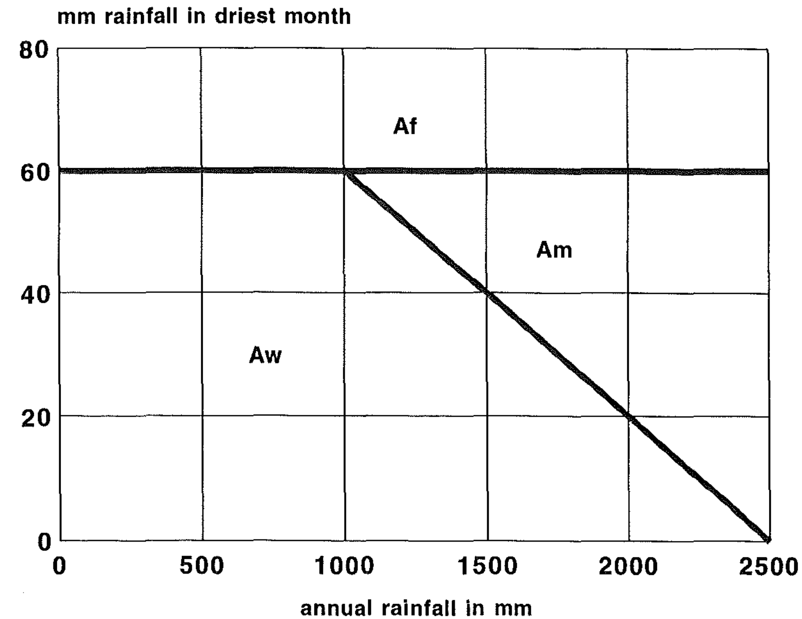
* Af climates (f = lacking a dry season)	with rain during all seasons; more than 60 mm every month
* Am climates (m = monsoon)	with short dry seasons, in which the deeper soil layers remain permanently moist because of high total annual rainfall
* Aw climates (w = winter-dry)	with summer rainfall, also known as savanna climates
* As climates (s = summer-dry)	rare exception

Figure 2.7 illustrates the individual A climates.

In a revised version of this system (TREWARTHA 1954), the lowest temperature limit for the A climates is set at a monthly mean of 17°C. After the Af climate, a further "Ar" climate, with 1-3 months having less than 60 mm, is added.

The boundary between Am and Aw climates can be determined using formula 1 given in Table 2.6. If the rainfall level is 20 mm in the driest month, then annual rainfall must come to at least 2000 mm for a climate to be classified as Am (Ar).

Figure 2.7. Diagram of tropical A climates



Source: Adapted from KÖPPEN (1936)

Tropical dry climates (B). In regions with tropical dry climates "all aspects of life are governed primarily by the lack of water" (KÖPPEN 1936). Because of the sparse cloud cover the temperature differences between night and day are more pronounced (radiation effect).

Table 2.6. Tropical lowland climates, as grouped and defined by KÖPPEN (1936)

Climate / boundary	Symbol	Rainfall
		high
Tropical wet climate	Af	
Boundary formula rn = 60 mm		
Monsoon climate	Am	
Boundary formula (1): R = 25 (100 - rn)		
Tropical wet and dry climate	Aw	
Boundary formula: a) with summer rain R = 20(t+14) b) with evenly distributed rain R = 20(t+7) c) with winter rain R = 20t		
Steppe climate*	BS	
Boundary formula: a) with summer rain R = 10(t+14) b) with evenly distributed rain R = 10(t+7) c) with winter rain R = 20t		
Desert climate	Bw	
		low

R: mean annual rainfall in mm; rn: rainfall in the driest month;
t: mean annual temperature; RS: average rainfall in the summer half of the year

* KÖPPEN's original terminology, used here, sometimes has a different definition nowadays and cannot therefore be used elsewhere. "Steppe", for example, is used today only to describe grasslands outside the tropics

Example: At a temperature of 25°C, the Bs climate boundary lies at 600 mm annual rainfall if all precipitation falls in the summer. If half the precipitation falls in winter, then the boundary lies at 450 mm annual rainfall.

