The Physical Environment

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It is appropriate that the technical sessions of the Sorghum in the Eighties Symposium should start with the physical environment because it is the medium in which the biological material expresses itself. The "properties" of the medium such as radiation, rainfall, temperature, and soils control the rate of the biological processes such as nutrient uptake, photosynthesis, respiration, dry matter accumulation, etc. An understanding of the interactions between the properties and processes should lead us to develop principles for improved productivity of the sorghum crop.

There is a wide range of environments in the world in which sorghum can be grown. In this paper, characterization of sorghum climates is limited to the semi-arid tropics (SAT). It should be mentioned here that the boundaries for delineation of the SAT in this paper have been drawn according to the classification given by Troll (19B5). Because of the limits imposed by the parameters used in Troll's procedure, the reader may find that these SAT boundaries differ from others published. For reasons of simplicity and space the discussion here is limited to Troll's SAT areas but this in no way should be taken to imply that sorghum growing areas falling outside these boundaries are any less important.

An extended description of the agrometeorology of sorghum and millet growing areas of the SAT will be the subject of an ICRISAT/World Meteorological Organization Symposium to be held at ICRISAT in November 1982. For additional information on the physical environment of sorghum the reader is referred to the proceedings of this symposium. The SAT are the areas located in the seasonally dry tropical climates, spread over four continents and 48 countries. The mean annual temperature in the SAT is > 18°C; rainfall exceeds potential evapotranspiration for only 2 to 4.5 months in the dry SAT and for 4.5 to 7 months in the wet/dry SAT (Troll 1965). The coefficient of variability of rainfall in the SAT is 20-30%. Over 55% of the world's sorghum production comes from the SAT (Davies 1980).

Using average production data for sorghum from 1974 to 1978 in different countries in the SAT, von Oppen and Ryan (1981) calculated the amount of sorghum production in the different SAT regions. From the data on sorghum distribution in the SAT they showed that India is the' largest single sorghum-producing country in the world contributing 34% of the SAT total. Pakistan and Thailand are the other major producers in Asia. In Central and South America, Mexico and Argentina together contribute 34%. We have, however, no data to show whether sorghum production in Mexico and Argentina comes solely from the semi-arid tropical areas of those countries or from other climatic regions also. The next region in importance is West Africa which contributes 15% of the sorghum production in the SAT. The major sorghum-growing countries there are Ghana, Niger, Nigeria, and Upper Volta. About 10% of the sorghum in the SAT is produced in eastern Africa, the countries of major importance here being Ethiopia, Kenya, Sudan, and Tanzania. In southern Africa, Malawi, Mozambique, Zimbabwe, and Zambia are the major producers. In west Asia, Saudi Arabia, and Yemen Arab Republic contribute together 3% of the total sorghum production in the SAT. Over 65% of the total sorghum in the SAT is produced in Asia and Africa and our assessment of the sorghum environment focuses primarily on these two continents.

Because sorghum in the SAT is grown mostly in developing countries, and also because the pace of economic and social progress in these countries varies from country to country, the advance of meteorological knowledge has been different. Accordingly, the availability of climatic data varies

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across these countries. We have drawn generalizations at several places for this reason and we hope the reader will appreciate the reasons for so doing.

Environment of Sorghum-growing Areas in Africa

Radiation

Direct measurements of global solar radiation are few and far between in Africa (Cocheme and Franquin 1967). Empirical estimation of solar radiation has been a common practice, especially using the data on sunshine hours. The mean annual solar radiation in semi-arid Africa ranges from 16.7 to 20.9 MJ/m^2/day (Thompson 1965). Areas situated in the northern and southern boundaries of semi-arid Africa receive the highest solar radiation amounts.

Cocheme and Franquin (1967) and Brown and Cocheme (1973) calculated the global solar radiation for several stations in West and East Africa. Monthly global solar radiation for selected stations in these areas is presented in Table 1. Average monthly global solar radiation at Nairobi varies from as high as 24.6 MJ/m^2/day during February to 13.8 MJ/m^2/day in July. During the sorghum-growing season at most locations the global solar radiation averages about 18.8 MJ/m^2/day. In areas north of the equator the yearly minimal values of solar radiation normally occur around the month of August. This period coincides with the wettest period of the year with increased cloudiness.

