Chapter 3. CLIMATE

by
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The region denoted in the Land Systems Map extends from a little north of the Tropic of Capricorn to the approximate position of the "meteorological equator" at 10°N. It thus encompasses two distinct climatic regimes-the equatorial (with little change in seasons) and the tropical (with stronger variations). The term "tropical" in this case refers to the areas found both north and south of the central equatorial regions and is preferred for preciseness over the loose term, the "tropics," which is generally used to refer to both regimes.

This chapter briefly describes the major factors determining the climate of these regions; presents a general analysis in terms of some of the better known climatic classifications; and then proceeds to a more detailed description of the estimation of growing-potential as used in the Land Systems Map.

Major Climatic Determinants

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The major climatic determinants of both the equatorial and tropical regimes are the South Atlantic anticyclone and the equatorial trough since the Andes effectively isolate the region from strong effects of the Pacific anticyclone. As do Snow (I 976) and Riehl (I 979), we prefer the term "equatorial trough" to Intertropical Convergence Zone (ITCZ), because, while the low-pressure trough may be readily distinguished, the actual zone, or zones, of convergence are ephemeral and the position may only be fixed by averaging over time. Thus the ITCZ may be considered an active part of the equatorial trough.

The Equatorial Trough

The position of the equatorial trough follows the seasonal march of the sun, but lags behind by about 2 months. The range of movement from north to south is very limited, when compared with other continental situations. The equatorial trough is centered at 5 to 10°N during its most northerly advance in August/September and at 0 to 5°S in February/ March (Figure 3-1). During the southern summer, a continental heat low develops over northern Argentina, Paraguay, and Bolivia. Fr6re et al. (1975) point out that some authors attribute this low to an extension of the equatorial trough, whereas others maintain that it is a separate phenomenon. In either case, the result is the same: an extended area of high instability and heavy rain in the western portion of the study area during the southern summer.

Polar Air Masses

Invasions of the cold polar air mass are common during the southern winter and can produce marked and rapid drops in temperature as the cold front passes northward. The air mass tends to be channeled between the Andean highlands and the central Brazilian shield, frequently reaching the upper Amazon and occasionally spilling over the Orinoco basin into the Caribbean. The cool change, known in Brazil as *friagem* and in Bolivia as *surazo,* may last for 3 to 5 days or, in exceptional cases, up to 15 days. The northerly extent of a typical cold front is shown in Figure 3-1 (Ratisbona, 1976).

Rainfall Patterns

Rainfall patterns follow the movement of the equatorial trough and the development of the continental heat low. They are further modified by interaction with the maritime air masses. Thus, the western equatorial zone has no distinct dry season, but a bimodality may be discerned in the rainfall figures. As one proceeds eastward in the equatorial zone, the dry season becomes more marked and the bimodality less so. The bimodality remains in the southeastern section of the equatorial zone as the *veranico,* a short dry spell that may occur in the middle of the wet summer.

On either side of the equatorial zone, typical tropical patterns of summer rainfalls and dry winter periods are noticed. Rain in the southeastern portion of the study area (Mato Grosso and Goias) appears to be due to winds from the upper Amazon. In this, the upper Amazon behaves more like a maritime zone than a continental one. Indeed, as is pointed out by Ratisbona (1976), the potential evaporation of the equatorial forest, greater than 1300 mm/year throughout the region, is actually higher than that from an ocean surface, due to its lower albedo (percentage reflection of radiation). The drylands of northeast Brazil (including the Caatingas) are the result of insufficient penetration of either the maritime or the moist upper Amazon (equatorial continental) air masses to this intermediate region.

Climatic Classifications

Köppen Classification

Many schemes have been devised to classify the climates of the world, but perhaps the most widely known is that of

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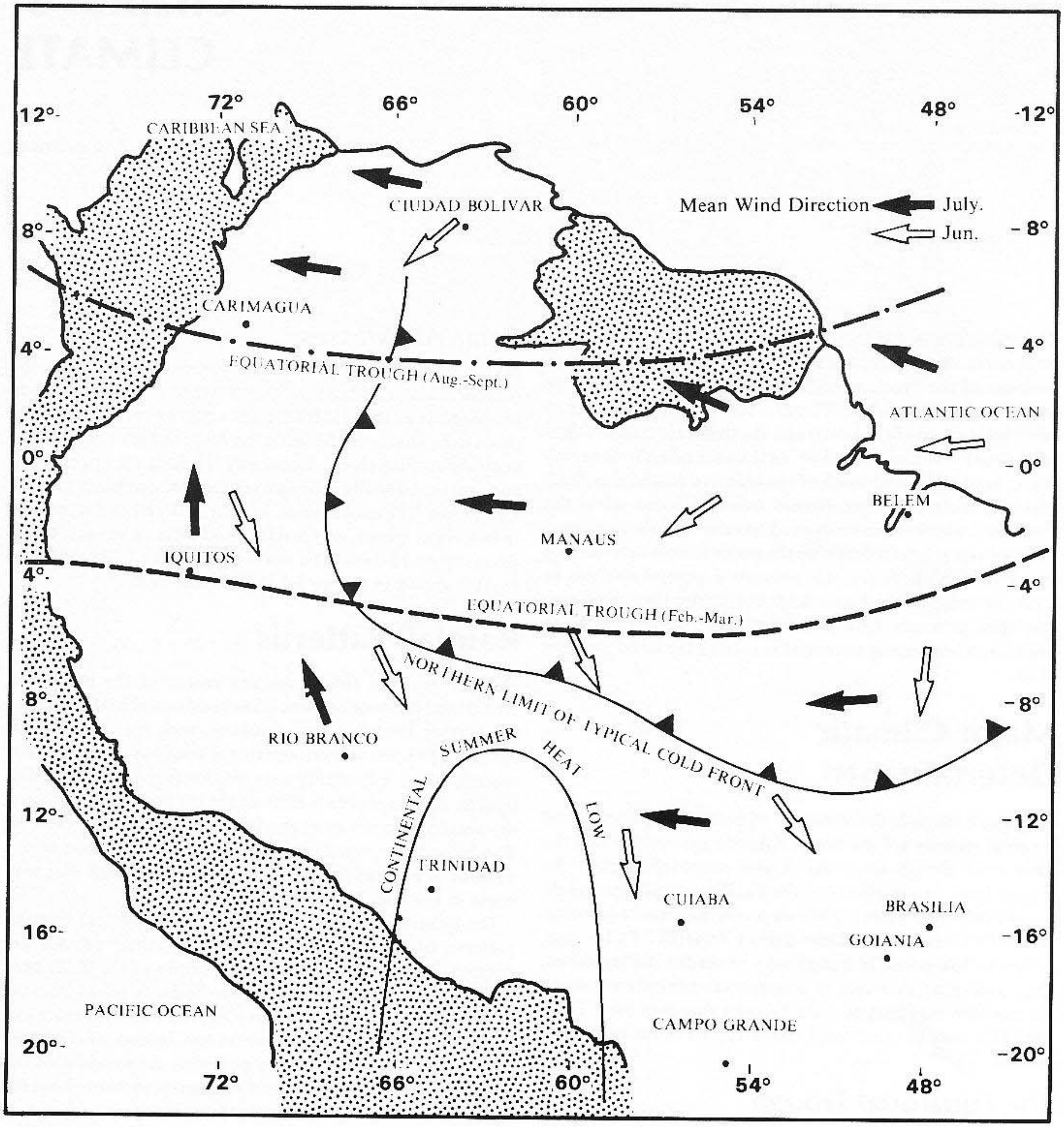

Fig. 3-1 Major determinants of climate throughout the study area, showing mean wind direction and position of the equatorial trough.