To further characterize a climate, the KÖPPEN system attaches additional lower-case letters. A climate may thus have an index "Afax" meaning:

A: tropical climate
f: humid (all months)
a: at least 1 month > 22° C
x: 2 somewhat bimodal rainy seasons

In the revised system, the letters G for mountain climate (>500 m a.s.l.) and H for alpine climate (>2500 m a.s.l.) are added. According to KÖPPEN (1936), the mountain climates of the tropics are often classified as C climates (non-tropical climates), because they do not fall within the defined temperature boundaries for A or B climates.

Table 2.7. Key to identifying tropical climates (TREWARTHA 1954)

1. Is the site over 500 m a.s.l.?

   yes ——————> 2.
   no ——————> 3.

2. Is the site over 2500 m a.s.l.?

   yes ——————> H climate
   no ——————> G climate

3. Is $R > 20\,(t - 10) + \frac{300\,RS}{R}$?

   yes ——————> 4.
   no ——————> 8.

4. Is the mean temperature of the coldest month $> 17°$ C?

   yes ——————> 5.
   no ——————> C climate (non-tropical)

5. Does rainfall exceed 60 mm in all months?

   yes ——————> Af climate
   no ——————> 6.

6. Is $R > 25\,(100 - rn)$?

   yes ——————> 7.
   no ——————> Aw climate

7. Do more than three months have less than 60 mm of rainfall?

   yes ——————> Am climate
   no ——————> Ar climate

8. Is $R > 10\,(t-10) + \frac{150\,RS}{R}$?

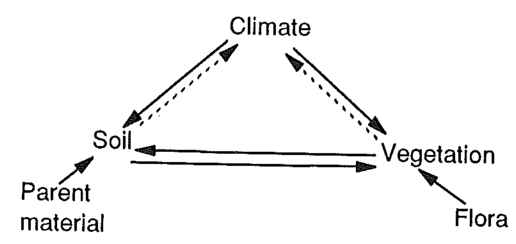
   yes ——————> Bs climate
   no ——————> Bw climate

Definitions: R: mean annual rainfall in mm; rn: rainfall in the driest months; t: annual mean temperature; RS: mean rainfall in the summer half of the year.

2.1.3 WALTER'S Zonation

WALTER's (1964, 1979) zonation is a predominantly geo-botanic, phyto-ecological classification. He divides the tropics into "biomes", which he defines as "large, homogeneous habitats within the geo-biosphere". The system thus strongly reflects the relationships between soil, climate and vegetation (Figure 2.8). WALTER identifies typical zonal habitats, which he describes as "zonobiomes" (having a homogeneous spectrum of life-forms), or "zono-ectones" (which are intergradations between ecological communities). Locations having distinctive features (e.g. sand, salt), or that are characterized by water or relief, occupy a special position.

Figure 2.8. Interaction between climate, soil, and vegetation



Source: Adapted from WALTER (1964)

One result of this phyto-ecological approach is that the quantitative framework varies widely and is therefore less convenient for quick orientation than, for example, the classifications of KÖPPEN or LAUER.[6] WALTER used climatic diagrams to

[6] The complex interaction between vegetation, climate and soil is, however, all the more apparent in WALTER's classification. These are also the most important factors for an agronomic evaluation of an area.

compare local climates. He divided the earth's climates into nine large zonobiomes, the tropics falling within three of these.

Zonobiome I: Equatorial Diurnal Climate (Evergreen tropical rainforest). Approximate statistical range of climatic factors:

Precipitation:	usually ≥ 2000 mm per year
Rainfall distribution:	10-12 humid months, 0-2 dry months (months with < 100 mm are regarded as dry)

This zone has a constant equatorial climate, exhibiting only slight fluctuations in rainfall over the year (one or two periods with somewhat less rainfall). Weeks without rainfall can also occur in this zone. The climate data from San Carlos de Rio Negro (Venezuela) are typical for this zone. Approximate range of further climatic data:

Temperatures:	annual mean of about 25 - 27°C
Temperature variation:	day - night: 2°C (cloudy) to 10°C (clear)
	monthly mean: 1-2°C
Relative humidity:	at 6:00 hrs usually ≥ 90%
	at 13:00 hrs ≤ 70%
Evaporation (E_o):	about 2-4 mm/day (possibly higher in open areas)