Temperature

In general, temperature determines the rate of plant growth and development. The effects of temperature stress on each critical stage of development of sorghum are discussed by Peacock (1982). We briefly describe here the range of temperatures under which sorghum is grown in semi-arid Africa. Africa is the world's hottest continent; the average annual temperature exceeds 21°C. As shown in Table 2, daily mean maximum temperatures are consistently high during the growing season and the seasonal variation is relatively small, especially for areas closer to the equator. The cooling effect of the rains reduces the mean monthly temperatures. general the lowest air temperatures are recorded in the month of August, which is also the wettest month of the year. The highest air temperatures normally occur at the beginning of the growing season. In the highlands of East Africa temperatures lower than 22°C are also recorded. For sorghum-growing areas south of the equator, maximum screen temperatures in January of up to 32°C are recorded in Zambia and Zimbabwe. At Sucoma in the Shire valley of Malawi maximum

Table 1. Monthly mean global radiation (MJ/m^2/day) at selected stations in Africa.

Location	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
Sokoto (Nigeria)	19.2	20.9	20.1	20.7	21.1	21.3	18.7	16.8	19.7	21.8	20.5	19.0
Kano (Nigeria)	18.9	20.1	20.6	20.3	21.4	20.3	18.6	16.4	20.1	21.7	20.5	18.8
Navrongo (Ghana)	20.1	22.4	21.5	20.7	20.6	19.9	17.7	16.7	18.3	21.2	20.5	19.8'
Maradi (Niger)	20.0	21.5	23.0	22.9	22.3	22.5	19.7	18.4	20.8	21.7	20.1	19.2
Niamey (Niger)	19.3	20.8	20.8	21.0	21.2	20.7	18.9	17.6	19.3	21.0	24.3	18.2
Ouagadougou (Upper Volta)	18.4	19.4	20.6	19.5	20.0	17.9	17.1	15.3	17.9	20.2	18.9	16.6
Asmara (Ethiopia)	21.3	23.3	24.8	25.3	25.6	23.0	17.7	17.4	22.7	23.0	20.8	20.0
Nairobi (Kenya)	23.0	24.6	23.0	19.5	17.2	16.4	13.8	14.7	18.8	20.1	19.5	20.9

Table 2. Mean maximum and minimum air temperature (°C) during the sorghum-growing season at selected locations in Africa.

Location	June Nov*	July Dec	Aug Jan	Sept Feb	Oct Mar	Nov Apr
Accra	28.9	27.3	27.2	28.5	29.6	30.9
(Ghana)	22.6	21.8	21.3	21.8	22.3	22.8
Navrongo	32.7	30.7	29.6	30.6	33.4	35.9
(Ghana)	23.2	22.5	22.3	21.9	21.9	20.1
Bobo Dioulasso	31.8	30.1	29.5	30.7	32.8	34.4
(Upper Volta)	21.3	20.7	20.6	20.4	20.6	19.2
Ouagadougou	33.1	31.2	30.3	31.8	35.6	36.9
(Upper Volta)	22.9	22.2	21.4	21.3	21.8	20.0
Maradi	36.7	32.3	30.6	32.1	35.9	35.5
(Niger)	23.8	22.0	21.1	21.5	19.3	15.4
Niamey	36.7	33.2	31.3	33.0	37.2	37.2
(Niger)	25.1	23.2	22.5	22.7	23.0	19.0
Sokoto	35.4	31.5	29.9	31.4	34.7	35.4
(Nigeria)	24.1	22.1	214	21.5	21.0	17.8
Kano	33.6	30.4	29,2	30.9	33.9	33.7
(Nigeria)	22.5	21.1	20.8	20.9	19.8	16.0
Muguga	21.6	22.4	22.5	23.9	25.4	23.4
(Kenya)	11.2	9.9	12.1	12.7	12.8	13.1

* Months in the lower column apply to locations south of equator.