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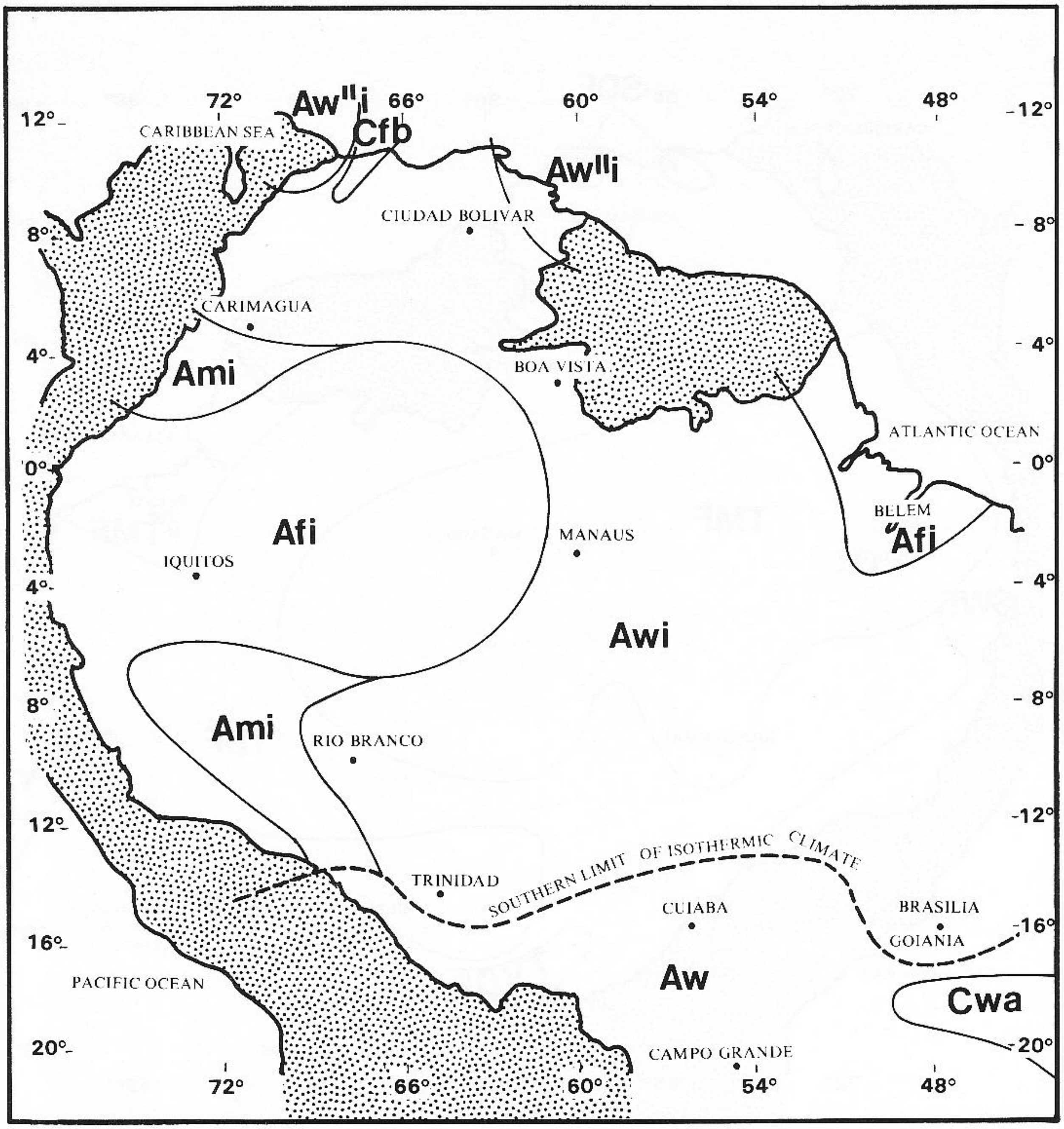
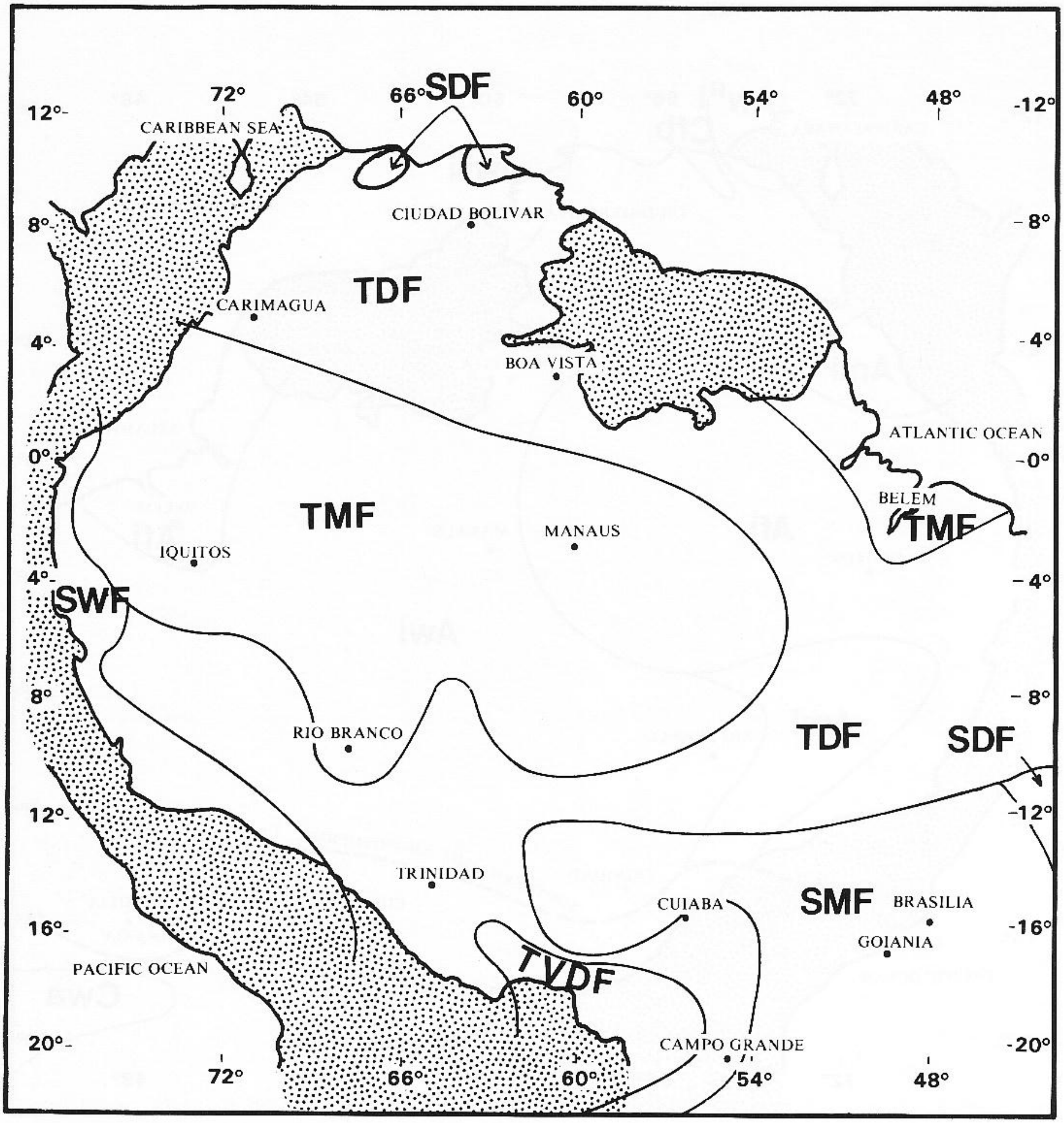


A. = tropical: no month with mean temperature less than 18°C
C. = temperature: some months less than 18°C

f. = rainfall all year round
m. = monsoonal rainfall
w = predominantly winter rainfall

w" = bimodal rainfall

Fig. 3-2 Köppen climatic classification of the study area.



TMF	= Tropical Moist Forest	**SWF**	= Subtropical Wet Forest
TDF	= Tropical Dry Forest	**SMF**	= Subtropical Moist Forest
TVDF	= Tropical Very Dry Forest	**SDF**	= Subtropical Dry Forest

Fig. 3-3 Holdridge life zone classification of the study area.