Zono-ectone I/II: Transition Zone (Semi-evergreen, tropical rainforest). This zone occupies an intermediate position between the constantly humid and the subhumid climates. It extends up to around 10° latitude. The dry periods of the "winter" season are more definite, whereas those of the summer decrease. Lambaréné, in the Congo, has such climatic conditions. Approximate range of climatic data:

Temperatures:	annual mean	24 - 27°C
Temperature variation:	monthly mean:	2 - 4°C
	day - night:	5 - 10°C
Precipitation:	1500 - 2000 mm/year	
Rainfall distribution:	8 - 10 humid months	
Evaporation (E_o):	2 - 4.5 mm/day	
Relative humidity:	varies with season: rainy season 70 - 100%	
	dry season 60 - 90%	

Zonobiome II: Tropical Summer-rainfall Climate (Deciduous forest zone). The climate in this zone is characterized by a warm, moist to perhumid summer season and an arid dry season during which temperatures increase until the next rainy season. The seasonal rhythm of vegetation and life (flora, soil-life, fauna) is well defined. Tamale, in northern Ghana, is an example of such a climate. Approximate range of climatic data:

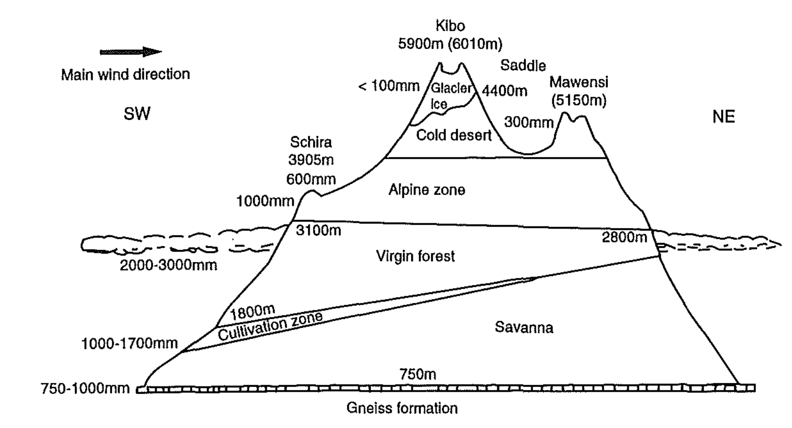
Temperatures:	annual mean about 25 - 28°C
Temperature variation:	monthly mean: 5 - 7°C
	day - night: about 10°C (8 - 15°C)
Precipitation:	usually 900 mm
Rainfall distribution:	7 - 9 humid months (3 - 5 arid months)
Evaporation (E_o):	3 - 5 mm/day
Relative humidity:	varies with season: rainy season 70 - 100%
	dry season 20 - 50%

The amount of rainfall (absolute) and the length of the rainy season can partially compensate each other in this zone, providing the soil is capable of storing water.

Zono-ectone II/III: Savanna Climate (shrub- and grassland). According to WALTER, the climatic savanna must be clearly distinguished from the anthropological and edaphic savannas. He regards a climatic savanna as a vegetation type that may develop over relatively extensive areas in the zone between moist or dry deciduous forests and deserts. Typically consisting of grass- and shrubland, dotted with single trees or groups of trees, climatic savanna most often occurs in areas receiving about 500 to 600 mm annual precipitation. Typical of this climate is a notable temperature increase before the start of the summer rainy season. Rainfall averages taken over many years show high variability. The climate diagram of Niamey (Niger) is an example. Approximate range of climatic data:

Annual mean:		26 - 29°C
Temperature variation:	monthly mean:	10 - 12°C
	day - night:	about 16°C (10 - 20° C)
Precipitation:	400 - 900 mm/year	
Rainfall distribution:	3.5 - 5 humid months	
Evaporation (E_O):	3.5 - 7 mm/day	
Relative humidity:	varies with season: rainy season: 60 - 90%	
		dry season: 10 - 50%

Figure 2.9. Schematic vegetation profile of Mount Kilimanjaro giving the approximate annual rainfall (mm) for various elevations



Source: WALTER (1964)

Zonobiome III: Desert (and semi-desert). Zones with less than 3 to 4 humid months and receiving less than 200 mm of rainfall are defined as desert climates.

Mountain climates, described as mountain habitats (orobiomes), occupy a special place in WALTER's system (see Figure 2.9). Such habitats will be further considered in Section 2.1.5.