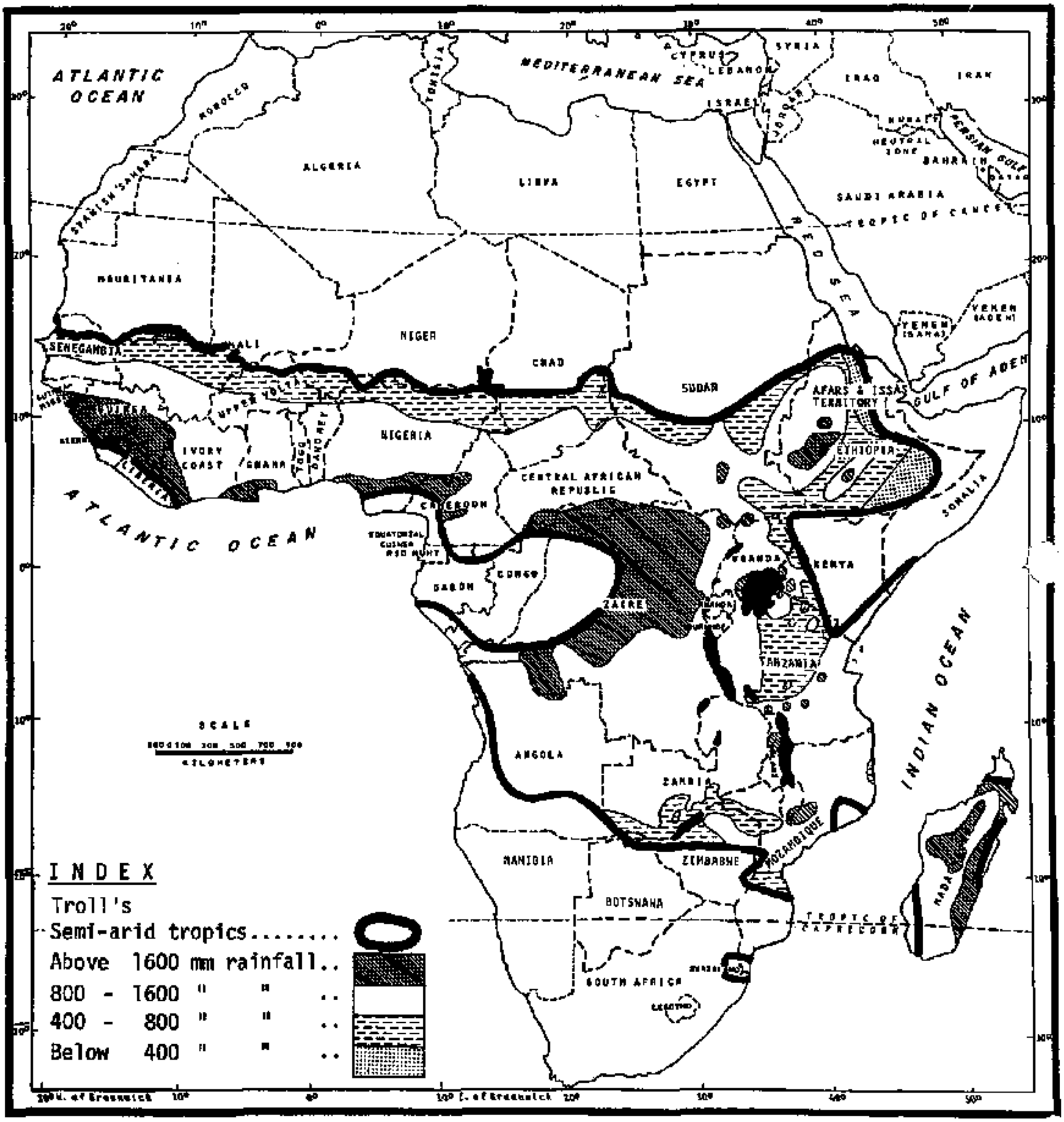
temperatures of 35°C are not uncommon (SVADP 1975). The diurnal range in temperature in the sorghum-growing areas north and south of the equator is very similar. In the highlands of East Africa, temperature variation due to altitude differences is important.

Rainfall

The pattern of air circulation over the African continent is determined by the earth's rotation and the temperature difference between the tropical and polar regions.

The intertropical convergence zone, commonly called the ITCZ or ITZ, has a particular role in this circulation. At a specific time during the season, the air in the equatorial region becomes very heated and rises to condense at a high altitude over the zone of maximum rainfall. These air currents of varying dryness move at great height towards the tropical high pressure anticyclone zone and then drop vertically, become compressed, warm up, and loose the rest of their moisture over the desert zones of the Sahara and Kalahari. These currents then move horizontally toward the ascending ITCZ, thus closing the cycle. Deflected by the earth's rotation, they then become tradewinds which blow from northeast to southwest in the northern hemisphere, and from southeast to northwest in the southern hemisphere. The ITCZ passes over the same region twice a year; there are two rainy seasons in the countries lying on both sides of the equator.