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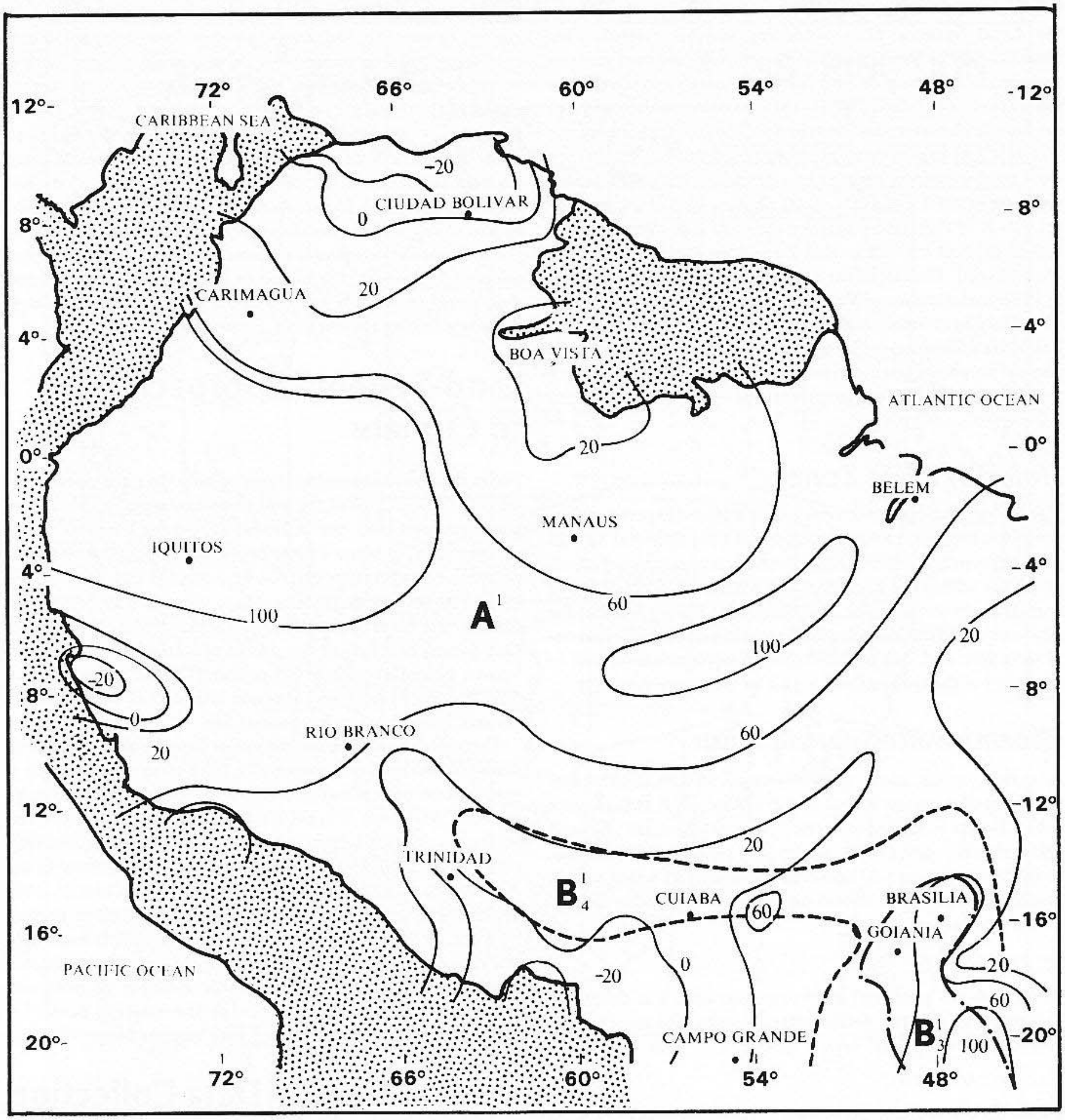

A¹ = Megathermal: thermal efficiency > 1150 mm
B^1_4 = Mesothermal: thermal efficiency 1000–1150 mm - - -
B^1_3 = Mesothermal: thermal efficiency 860–1000 mm -.-.-.-

Fig. 3-4 Thornthwaite moisture index isolines and thermal provinces in the study area.

Köppen (see Stringer, 1972). Figure 3-2 classifies the area in the Land Systems Map according to this system. This classification is based on rainfall and temperature regimes and separates the region into two areas: north and south. The separation lies at about 15'S-the line between the northern isothermic climate types (less than 5'C difference between the warmest and coolest months) and the southern climate types with cooler winters (more than 51 difference). The upper Amazon is differentiated as **Af**, that is, as having no dry season. It is flanked by smaller zones of **Am** where the dry season is short enough so that no serious moisture deficit is encountered. The rest of the area has one marked dry season, or in restricted zones of Venezuela, two dry seasons (denoted w"). Only very small high-altitude areas in Venezuela and Brazil are differentiated by their lower temperatures from the general tropical classification. It is obvious from the figure that this system does not sufficiently delineate the area on the Land Systems Map.

Holdridge Life Zones

The Holdridge (1967) life zone classification (Figure 3-3) is a simplistic scheme, taking into account only the total annual precipitation and the mean annual biotemperature, which, at all points within the Land Systems Map area, is equal to the annual mean temperature. It is clear from Figure 3-3 that the life-zone classification fails to differentiate climates by seasonal variation, and, due to difficulties of nomenclature, fails to account for the tro ical rain forest in the upper Amazon.

Thornthwaite Classification

A system much more closely related to the agricultural potential of a region is that of Thornthwaite (1948) (Figure 3-4). Climate is defined in terms of a moisture index (Im) and thermal efficiency (TIE), which is equal to the potential evapotranspiration (e). Seasonal variations in water supply and temperature (not shown on Figure 3-4) are also used as classifying factors. Thus,

$$I_m = I / e\ (100s\text{-}60d)$$

where e is the potential evapotranspiration, s is the water surplus, and d is the deficit after allowing for rainfall and stored soil water. And,

$$e = 1.6(10\ t/I)^a$$

where t is monthly temperature (°C), I is the heat index, a is a cubic function of the heat index, and e is the evapotranspiration in cm per month. The sum

$$I = \sum_{j=1}^{12} (t_j / 5)^{1.514}$$

defines the heat index (1), where t is the mean temperature of month j.

The Thornthwaite method suffers from the fact that evapotranspiration is estimated from temperature data and is not necessarily universally reliable, but it does allow an estimate in many situations where more accurate formulas cannot be applied. Using this system, the majority of the region in the Land Systems Map is classified as megathermal (thermal index > 1150 mm), with only the highlands of the Brazilian shield falling into the mesothermal (< II 50 mm) class. The moisture index was calculated assuming a 150 mm soil water-holding capacity. The perhumid region, with a moisture index above 100, quite closely follows the actual extent of the tropical rain forest in the upper Amazon. Due to lower evapotranspiration rates in the rather cooler region to the south of the Amazon and east of Manaus, however, there appears to be a second perhumid region, which does not correlate with rain forest. Because no attempt was made to follow topography in the sketch map, the extent and shape of this area are not necessarily realistic depictions. The subhumid areas in Venezuela, the Peruvian foothills, the area around Boa Vista in northern Brazil, and the Brazilian shield are well delineated using this method, however.

Land-Systems Approach to Climate

From the above examples, it can be seen that it is possible to classify the climates of the area in several ways, all similar in some respects and yet different in others. Each of these systems fails, in some way or other, to account for observed patterns of vegetation and/or agricultural potential of the area. For the Land Systems Map, then, it was decided to concentrate on recording characteristics of the environment that would best reflect the range of variation in growing season potential within the region. This is intended as a description of the region; it is not intended as an alternative climatic classification for general use.