2.1.4 HOLDRIDGE'S Classification

HOLDRIDGE's (1967) classification, which also attempts to use vegetation formations as a basis, classes elevation and latitudinal zones together.

Annual mean temperatures, annual precipitation, and potential evapotranspiration (measured from an unrestricted water surface) are components in this classification system.

Rainfall distribution is not taken into account at all. The result is that the grasslands of the *llanos* in South America appear in the same zone as the rainforests of the Amazon Basin. This classification, which is often used in South America, is thus less useful for agricultural purposes. It is depicted in Figure 2.10.

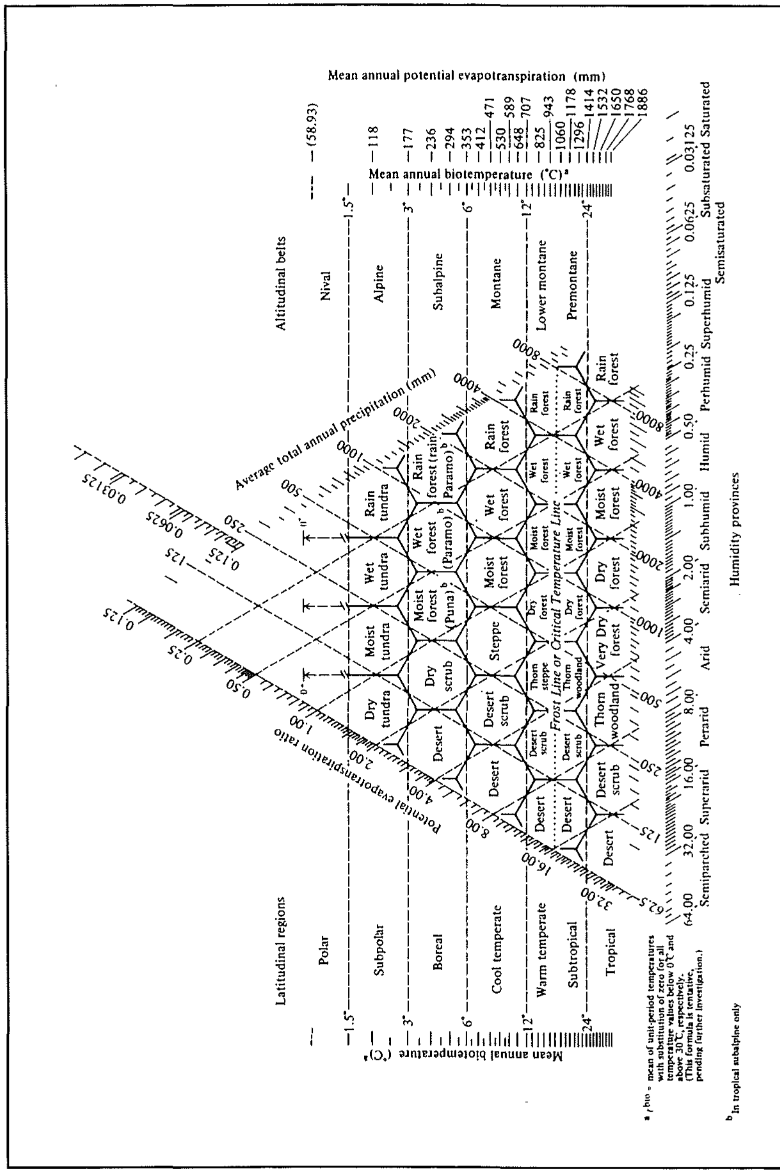


Figure 2.10. HOLDRIDGE´s classification

Source: HOLDRIDGE (1967)

2.1.5 Mountain habitats

Highlands are nowadays considered as land form better rather than a specific agro-ecological zone. The growing conditions they provide for crops vary considerably according to altitude, slope, soil depth and type. Because temperatures are relatively even throughout the year, rainfall (and its distribution), humidity and water resources also characterize the seasons in tropical mountain areas. In addition, there is the impact of specific thermal conditions (such as dramatic cooling at night due to surface radiation), special sunlight conditions[7] and the effect of topographical features, which greatly influence the local situation. These contribute to the development of ecological communities that cannot be compared with those of lowland climates, nor with temperate climates. The example of maize cultivation clearly demonstrates this point. Bogotá and a location in Europe both have a mean annual temperature of 14.5°C; during an average summer in Europe, maize requires some 5 months to mature, whereas in Bogotá, due to the widely fluctuating diurnal temperatures, 9 to 11 months is required for the crop to assimilate the warmth necessary to reach maturity.