In Africa, the southward and northward influence of the ITCZ is clearly seen (Fig. 1). In West Africa,the mean annual rainfall varies from 250 to 1250 mm. Studies by Cocheme and Franquin (1967) for the semi-arid areas south of Sahara in West Africa showed that rainfall isohyets run parallel with the equator with bands or zones



receiving more rain the further south they are. On the dry north side of the area, the decrease in rainfall with longitude is most pronounced in Niger. The rainy season is short and the dry season is severe. In Niger most areas receive rainfall ranging between 200 and 800 mm (Sivakumar et al. 1980). Mean annual rainfall in Upper Volta ranges from 400 to 1200 mm, with the southwest region bordering Mali and the Ivory Coast receiving the largest amounts of rainfall in the country. The mean annual rainfall in Nigeria varies widely from north to south but, in the northern semi-arid states, the rainfall ranges from 500 to 1250 mm/yr. Kowal and Knabe (1972} showed that for the northern states of Nigeria annual rainfall decreases by 119 mm for every degree of latitude. The variability in the annual rainfall also increases with aridity from south to north, Cocheme and Franquin (1967) calculated coefficients of variability in annual rainfall for the semi-arid regions in West Africa south of Sahara that range from 15 to 38%. In West Africa the monthly mean rainfall increases gradually from the beginning of the rainy season in late spring or early summer to a maximum in August. The duration of the rainy season varies with mean annual rainfall (see discussion below in the section under growing period).

In East Africa, the rainfall zones are more complex because of the Ethiopian highlands with altitudes of 3000-5000 m. Brown and Cocheme (1973) presented consolidated and simplified maps of annual rainfall isohyets for the highlands of eastern Africa. The mean annual rainfall for two-thirds of the stations investigated is between 600 and 1200 mm, the remainder being stations receiving amounts in excess of 1200 mm. The -highlands receive generally more rain than adjoining lowlands. On the western scarp of the high pattern in the Ethiopian highlands, rainfall exceeds 1200-1300 mm/yr, while on the eastern scarp the rainfall is less. Latitudinal effects are largely concealed by those of height and of the exposure complex (Brown and Cocheme 1973). Whereas latitude is a fair guide for the annual rainfall variations in West Africa, in East African highland stations it is not possible to forecast with any degree of accuracy the annual rainfall in terms of the geographical coordinates. Rainfall zonation in Sudan also is fairly precise as one moves towards the equator. Rainfall variability in southern Africa is again fairly large. For example, in the Republic of Zambia, the mean annual rainfall varies from 700 mm in the south to 1400 mm in the north-western areas.

Average rainfall figures do not yield information on the dependability of precipitation. Hargreaves (1975) has defined dependable precipitation (DP) as the amount of rainfall which could be received at 75% probability. The moisture availability index (MAI)—defined as the ratio of dependable precipitation to potential evapotranspiration —could give an idea of the precipitation adequacy for crop growth. Monthly values of MAI during the sorghum-growing season at selected locations in semi-arid Africa are shown in Table 3. The data show that in West Africa moisture availability for sorghum growth is fairly adequate until September. October and November are very undependable. In eastern Africa, particularly at Mombasa and Dar es Salaam moisture availability is fairly low. Moisture availability at Livingstone in Zambia is comparatively favorable.

Table 3. Moisture availability index (MAI) during the sorghum-growing season at selected locations in the semi-arid tropics.

	June	July	Aug	Sept	Oct	Nov
Location	Dec*	Jan	Feb	Mar	Apr	May
Ouagadougou (Upper Volta)	0.47	1.00	1.47	0..75	0.06	0.00
Kano (Nigeria)	0.48	1.07	1.76	0.59	0.00	0.00
Geneina (Sudan)	0.07	0.67	1.36	0.29	0.00	0.00
Mombasa (Kenya)	0.17	0.02	0.01	0.10	0.55	1.20
Dar Es Salaam (Tanzania)	0.22	0.09	0.15	0.40	1.45	0.01
Inhambane (Mozambique)	0.37	0.32	0.36	0.36	0.36	0.31
Livingstone (Zambia)	0.62	0.80	0.55	0.29	0.03	0.00

* Months in the lower column apply to locations south of equator.

Length of the Growing Period

For a rainfed crop such as sorghum to be successful, it is necessary that its growth cycle should be of such a length that it is comfortably contained within the available growing period. Failure to match these characteristics does not completely exclude cultivation of the crop, but can result in reduction of yield and quality. There are several methods of calculating the growing period. But the methods adopted by the agroecological zones project of FAO (1978) appear to be useful. The growing period is defined as the period (in days) during a year when precipitation exceeds half the potential evapotranspiration, plus a period required to evapotranspire an assumed 100 mm of water from excess precipitation stored in the soil profile. The choice of 100 mm was based on experimental evidence from East and West Africa which indicates that the crops of the study can utilize stored soil moisture in the range of 75-125 mm by the time of harvest.