Throughout the tropics, the major determinant of growing season is soil moisture. Normally, long-term mean rainfall is used to determine moisture availability, but this does not take seasonal variation in rainfall into account. The expected seasonal variation within the area on the Land Systems Map ranges from a 10-15% average departure from normal in the Amazon basin and northern regions of the area to a 25-30% departure in the drier eastern Brazilian re ions (Biel, quoted by Riehl, 1979). Clearly an estimate of water supply must take this range into account. Therefore, an estimate of dependable precipitation and the best available estimate of potential evapotranspiration were chosen as the starting point for climatic determination for the Land Systems Map.

Meteorological Data Collection and Compilation

Long-term (more than 20-years) data records from over I 100 meteorological stations (Figure 3-5) were initially gathered, and meteorological data sets were compiled as an integral part of the land-resource database. [b]

Table 3-1, prepared from the computer printout of the climatic data for Luziania (Hancock et al., 1979), located in

b. This work was carried out as a subcontract to the survey by Hancock, et a]. (1979) of Utah State University; it has since been assimilated into CIAT's South American Meteorological Data (SAMMDATA) computer files.

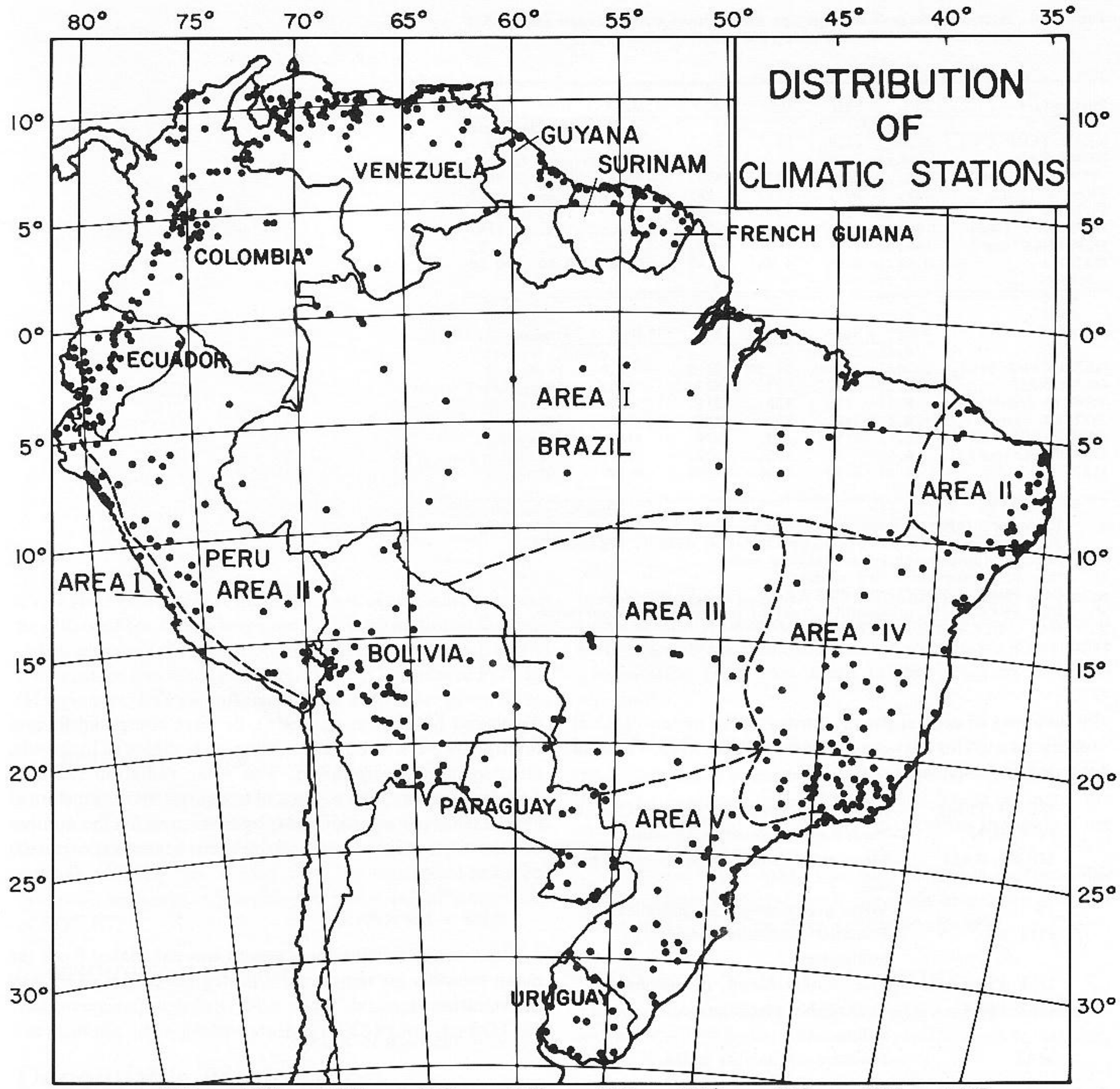

Fig. 3-5 Distribution of meteorological stations (●) and regions for dependable precipitation calculations (country and area boundaries). (Source: Hancock et al., 1979)

Table 3-1. A meteorological data set of Luziania, Central Brazil (16°15'S latitude, 47°56'W longitude, 958 amsl).

Parameter[a]	Jan	Feb	Mar	Apr	May[b]	Jun[b]	Jul[b]
MEAN TEMP (°C)	21.9	22.0	21.7	21.1	19.4	18.3	18.1
MEAN RAD (Langleys/day)	574.	523.	481.	495.	452.	440.	461.
PRECIP (mm)	228.	201.	229.	96.	16.	7.	4.
POT ET (mm)	164.	135.	136.	134.	120.	110.	118.
DEF PREC[c] (mm)	-65.	-66.	-93.	38.	104.	103.	114.
DEP PREC[d] (mm)	141.	123.	142.	53.	0.	0.	0.
MAI[e]	0.86	0.91	1.04	0.40	0.00	0.00	0.00

	Aug[b]	Sep[b]	Oct	Nov	Dec	Annual
MEAN TEMP (°C)	20.0	22.1	22.3	21.9	21.6	20.9
MEAN RAD	512.	526.	529.	527.	475.	500.
PRECIP (mm)	5.	27.	130.	215.	317.	1475.
POT ET (mm)	139.	146.	152.	145.	134.	1632.
DEP PREC[c] (mm)	133.	119.	22.	-70.	-183.	157.
DEF PREC[d] (mm)	0.	7.	76.	132.	200.	
MAI[e]		0.00	0.05	0.50	0.91	1.49

a. In order, refer to mean temperature, mean radiation, precipitation, potential evapotranspiration, precipitation deficit, dependable precipitation, moisture availability index.
b. May to September = dry season.
c. DEF PREC = PRECIP - POT ET.
d. DEP PREC = 75% probability level of precipitation occurrence.
e. MAI = DEP PREC ÷ POT ET.

the savannas of central Brazil, illustrates the meteorological summaries used for drawing the Land Systems Map. The data recorded and calculated are:

MEAN TEMP	Mean temperature, in degrees Celsius.
PCT SUN	Percentage of possible sunshine.
MEAN RAD.	Mean solar radiation, in Langleys per day.
PRECIP.	Mean precipitation, in millimeters.
POT ET	Potential evapotranspiration, in millimeters.
DEF PREC	Precipitation deficit, in millimeters.
DEP PREC	Dependable precipitation, in millimeters.
MAI	Moisture availability index.

For some stations, the relative humidity was also estimated and appears on the printout as MEAN R.H.; for others, mean maximum and minimum temperatures are also recorded.

Mean Temperature

When temperature data (MEAN TEMP) were not available for a station, an estimate was made based on data from stations closely related geographically and by taking into account the relationship between elevation and temperature. Temperature decreases by an amount of about 0.0055 times the elevation in meters, or 5.5'C for every 1000 meters of increase in elevation.