Slope gradient has a strong bearing on local climate. Moreover, in the inner tropics, a distinction must be made between east- and west-facing slopes. Slopes facing eastwards receive sunlight longer, as cloud cover typically begins to develop around noon.

The vegetation has a stabilizing effect on temperature changes near the soil surface. By planting shade trees (*Inga* spp.) above coffee bushes, farmers in Colombia are able to grow coffee up to almost 2000 m a.s.l.

The physical character of the mountains is a further important factor. The upper elevation limit for cultivation is reached far sooner on isolated mountains than on extensive, raised land masses. Hence coffee is grown in the Cameroon Mountains

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[7] At tropical alpine elevations, especially in the outer tropics, direct solar radiation under a clear sky is very intense and the contrast between light and shadow extremely high, resulting in pronounced differences in exposure for the vegetation (WEISCHET 1979). In the humid intertropics, this effect is lessened by the high humidity, and more particularly by increased cloud cover.

only up to 1200 m a.s.l., while it can be found in the South American tropics at almost 2000 m (TROLL 1959).

The upper limit for cultivation, like the timber line, is determined by the air temperature and precipitation conditions (TROLL 1966). WALTER (1979) highlights the significance of soil temperature as a limiting factor (for root growth, etc).

Classification. Based on conditions prevailing in South America, TROLL (1959) classes the elevation levels in the tropics into five categories (see Figure 2.11). In the humid tropics, the term ***tierra caliente*** (up to ~ 1000 m) describes the vegetation level of the tropical lowland rainforest.

The ***tierra templada*** (above about 1000 m) describes the tropical lower montane forest. This zone is still completely free of frost, and coffee, tea and numerous fruits are typical of this zone, which usually has high convective rainfall.

In the ***tierra fria*** (about 1800 to 2300 m) tropical upper montane forest is the typical vegetation. Occasional frost may be expected in this zone. The crops grown here are often those common in temperate zones. The forests are characterize by declining temperatures and increasing moisture as elevation increases. Epiphytes, ferns, mosses and bamboo (the latter especially in Africa) characterized the more dense forests, which derive a considerable share of their moisture from cloud and mist.

The level at which maximum rainfall occurs may be higher or lower, depending on rainfall amounts or conditions (see Figure 2.12). In humid climates, rainfall and cloud layers occur at lower elevations (in Colombia, as low as about 1000 to 1500 m), whereas in drier regions they rise to higher levels (in Ethiopia, 1800 to 2500 m).

Adjoining the *tierra fria* is the ***tierra helada***, with its *Páramo* vegetation and tropical tallgrass ranges. And beyond that lies the permanently snow-covered ***tierra nevada***.

HOLDRIDGE's (1967) high-altitude climates are shown in Figure 2.12.

