Chapter 1
Introduction

Abstract Chapter 1 deals with general problems and methodology: Scope of the study, Basic concepts, Classification criteria: Energy flow, Water stress, Dry seasons and drought, Cold stress and its relationship to latitude and altitude, Frost hazard occurrence, Rainfall distribution and amount, Potential evapotranspiration, *P*/PET ratios, Temperature and frost sensitivity/tolerance, Relationship between annual temperature and ETo, Ratios between *P* and ETo as aridity indices, Effect of wind on PET or ETo, Other significant climatic parameters: Vapour pressure, Relative humidity, Saturation deficit, Soil distribution, Impact of agro-hydraulic works, Land-use patterns and agricultural production systems, Flora, Vegetation, Fauna, Wildlife and livestock populations, Human and animal diseases as related to climate, Human comfort.

The methodology is based on a series of criteria at distinct levels of classification:

- Seasonality of rainfall resulting in Mediterranean (winter precipitation, summer drought), Tropical (summer monomodal precipitation, winter drought) and Equatorial (bimodal, spring and fall precipitation, winter and summer drought) families of bioclimates, based on the annual patterns of rain and temperature, as expressed in the climatic diagrams of Bagnouls and Gaussen, popularized by Walter and Lieth in their Klimadiagramm Weltatlas.
- Amount of precipitation and *P*/PET ratios within each family (hyper-humid, humid, sub-humid, semi-arid, arid to hyper-arid), based on decreasing *P*/ETo ratios.
- Mean minimum daily temperature of the coldest month as an index of winter cold stress in each family, and its relationship to elevation (lowlands, midlands, highlands and Afro-alpine zones).

A large table (17 pp.) shows the annual values for ten key climatic parameters for the 962 weather stations of the database.

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1.1 Scope

The aim of the present bioclimatic and biogeographic classification is to provide a basis of comparison between various regions and zones within the African continent, and with comparable areas from other continents such as Latin America (Le Houérou 1990c) or the Indian subcontinent (Le Houérou 1992f). The present classification shows, for instance, the main differences and similarities between agro-bioclimatic conditions in West Africa and in East Africa on the one hand and, on the other hand, between the Sudanian ecological zone beyond 10°N and the Miombo Woodland zone south of 10°S, and also between the extra-tropical and Mediterranean zones of northern and southern Africa.

Moreover, the present classification also shows the remarkable latitudinal climatic homogeneity of the Sahelian and Sudanian ecological zones, as opposed to the striking and contrasting climatic heterogeneity of the comparable zones of eastern and southern Africa (Le Houérou 2006c). It should also constitute a rational basis for national, regional and sub-regional rural development planning and for agricultural research organization such as plant and animal introduction, the extrapolation or interpolation of experimental or developmental findings, and systems research.

It should be kept in mind, however, that the continental scale of this study does not allow, in principle, for country-level direct application. Nevertheless, it does provide a methodology and a framework for such national or provincial applications. The problem of possible applications will be examined in the concluding chapter.

1.2 Basic Concepts

1.2.1 General

The core of the present classification was first published in a study of afforestation in the Sahel (Le Houérou 1976), then in a study of the grasslands of Africa, a plenary lecture at the XIIIth International Grassland Congress (Le Houérou 1977), and in an Ecological Study of Ethiopia (Le Houérou 1980a, 1984a). It was further developed in an Ecoclimatic Classification of Inter-Tropical Africa (Le Houérou and Popov 1981), the agro-bioclimatic classification of Africa (Le Houérou et al. 1993), the classification of the Arid Zones of Northern Africa (Le Houérou 1989a), of the bioclimatology and biogeography of northern Africa (Le Houérou 1995a), of the Red Sea Basin of East Africa and Arabia (Le Houérou 2003), and of Marmarica (Egypt-Libya; Le Houérou 2004a). It therefore results from a stepwise approach as my field experience progressed. This classification is based on both aridity and frost tolerance, unlike many others based only on a sole aridity index.

A similar classification, based on the same principles, was proposed for Kenya in a seemingly independent approach (Braun 1982; Jätzold and Schmidt 1982).

The originality of the present classification is the combination of a rather large number of criteria of various climatic and biological nature, following the concepts of the early phytogeographers (Köppen 1900; Flahault 1904; De Martonne 1926; Emberger 1930; Köppen and Geiger 1930; Gaussen 1938; Bagnouls and Gaussen 1953a, b), as shown below.

A. Climatic criteria
- Seasonal patterns of rainfall distribution:
  winter vs. summer rainfall;
  monomodal vs. bimodal patterns.
- Amount of annual rainfall.
- Variability of annual rainfall.
- Dependability of annual rainfall.
- Length of the rainy season.
- Dry seasons and drought (water stress), severity and length of the annual dry season.
- Temperatures and thermal limiting conditions to plant growth (cold stress and heat stress).

B. Biological criteria
- Distribution of community types of vegetation.
- Distribution of individual native plant species, phytogeography and centres of endemism.
- Distribution of wildlife and game species.
- Distribution of livestock species and breeds.
- Occurrence of major pests and diseases (sleeping sickness, malaria, schistosomiasis, river blindness, piroplasmosis, rinderpest, contagious pleuro-pneumonia, etc.).
- Human comfort and tolerance to heat.

C. Agronomic criteria
- Land use as controlled by climatic criteria.
- Soil distribution.
- Crop distribution patterns.
- Distribution of agricultural production systems.
- Distribution of livestock species and breeds and of livestock production systems.