Mean Solar Radiation

When solar radiation data (MEAN RAD.) were not available for a station, estimates were made from solar radiation maps developed by Loft et al. (1966), or were computed from a multiple-regression equation using such values as longitude, latitude, and precipitation. The solar radiation (RS), in Langleys . per day, was converted to equivalent millimeters of evaporation per month *(RSA4)* by correcting for the number of days in the month (D* and the latent heat of vaporization of water (L) as:

$$RSM = DM \times RS/L$$

The average L value for a month was calculated from the mean monthly air temperature in degrees Celsius *(TMC)* by the equation:

$$L = 595.9 - 0.55 \times TMC$$

Potential Evapotranspiration

Potential evapotranspiration (POT ET) was calculated to determine the water balance and growing seasons. It is usually referred to as the water consumption of an extended surface of 8- to 15-cm tall, green grass cover that is actively growing and completely shading soil well supplied with water. However, Monteith (1 973) notes that "experience on experimental sites ranging from field plots to large catchments has shown that the restriction to short green cover is unnecessary." An accurate estimate of POT ET is a most useful climatic parameter in helping to judge the agricultural potential of an area, especially in comparing similarities and differences in climatic regimes and predicting irrigation and drainage needs.

From physical considerations, it is well recognized that air temperature, radiation balance, humidity, and wind speed are all necessary factors in estimating evaporation from a surface (Penman, 1963). Many workers have shown that empirical relationships using only temperature are inadequate, but that

Table 3-2. Regression coefficients for determining dependable precipitation, by location.

Region/Country	Area	A value	B value
Central America		-23.0	0.84
South America			
Brazil	I	-20.0	0.85
	II	- 9.0	0.57
	III	-23.0	0.79
	IV	-11.0	0.67
	V	-11.0	0.67
Bolivia		-10.0	0.69
Colombia		-25.0	0.84
Ecuador		- 5.0	0.64
French Guiana		-25.0	0.84
Guyana		-14.0	0.77
Paraguay		-10.0	0.69
Peru	I	- 1.0	0.18
	II	- 5.0	0.70
Surinam		-14.0	0.77
Uruguay		-10.0	0.69
Venezuela		-14.0	0.77
Caribbean Islands		-23.0	0.84

if radiation estimates are included, an acceptable estimate can be obtained for sites where complete information is lacking.

Hargreaves' (1977a) equation based on solar radiation and temperature was used to calculate POT ET; values of POT ET (Hargreaves' ETP) in millimeters per month are given by his equation:

$$ETP = 0.0075 \text{ X } RSM \text{ X } TMF$$

in which *RSM* is incident solar radiation, expressed as equivalent millimeters of evaporation per month, and TMF is the mean monthly temperature in degrees Fahrenheit. Hargreaves (1977b) has shown that his equation compares favorably with other equations that give acceptable estimates of POT ET.

Precipitation Deficit

The precipitation deficit (DEF PREC) is simply the difference between the mean precipitation (PRECIP) and the POT ET.

Dependable Precipitation

Dependable precipitation (DEP PREC), at the 75% probability of precipitation occurrence, is the amount of precipitation that will be equaled or exceeded in 3 out of 4 years. The probability distribution of monthly rainfall amounts is known to be skewed markedly toward the lower values. For this reason, some workers, for example Fr6re et al. (1975), have used a log normal distribution to estimate the dependability of rainfall. A better approximation is the gamma distribution; although it is rather more trouble to calculate, the gamma distribution can now be done readily with the aid of a highspeed computer. Hancock and his collegues at Utah State University have produced gamma-distribution estimates of dependable precipitation for many stations in the area shown in the Land Systems Map. However, in order to be able to fit the distribution, a large number of years of record must be available. Unfortunately, many stations in the area have an insufficient period of record. It was noticed (Hancock et al., 1979), however, that there is a strong linear relationship between the mean monthly rainfall and dependable precipitation if the sample is restricted to a climatically uniform area. It is thus possible within each subarea to estimate dependable precipitation (Pd) from mean rainfall (Pm) by a simple equation:

$$P_d = a + bP_m$$

The coefficients *a* and *b* were estimated by the Utah group from the existing gamma distributions. These estimates are shown, by region, in Table 3-2; the regions themselves are indicated in Figure 3-5.

The linear relationship was used to estimate dependable precipitation for all stations in the study area using as a base the mean rainfall data given in Wernstedt (1972).

Moisture Availability Index

The moisture availability index (MAI) is a moisture adequacy index at the 75% probability level of precipitation occurrence. It is defined as:

MAI = DFP PREC ./ POT ET

An MAI value of 1.00 means that dependable precipitation equals potential evapotranspiration.

The MAI concept was introduced by Hargreaves in 1972 to develop a classification that includes soil-moisture adequacies. He proposed that MAI be adopted as a standard index for measuring water deficiencies and excesses and suggested the following classifications:

MAI value	**Category**
0.00 to 0.33	Very deficient
0.34 to 0.67	Moderately deficient
0.68 to 1.00	Somewhat deficient
1.01 to 1.33	Adequate
1.34 and above	Excessive

Hargreaves showed that there is a good relationship between MAI and crop production when soil moisture is adequate for

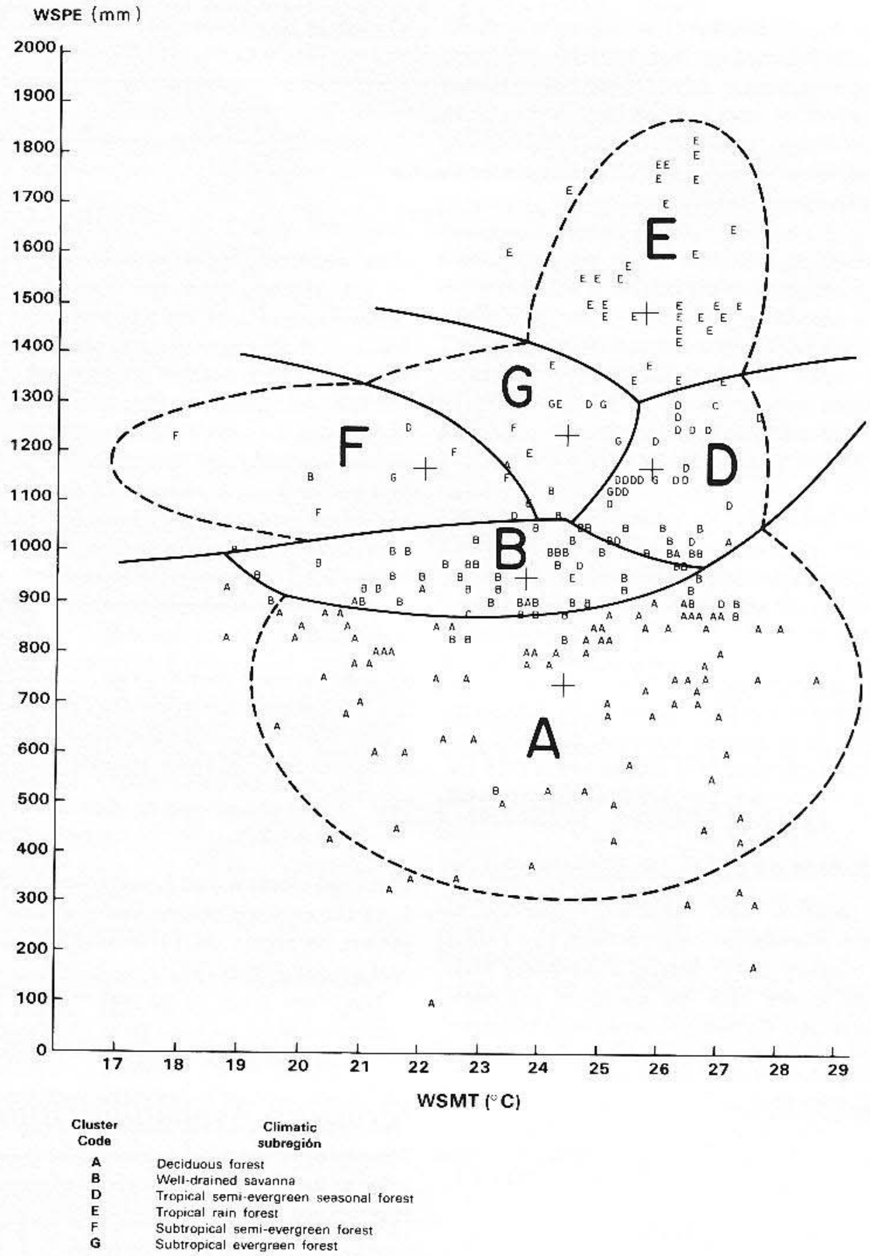

Fig. 3-6 Cluster diagram of vegetation classes throughout tropical South America in terms of total wet-season potential evapotranspiration (WSPE) and wet-season mean monthly temperature (WSMT). (Source: Cochrane and Jones, 1981).

a week or more and recommended a level "less than 0.34" to define a dry month. A wet month, then, was defined as one with an MAI greater than 0.33, bearing in mind that this level may be too low for soils with very low moisture-holding capacities.