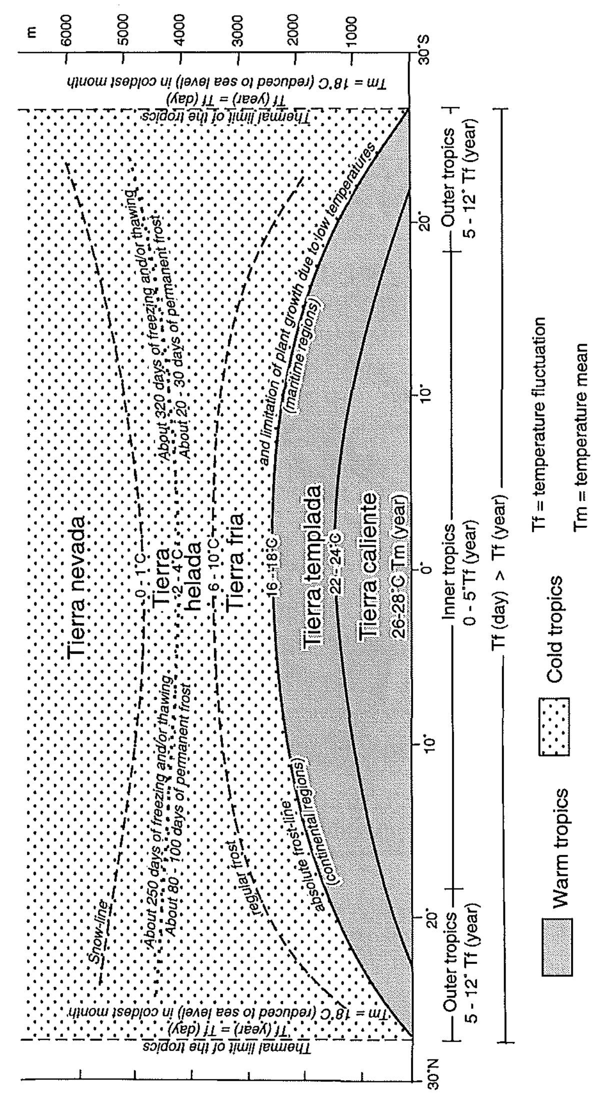
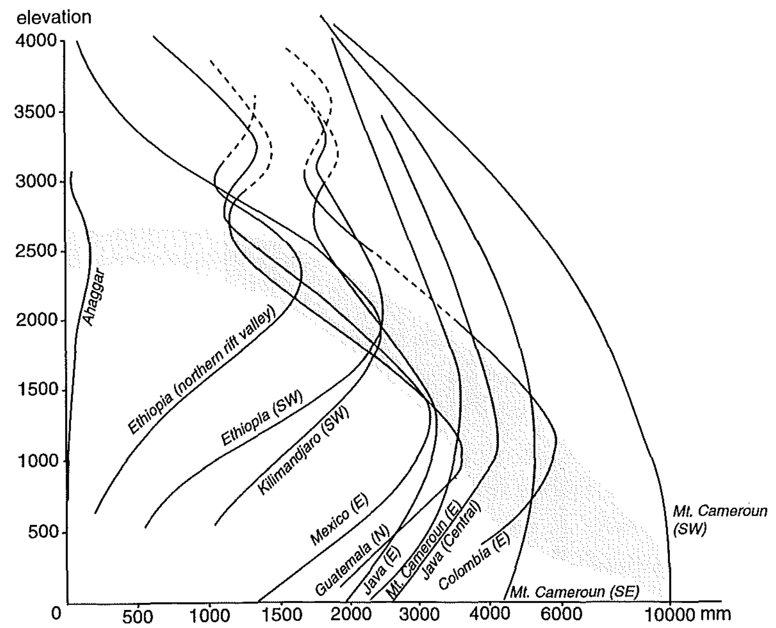


Figure 2.11. Elevation zones in the tropics

Source: LAUER (1975)

Figure 2.12. Annual rainfall totals for various mountain slopes related to height above sea level.*



* Hatched area = elevation of maximum rainfall

Source: Adapted from LAUER (1976), cited in HAFFNER (1982)

2.1.6 Proposed climatic zonation of the tropics: Comparison with other classification systems

The zonation proposed for the purposes of this book is identical with LAUER's (1952) and was also used by TROLL (1964). It has the advantage of being comparatively easy to use, while the terms it employs for individual vegetation zones are in general use in the German literature.

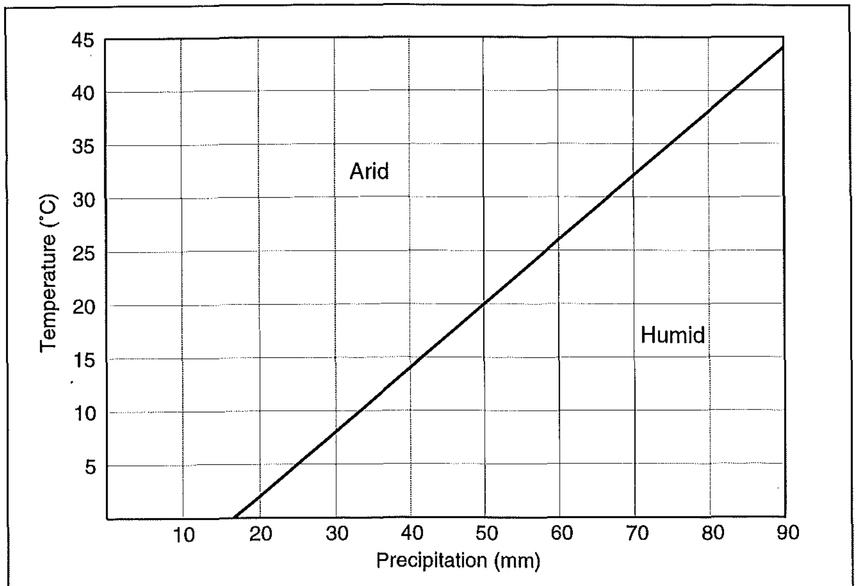
The basis for classification is the number of humid months. Research by LAUER (1952) in Africa and South America showed this to be a viable criterion for categorizing vegetation formations. In addition, the humidity of a month is defined by means of the following aridity index:

$$N \geq 5 \frac{(t + 10)}{3}$$

where N = Mean monthly rainfall, T = Mean monthly temperature (adapted from DE MARTONNE 1926; cited in LAUER 1952). This is because evaporation values are only available for a few locations. If values from evaporation tanks (E_O) are used, $N \geq 0.5\ E_O$ can be regarded as a crude equivalent. However, the duration of humid periods defined in this way only roughly equals that of the growing periods.

Given the mean monthly rainfall and monthly temperature, the nomogram shown as Figure 2.13 can be used to determine the aridity or humidity of a site without calculation.

Figure 2.13. Nomogram for determining the aridity or humidity of a month.
Aridity index adapted:
$12n = 20\ (t + 10) \rightarrow n = 5\ (t + 10)/3$.



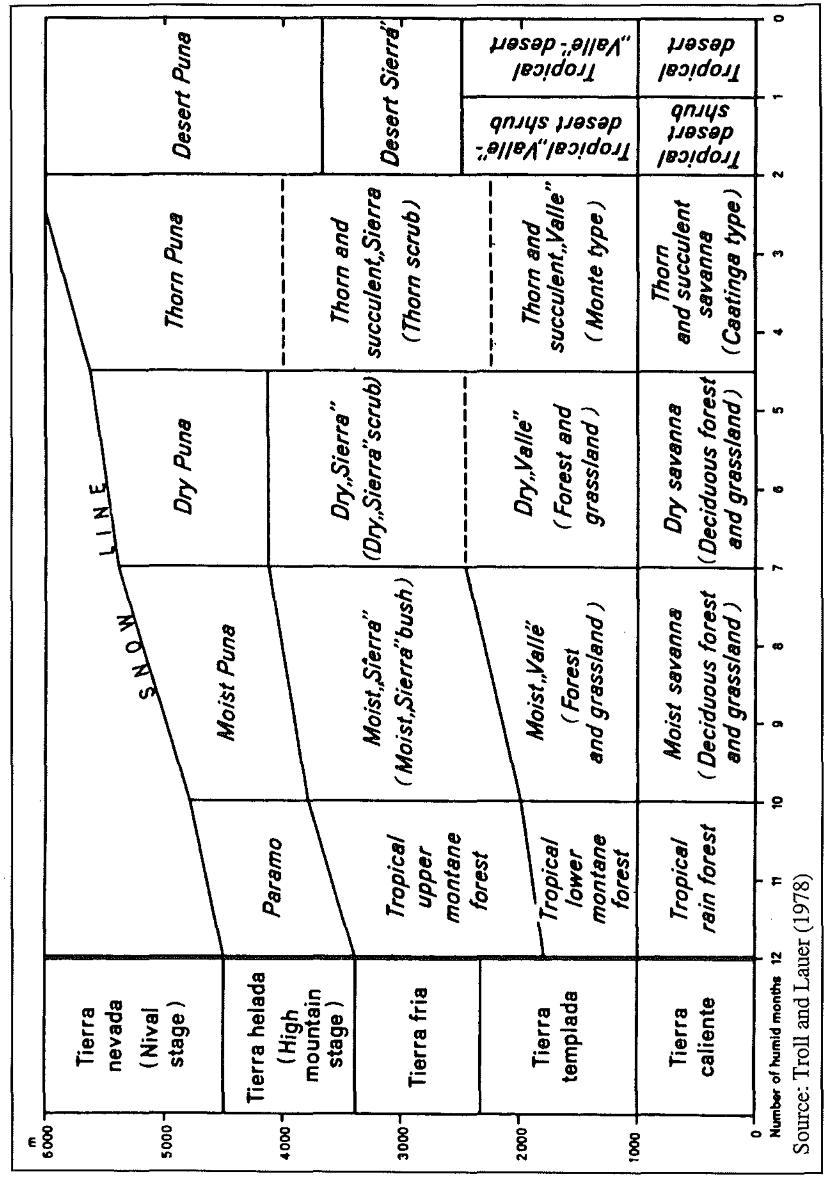
n = Monthly rainfall (mm); t = Temperature (°C)