D. Geographic criteria
- Relationship between altitude, latitude and temperature: lowlands, midlands and highlands.
- Relationship between continentality, rainfall and temperature.
- Relationship between ocean currents and coastal deserts.
- Relationship between ocean and land masses: the monsoons and trade winds.

The basis of the classification is the relationship between various biological criteria (including agronomic) and climatic factors, as the latter are much easier to apprehend, discriminate and quantify, since they are represented on cartographic documents.

1.2.2 Energy Flow and Budget

Global radiation is shown in Tables T1–3 and Fig. 11. Radiation is, for a large part, controlled by latitude (Fig. 11); the highest values in Africa are found in the central and southern Sahara (R_g = 200–220 kcal cm^{-2} year^{-1}), the lowest in the Gulf of Guinea (R_g = 140 kcal cm^{-2} year^{-1}), due to cloudiness. Africa is objectively the warmest continent of the planet (Le Houérou 1990a, 1992a, 1996a). At higher latitudes, radiation is reduced due to the smaller incident energy flow.

An approximate relationship exists between global radiation and potential evapotranspiration whereby ETo ≈ 0.0085 R_g (global radiation), where ETo is expressed in mm of mean annual reference potential evapotranspiration, computed via the Penman-Monteith equation, and R_g in cal cm^{-2} year^{-1} (Le Houérou 1972, 1984a). Since this relationship accounts for neither advective lateral energy (oasis effect) nor wind speed, it provides a low estimate in windy areas such as the Sahara and the Sahel (NE continental trade winds = "Harmattan") but is approximately correct in other African zones such as northern, central, eastern and southern Africa. In Fig. 11, the isolines of R_g can be equated with the values of global radiative evapotranspiration potential (GREP) shown in Table T1 (Le Houérou and Norwine 1985).

Net radiation (R_n) is about 45% of global radiation R_g (Uchijima and Seino 1987). The *P*/GREP ratio, similar to Budyko's dryness index, is a reasonable approximation of the *P*/ETo ratio; it may be used as such for depicting broad ecological zones—e.g. the value of 0.06 corresponds with the upper limit of hyper-arid zones (i.e. true deserts); the 0.30 value may be equated with the limit between arid and semi-arid zones, etc.

Photosynthetically active radiation (PAR) is approximately 40% of R_g and 80% of R_n (Le Houérou 1980b, 1982a, 1989b; Le Houérou and Norwine 1985). Figure 11 gives a reasonable approximation of GREP, R_n and PAR, in addition to R_g.

Variations in the quotient between ETo and *T* appear directly related to the magnitude of the aerodynamic parameter in the final expression of the Penman equation: ETo/*T* averages 96.9 in the Sahara, dropping progressively to 45–55 towards the equator, to the zone of so-called equatorial stillness (Table T2; see Table A1 for details). One exception to this rule is the Red Sea shores area and N. Somalia where the values of this ratio are comparable with those of the Sahara and of the Kalahari.

Table T1 Relationship between global radiation and global radiative evapotranspiration potential (GREP), disregarding the aerodynamic term of the theoretical equation (Le Houérou et al. 1993)

Global radiation (kcal cm^{-2} year^{-1})	GREP (mm)
120	≈1,000
140	1,200
160	1,400
180	1,550
200	1,700
220	1,900

Similar trends have been observed in other zones of strong persistent winds—in Patagonia, for instance (Le Houérou 1999b).

Table T3 shows the relationship between rain-use efficiency (RUE) and the equivalent water-use efficiency (WUE). This aspect is developed in more detail below.

1.2.3 Drought

In nature, as well as for crops, there are large differences between plant species (and cultivars) in terms of tolerance to water stress and drought. In most ecological classifications, water stress tolerance is given as the first discriminating criterion, commonly followed by tolerance to low temperatures, i.e. frost. Physiological drought usually occurs in plants when soil water matric potential drops to −1.5 MPa (−15 bars) or below, which corresponds to the permanent wilting point of

Table T2 Regional relationship between mean annual temperature (*T*, °C) and mean annual reference potential evapotranspiration (ETo; see also Tables T13, T14 and A1 for details; *SD* standard deviation, *CV* coefficient of variation, *SE* standard error)

Ecological zones	No. stations	ETo/*T*	SD	CV	SE
Arid, semi-arid & sub-humid					
The Sahara	109	96.9	8.1	0.08	2.5
Northern Africa	98	79.4	11.2	0.14	2.7
The Sahel	141	79.2	9.5	0.12	2.2
Eastern Africa	198	74.1	11.0	0.15	1.8
Southern Africa	75	86.5	10.9	0.13	2.2
Sub-total/mean					
Arid, semi-arid & sub-humid	621	79.8	10.7	0.14	2.2
Humid, hyper-humid & Central Africa	221	51.2	12.5	0.24	0.84
Global total/mean	842	65.5	11.6	0.19	1.5

Table T3 Rain-use efficiency (RUE, kg DM ha^{-1} $year^{-1}$ mm^{-1}; *DM* dry matter) and equivalent water-use efficiency (WUE, kg H_2O kg^{-1} DM; Le Houérou 1984b)

RUE	WUE	RUE	WUE	RUE	WUE
20	200	15	500	10	1,000
9	1,111	8	1,250	7	1,326
6	1,666	5	2,000	4	2,500
3	3,300	2	5,000	1	10,000
g DM kg^{-1} H_2O					
20	2.0	15	1.5	10	1.0
9	0.9	8	0.8	7	0.7
6	0.6	5	0.5	4	0.4
3	0.3	2	0.2	1	0.1

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