Moisture Availability Index and Soil Moisture

Interestingly, the MAI, if qualified by the corollary "when soil moisture is adequate for a week," would describe soil moisture availability in terms of the climatic potential to both supply and extract soil moisture at a given location during a given period of time, as well as imply the ability of a soil to store and supply water. In this sense, the criterion would more sensitive for a given soil during periods of high potential evapotranspiration than during periods with lower potential evapotranspiration; further, it would be more critical for soil with low moisture-holding capacities. Therefore, the need to take soil moisture-holding capacities into account in relation to the water balance at a given time of the year must be emphasized. Soil moisture-holding capacities are defined in Chapter 6

Meteorological Data Sets

Part 2 of the *Computer Summary* (Volume 3) contains a range of meteorological data sets representative of those for the land systems in the Land Systems Map. These were originally compiled by Hargreaves and his coworkers for the landsystems study (Hancock et al., 1979). The CIAT SAMMDATA (South America Meteorological Data) computer file currently includes over 4000 data sets from stations throughout tropical America, many of which were adapted from Hargreaves' data file. These stations are indexed by names and geographical coordinates to help delineate and describe land systems.

Climate and Physiognomic Vegetation Patterns

In spite of the large number of meteorological data sets, a problem arose for the Amazonian region and parts of Central Brazil in that the distances between meteorological stations with long-term data were often too great to enable acceptable extrapolations.

In an attempt to overcome the problem of extrapolating climatic patterns between meteorological stations separated by large distances, it was decided to investigate the dependency of the natural vegetation on climate (Cochrane and Jones, 1981).

Vegetation Classes

Physiognomic -vegetation classes, as defined in Chapter 4, were used to describe the vegetation of the land facets of the land systems. Map 2 (see Map Plates) provides a picture of the major vegetation classes throughout the region. It was made by assigning the vegetation class of the major land facets to the land systems and by compiling computer printouts. The vegetation classes include poorly drained savannas, welldrained savannas, tropical rain forest, tropical semi-evergreen seasonal forest, tropical deciduous forest, caatinga, and others (including subtropical and submontane forests, swamp forests, and other vegetation classes). These are briefly described in Chapter 4. The term "well-drained savannas" covers those vegetation types referred to in Brazil as "Cerrados," described in detail by Eiten (1972). The definitions of forest types follow the descriptions by Eyre (1968).

Discriminant Analyses of Meteorological Data

A vegetation class was assigned to each of 251 meteorological data sets, from stations spaced as evenly as possible throughout the region, on the basis of the native vegetation growing on the well-drained soils in their vicinities. Sixty-onc meteorological stations were located throughout the savannas, 38 in tropical semi-evergreen seasonal forests, 49 in tropical rain forests, 84 in deciduous forests, 8 in subtropical semievergreen forests, and I I in subtropical evergreen forests. Many combinations of different climatic parameters from the data sets, including the number of wet months, wet-season mean monthly temperatures (WSMT), wet-season radiation, wet-season potential evapotranspiration (WSPE), and dry season moisture availability (DSMA) (an index of the severity of the dry season, in contrast merely to its length), were then examined through discriminant analyses, both parametric and nonparametric, to see if they followed the vegetation classes.

Vegetation and Wet-Season Potential Evapotranspiration

Figure 3-6 summarizes the investigation of the dependency of the vegetation classes on WSPE (wet-season mean potential evapotranspiration) and WSMT (wet-season mean monthly temperatures). The observations were computer plotted in the WSPE X WSMT space, and clustering of the vegetation classes can readily be seen. To delineate the classes, the lines of equiprobability of assignment were manually plotted between the various populations, by graphically finding the intersects of successive confidence elipsoids.

The posterior probability of correct assignment for the vegetation classes was estimated as:

Computer cluster codes (from Figure 3-6)	
A Deciduous Forest	0.91
B Well-drained savanna	0.68
D Tropical semi-evergreen seasonal forest	0.71
E Tropical rain forest	0.87
F Subtropical semi-evergreen forest	0.67
G Subtropical evergreen forest	0.60

The poorly drained savannas (C) could not be included in this analysis because there were records from only two sites.

Using the nonparametric technique of nearest neighbor classification described by Cover and Hart (I 967) as implemented by Barr et al. (1976), the data set was divided into two randomly selected halves and each subset used both as a calibration set and a test set. The two sets of results were then combined to form estimates of the probability of correct classification. These were A = .77; B = .73; D = .4 1; and E = .88. F and G contained no correct classifications due to the small sample size.

WSPE and Well-Drained Savannas

To check the possible variation of WSPE between well drained savaunas with different wet-season lengths, the 61 meteorological data sets from the stations located in the savannas were subdivided into three groups with 6, 7, and 8 months of wet season, respectively, and the total wet-season POT ET values and the wet-season average monthly POT ET values of the groups were compared. Table 3-3 shows that there is no significant difference between the total wet-season POT ET values for savannas having a 6-, 7-, or 8-month wet season ($P > .2$). On the other hand, it shows that the monthly average wet-season POT ET values are significantly different ($P < .001$). The monthly average wet-season POT ET values decrease with an increase in the length of the wet season.

It is clear that the WSPE throughout the well-drained savanna regions is virtually constant. In Figure 3-6, the group of well-drained savannas (cluster code B) falls in a compact band right across the center of the cluster diagram, indicating that they can be differentiated on WSPE alone. Indeed, the range of WSPE experienced is remarkably small in spite of considerable difference not only in wet-season length, but also in wet-season temperatures.

Climatic Potential for Growth of Vegetation

For any given month, providing that MAI is high enough to allow relatively unrestricted water availability, the actual evapotranspiration would closely follow the POT ET under the natural vegetation cover. Therefore, the WSPE approximates the annual consumptive water use of the vegetation. As such, the WSPE is a proxy estimate of the amount of annual energy the savanna vegetation can use for growth in the absence of irrigation. It follows, therefore, that the savannas occupy a well-defined habitat delimited by the climatic potential for growth; this potential is greater than that of deciduous forests but less than that of evergreen and semievergreen forests. Subtropical vegetation classes, although dependent on WSPE, appear to be further differentiated, as expected, by growing-season temperature. The group of deciduous forests (cluster code A) is a composite group. Caatingas, the thorn scrub of northeast Brazil, may be differentiated from this group using the dry-season moisture availability index (DSMA), as shown by Figure 3-7. The DMAI indicates the intensity of the dry season, as opposed merely to its length. It is the mean monthly moisture availability index of the dry-season months (those with an MAI < 0.34), corrected to run from zero to 1, where l = an average dry season monthly MAI of 0.33; thus "zero" is the most severe rating.

Further work needs to be carried out to examine the climate-vegetation interrelationships more thoroughly; nevertheless, the finding that WSPE regimes follow major vegetation classes provides for a better understanding of these interrelationships. In the context of tropical South America, with its rapidly expanding agricultural frontiers, where as often as not little or no recorded climatic data are available, it is evident that the natural vegetation growing on well-drained soils can be used as a guide to extrapolating climatic patterns.