Source: Adapted from DE MARTONNE (1926), cited in LAUER (1952).

For rapid orientation, maps are even more practical. The charts by TROLL (1964) show the "seasonal climates of the earth". On these, the lowland tropics are grouped following the system used by LAUER (1975). They can therefore be used directly as synoptic charts.

The disadvantage of these charts is that they are drawn to a very large scale (1 : 36 million and 1 : 45 million). The impression they give of local conditions is therefore inaccurate. Whenever sufficient data are available, the user should work out the classification of the locality himself.

Figure 2.14. Horizontal and vertical pattern in the tropical Andes



Source: Troll and Lauer (1978)

Figure 2.15. Climatic zonation of the tropics and comparison of different systems of classification

Zone	Humid months (according to LAUER (1975))	Vegetation (according to LAUER (1975))	CHEVALIER(1933)	KÖPPEN (1936)	HOLDRIDGE (1967)	WALTER (1979)	Important crops
I Humid	9.5-12[1]	Tropical rainforest	Forêt equatoriale ca. >1500 mm[2]	Af, Am, Aw	Rain forest Wet forest Moist forest (Dry forest)[3]	Evergreen tropical rain forest ca. > 2000 mm[2]	Rubber Oil palm Cocoa Robusta coffee
II Semi-humid	7-9.5	Moist savanna (Deciduous forest and grassland)	Zone guinéenne/ Savanne sub-forestière ca. 800-1500 mm	Af, Am, Aw	Dry forest Very dry forest	Semideciduous forests ca. 1200-2000 mm	Coconut Banana Yam
III Semi-humid/ Semi-arid	4.5-7	Dry savanna (Deciduous forest and grassland)	Zone soudanaise ou du brousseparc ca. 500-900 mm	Aw, BS	(Dry forest) Very dry forest (Thorn woodland)	Deciduous forests ca. 500-1200 mm	Cassava Cotton Maize Groundnut
IV Semi-arid	2-4.5	Thorn and succulent savanna	Zone sahelienne ou des épineux ca. 150-500 mm	(Aw), BS, BW	(Very dry forest) Thorn woodland	Climatic savannas ca. 200-500 mm	Sorghum Millet Climatic limit of rainfed cropping
V Arid	0-2	Tropical desert and desert shrub	Zone sub-saharienne et saharienne	BS, BW	Desert scrub Desert	Semidesert and deserts ca. <300 mm	

(Humid-months scale: 12, 11, 10, 9, 8, 7, 6, 5, 4, 3, 2, 1, 0)

1) The principal criterion of this zonation is the number of humid months, calculated according to the aridity index of DE MARTONNE/LAUER (see Figure 2.13).
2) The figures for annual rainfall are indicative only. Large differences may occur in specific regions. For example, Conakry, with 7 humid months lies in zone II, but has 4500 mm annual rainfall.
3) Zones indicated in parenthesis occur only in exceptional cases.

Figure 2.15 continued. Climatic zonation of the tropics and comparison of different systems of classification

Zone	Mean annual temp.	Altitude (approx.)	TROLL (1959) LAUER (1975)	CHEVALIER(1933)	KÖPPEN (1936)	HOLDRIDGE (1967)	WALTER (1979)	Important crops
VI High mountain climate	3 C 6 C	4000 m 3500m	tierra helada		C	Subalpine	Orobiomes	
	9 C 12 C	3000 m 2500 m	tierra fria			Montane	(Mountainous live spheres)	Pyrethrum Barley Potato Tea Arabica coffee
	15 C 18 C 21 C	2000 m 1500 m 1000 m	tierra templada		A, B, C	Lower montane Premontane		
I-V	24 C	500 m	tierra caliente			Tropical		