Climatic Subregions

The WSPE regimes within the major vegetation zones were consequently used to help define climatic subregions (Map 3). Together with the length of the wet season and the WSMTS, they provide a convenient subdivision of the region into five main and two less-defined climatic subregions, summarized in Table 3-4. WSPE approximates the total annual energy available for plant growth, assuming that the soils hold sufficient moisture to enable no stress growth for at least a week under the prevailing POT ET regimes. Further, only the natural rainfall at the 75% probability level is considered, without supplemental irrigation.

Table 3-3. Total wet-season potential evapotranspiration (POT ET) values and monthly average wet-season POT ET values, according to the number of wet season months of the well-drained savannas.

	Length of wet season		
	6 months	7 months	8 months
Meteorological data sets (no.)	13	39	9
Total wet-season POT ET[a]			
Mean (mm)	904.7	969.4	976.1
Variance	1696	2528	2115
S.D.	42.86	50.94	48.78
Monthly average wet season POT ET[b]			
Mean (mm)	150.8	138.3	122.1
Variance	47.13	49.77	33.05
S.D.	6.146	7.147	6.097

a. t-test probability of difference between means: 0.2 (not significant).
b. t-test probability of difference between means: 0.001 (very highly significant).

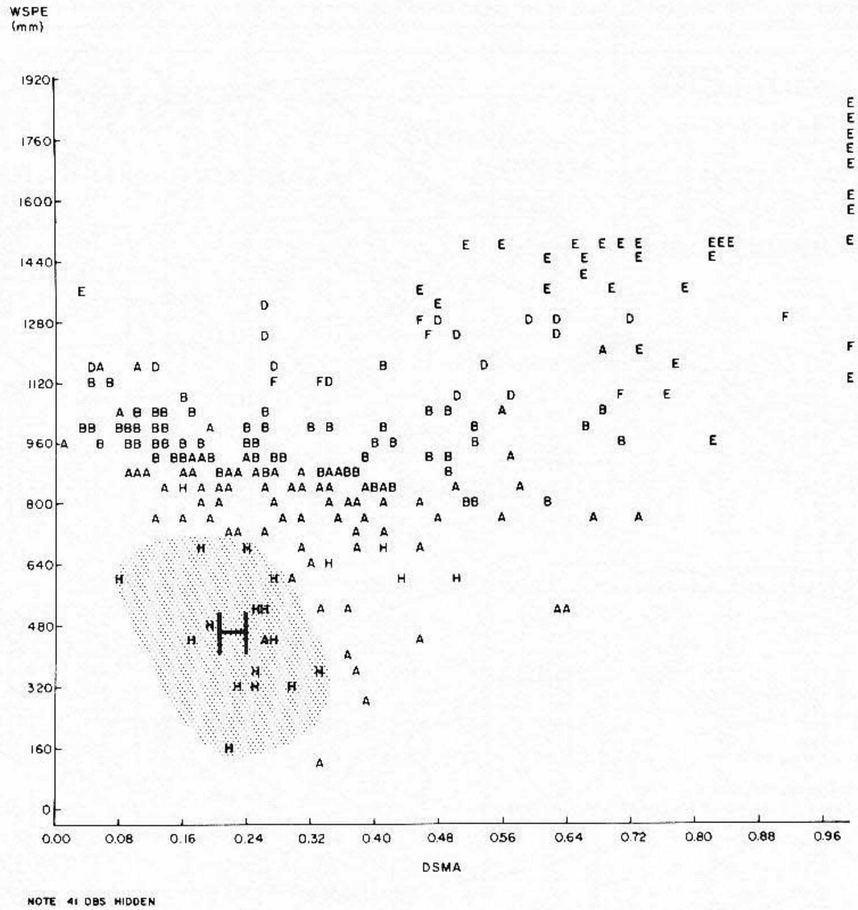

Fig. 3-7 Plot of total wet-season potential evapotranspiration (WSPE) by the dry season moisture availability index rating (DSMA).

Table 3-4. Climatic subregions of the central lowlands of tropical South America.

Climatic subregion code	Climate WSPE[a] (mm)	Wet months[b] (no.)	WSMT[c] (°C)	Subregion name
a	> 1300	> 9	> 23.5	Tropical rain forest
b	1061-1300	8-9	> 23.5	Semi-evergreen seasonal forest
c	900-1060	6-8	> 23.5	Isohyperthermic savanna[d]
d	900-1060	6-8	< 23.5	Isothermic savanna[d]
e	< 900	< 6	> 23.5	(Semi-)deciduous forest
f	-	-		Subtropical vegetation[e]
o	-	-		Other[f]

a. WSPE: total wet-season potential evapotranspiration, the sum of the potential evapotranspiration of the wet months.
b. Wet months are months with a moisture availability index (MAI) > 0.33%.
c. WSMT: wet-season mean monthly temperature.
d. Terms not used in the strict sense in accordance with U.S. Soil Taxonomy (Soil Survey Staff, 1975).
e. Other vegetation on predominately poorly drained or seasonally flooded lands.
f. Nonclassified, or submontane or subtropical forests.

Table 3-5. Climatic data sets of sites located in each of the major climatic subregions of the central lowlands of tropical South America.

Parameter[a]	Month: Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Climatic subregion a: Tropical rain forest Site: Cruz do Sul, AC, Brazil. Lat. 7°38'S, Long. 72°40'W, 170 masl													
MEAN TEMP	24.4	24.6	24.4	24.2	24.1	23.4	22.9	23.8	24.5	24.6	24.7	24.6	24.2
MEAN R.H.	92.	92.	92.	89.	80.	73.	74.	77.	89.	94.	87.	96.	86.
PCT SUN	30.	30.	31.	36.	50.	57.	56.	53.	36.	28.	40.	23.	39.
MEAN RAD	390.	391.	386.	384.	413.	418.	425.	451.	405.	372.	447.	339.	402.
PRECIP	246.	244.	269.	241.	138.	104.	47.	86.	147.	251.	216.	241.	2230.
POT ET	118.	108.	117.	112.	124.	120.	124.	135.	119.	113.	132.	103.	1426.
DEF PREC	-128.	-136.	-152.	-129.	-14.	16.	77.	49.	-28.	-138.	-84.	-138.	-804.
DEP PREC	189.	187.	209.	185.	97.	68.	20.	53.	105.	193.	163.	185.	
MAI	1.60	1.74	1.78	1.65	0.78	0.57	0.16	0.40	0.88	1.71	1.24	1.79	
Climatic subregion b: Semi-evergreen seasonal forest Site: Manaus, AM, Brazil. Lat 3°8'S, Long. 60°1'W, 48 masl													
MEAN TEMP	25.9	25.8	25.8	25.8	26.4	26.6	26.9	27.5	27.9	27.7	27.3	26.7	26.6
MEAN R.H.	88.	89.	89.	88.	81.	74.	71.	63.	67.	76.	78.	85.	79.
PCT SUN	38.	36.	37.	38.	48.	56.	59.	67.	63.	54.	51.	43.	49.
MEAN RAD	420.	415.	418.	404.	426.	441.	462.	525.	541.	509.	491.	443.	458.
PRECIP	276.	277.	301.	287.	193.	99.	61.	41.	62.	112.	165.	228.	2102.
POT ET	132.	118.	131.	123.	135.	136.	149.	172.	173.	167.	155.	142.	1732.
DEF PREC	-144.	-160.	-170.	-164.	-58.	37.	88.	131.	111.	55.	-11.	-86.	-370.
DEP PREC	215.	215.	236.	224.	114.	64.	32.	15.	33.	75.	120.	174.	
MAI	1.62	1.83	1.80	1.82	1.06	0.47	0.22	0.09	0.19	0.45	0.78	1.22	
Climatic subregion c: Isohyperthermic savanna Site: Conceição do Araguaia, PA, Brazil. Lat. 8°15'S, Long. 49°12'W, 90 masl													
MEAN TEMP	25.1	24.9	25.2	25.6	25.6	25.1	24.9	26.0	26.7	25.8	25.6	25.2	25.5
MEAN R.H.	88.	89.	88.	79.	65.	48.	44.	54.	70.	83.	83.	89.	73.
PCT SUN	38.	37.	38.	50.	66.	79.	82.	74.	60.	46.	45.	36.	54.
MEAN RAD	437.	431.	428.	453.	470.	488.	510.	530.	521.	479.	477.	427.	471.
PRECIP	253.	252.	263.	163.	60.	8.	7.	15.	64.	163.	196.	227.	1671.
POT ET	135.	119.	132.	137.	147.	146.	156.	167.	162.	150.	144.	132.	1727.
DEF PREC	-118.	-133.	-131.	-26.	87.	138.	149.	152.	98.	-13.	-51.	-95.	56.
DEP PREC	195.	194.	204.	119.	31.	0.	0.	0.	34.	119.	146.	173.	
MAI	1.45	1.63	1.54	0.87	0.21	0.00	0.00	0.00	0.21	0.79	1.01	1.31	
Climatic subregion d: Isothermic savanna Site: Luziania, GO, Brazil. Lat. 16°15'S, Long. 47°56'W, 958 masl													
MEAN TEMP	21.9	22.0	21.7	21.1	19.4	18.3	18.1	20.0	22.1	22.3	21.9	21.6	20.9
MEAN R.H.	72.	78.	79.	61.	52.	41.	38.	43.	63.	75.	79.	87.	64.
PCT SUN	59.	52.	51.	69.	76.	84.	87.	83.	67.	55.	50.	40.	64.
MEAN RAD	574.	523.	481.	495.	452.	440.	461.	512.	526.	529.	527.	475.	500.
PRECIP	228.	201.	229.	96.	16.	7.	4.	5.	27.	130.	215.	317.	1475.
POT ET	164.	135.	136.	134.	120.	110.	118.	139.	146.	152.	145.	134.	1632.
DEF PREC	-65.	-66.	-93.	38.	104.	103.	114.	133.	119.	22.	-70.	-183.	157.
DEP PREC	141.	123.	142.	53.	0.	0.	0.	0.	7.	76.	132.	200.	
MAI	0.86	0.91	1.04	0.40	0.00	0.00	0.00	0.00	0.05	0.50	0.91	1.41	
Climatic subregion e: (Semi-)deciduous seasonal forest Site: Ibipetuba, BA, Brazil. Lat. 11°1'S, Long. 44°31'W, 434 masl													
MEAN TEMP	24.6	24.6	24.6	24.5	23.4	21.9	21.5	22.3	24.9	26.3	25.5	24.8	24.1
MEAN R.H.	56.	65.	73.	56.	46.	44.	45.	38.	52.	59.	69.	74.	56.
PCT SUN	73.	65.	57.	73.	81.	83.	82.	87.	76.	71.	61.	56.	72.
MEAN RAD	621.	578.	520.	535.	503.	478.	489.	557.	579.	596.	568.	546.	547.
PRECIP	125.	145.	136.	73.	12.	1.	1.	1.	7.	53.	158.	198.	910.
POT ET	189.	159.	158.	157.	149.	132.	138.	160.	172.	189.	171.	167.	1942.
DEF PREC	64.	14.	23.	84.	137.	131.	137.	159.	165.	136.	13.	-31.	1032.
DEP PREC	72.	86.	80.	38.	0.	0.	0.	0.	0.	25.	94.	121.	
MAI	0.38	0.54	0.50	0.24	0.00	0.00	0.00	0.00	0.00	0.13	0.55	0.72	

a. MEAN TEMP: mean temperature (°C); MEAN R.H.: mean relative humidity (%); PCT SUN: percentage of possible sunshine (%); MEAN RAD: mean solar radiation; PRECIP: mean precipitation (mm); POT ET: potential evapotranspiration (mm); DEF PREC: precipitation deficit (mm); DEP PREC: dependable precipitation (mm); MAI: moisture availability index.

Approximately 27% of the region falls into the tropical rain forest subregion, (climatic code a) mainly in the western half of the Amazon basin. The semi-evergreen seasonal forests, (climatic code b) characterized by the narrow range of an 8- to 9-month wet season, occupy 38% of the area, most of it in Brazil east of Manaus. The isohyperthermic savannas (climatic code c), 16% of the region, are well-drained native grasslands surrounded by forest vegetation. They include parts of the Brazilian Cerrados, the northern and western Bolivian *pampas,* the eastern Llanos of Colombia, a large part of the central Llanos of Venezuela, and parts of the Rupununi plains and the Boa Vista and Amapa Cerrados of Amazonia. Climatic subregion d, the isothermic savannas, comprises mainly the central plateau areas of the Cerrados of Brazil; these differ from the Llanos in terms of a cooler temperature regime. They occupy 5% of the region. Climatic subregion e is comprised of areas covered with deciduous vegetation.

The characterization of climatic subregions does not take into account the differences between well-drained and poorly drained savannas. This fundamental difference between savannas has led to a lot of confusion in the past concerning the nature of savannas; poorly drained savannas are found in climatic subregions with 2 to 6 months of dry season, and a wide range of WSPES, as the edaphic circumstance of waterlogging overrides the climatic effect. Table 3-5 shows a meteorological data set from a site in each of the climatic subregions.

Soil-Moisture Stress and the Veranicos

In considering the relationship between WSPE and vegetation, it has been noted that soil-moisture stress is described in terms of the climatic potential to supply and extract soil moisture at a given location during a given period of time, and the ability of well-drained, medium-textured soils to store and supply water. In soils that have less than the medium capacity to store plant-available water, such as sandy Spodosols and many Oxisols, vegetation can quickly suffer moisture stress. Such situations occur both in the Amazon basin and in the Brazilian Cerrados. In Amazonia, Alvim and Silva (1980) note that areas of *campinarana* vegetation (a type of low, open forest) are prevalent on sandy soils with very low moistureholding capacities, surrounded by soils with higher moistureholding capacities covered in semi-evergeen seasonal forests. (It may be noted that many of these *campinarana* areas also suffer from a wet-season hydromorphic condition.)

The veranicos are erratic, but often prolonged (10- to 20day) periods with no rainfall commonly occurring during the "wet-season" months of January and February in the Cerrados (well-drained savannas) of Central Brazil. They are often cited as the cause of considerable yield reductions in shallow rooting annual crops.

Veranicos can usually be identified from the monthly meteorological data sets as comparative differences between the MAI values of the peak wet-season months of December to March. For example, a meteorological data set for Luziania (see Table 3-1) shows lower MAI values in January and February than in December or March; nevertheless, the actual monthly MAI values for all 4 months are well above the value 0.33 used to signify a dry month. This would suggest that the moisture-stress condition resulting in reduced crop yields is not only a climatic problem but also a soil problem; a function of shallow rooting in soils with low moisture-holding capacities. In fact, it has recently been demonstrated in the Cerrados Center (CPAC, EMBRAPA) near Brasilia that this moisture-stress condition can be obviated in soybeans growing in Oxisols if deeper rooting is encouraged by applying single superphosphate to help overcome soil Al toxicity and P and Ca deficiency conditions (E. Wagner, CPAC, pers. comm.).

Monthly MAI values and the soil moisture-holding capacity rating, with or without a rating for soil chemical factors including Al toxicity and P and Ca deficiencies as given by the present study, have recently been used to form a preliminary zonification of the propensity of the Cerrados of Brazil to be affected by the wet-season drought periods.

A Fresh Approach to Climatic Zoning

Although the authors of this study do not intend to put forward a universal climatic classification on the basis of their analyses, the wet-season potential evapotranspiration (WSPE) concept has provided a fresh approach for zoning climatic subregions throughout lowland tropical America for nonirrigated, perennial crop production. It is leading to a better understanding of the region and has provided CIAT a basis for defining broadly comparable climatic conditions for the selecting, testing, and transferring of new pasture plant accessions (CIAT, 1980b). This is described in Chapter 1. The concept is compatible with the recently developed theory of unifying principles for water movements in biological tissues, including plants (Cochrane 1983, 1984). Studies, including those recently published by Ranzani (1978), will help to define more precisely the ability of the different soils to supply soil moisture and improve the water-balance estimates for specific agricultural systems.