The length of the sorghum-growing period (FAO 1978) in the sorghum-growing areas of semi-arid Africa ranges from 90 days in Senegal, Mali, Upper Volta, Niger, and Chad on the northern Sahelian boundary to 270 days in southern regions of Ghana, Nigeria, and Sudan. South of the equator the sorghum growing season is again reduced to 90 days in parts of Namibia, Botswana, Zimbabwe, and Mozambique. Medium growing period lengths of 150-210 days are common throughout the sorghum-growing areas in SAT Africa. The importance of the length of growing period and the adaptation of local photosensitive varieties to the long growing seasons has been extensively studied at the Institute of Agricultural Research in Samaru, Nigeria (Andrews 1970; Kowal and Andrews 1973; Kassam and Andrews 1975). For example, Kassam and Andrews (1975) showed that for short Kaura, a photosensitive Nigerian sorghum, total dry weight and grain yield decreased with delay in sowing after 26 May at rates of 1700 kg/ha per week and 360 kg/ha per week respectively. Bunting and Curtis (1968) showed that the date of heading of the local sorghum is closely related to the average date of the end of the local rains.

Soils of Sorghum-growing Areas in SAT Africa

The growing periods calculated above take into consideration only the water supply and water demand at a given location. However, the soil profile serves as a means of balancing, over time, the discontinuous water supply with the continuous atmospheric evaporative demand. The properties of the soil profile obviously affect its moisture retention, runoff, and drainage as well as the losses of water by evaporation and transpiration (Russell 1980). The soil map of Africa published by FAO (1977) identifies 53 broad soil regions in Africa. In the sorghum-growing areas of semi-arid Africa, 11 major soil zones were identified. The grouping here is done with the purpose of identifying a broad soil type, and it is necessary to point out that the soil type identified in a given zone often will have associated soils and other soil types. For a comprehensive description of the soils of Africa the reader is referred to FAO (1977), Swindale (1982), and Jones and Wild (1975).

Arenosols

These are sandy soils (up to 95% sand) that occur extensively, mostly on flat to undulating topography, in the northern boundary of SAT Africa in Upper Volta, Niger, Nigeria, Sudan and along the southern boundary covering Mozambique, Zimbabwe, and Zambia. In Upper Volta, Nigeria, Zimbabwe, and Zambia, Cambic Arenosols predominate while in Niger, Luvic Arenosols occur. In Mozambique, Cambic and Luvic Arenosols coexist. Cambic Arenosols are sandy soils with a slight color or structural B horizon. The clay fraction is made up of kaolinite and oxides of iron and aluminum. Luvic Arenosols occur in moister climates than the Cambic Arenosols. The clay fraction in the B horizon could exceed 14%, Charreau (1974) reports that for Cambic Arenosols at Bambey, Senegal, volumetric water content (cc/cc) at field capacity varies from 12 to 15%, and the permanent wilting point from 3 to 4%.

Luvisols

Luvisols or Alfisols occur in the more moist climates of the Sudanian ecological zone in Ghana, Upper Volta, Niger, Nigeria, and Sudan. Ferric Luvisols, which are underlain by indurated ironstone, are most common. The clay fraction is dominated by kaolinite and other low-activity clays. The associated soils include Gleyic and Plinthic Luvisols. Volumetric water content (cc/cc) at field capacity varies from 17 to 22%, and permanent wilting point ranges from 7 to 8%.

Ferralsols

These are the most weathered soils which are situated towards the wet boundary of a region. These occur in Nigeria and Zambia. Orthic ferralsols are yellowish brown to reddish brown in color, and Rhodic Ferralsols are red, while Xanthic Ferralsols are yellow to yellowish brown. In Nigeria all the three types coexist, while in Zambia Rhodic and Orthic Ferralsols are common. Physical constants data for Ferralsols in Africa are not available, but for Rhodic Ferralsols located at Jaiba in Brazil, it was reported (Swindale 1982) that volumetric water content (cc/cc) at field capacity varies from 28 to 32% and wilting point from 20 to 22%.

Vertisols and Gleysols

These soils occupy large areas in Sudan and Ethiopia. Chromic Vertisols are slightly yellower, browner or redder and are contiguous with Pellic Vertisols. The clay fraction predominates, with 50-60% in most horizons. The water-holding capacity of Vertisols is normally above 200 mm. The Gleysols are poorly drained and the hydromorphic properties dominate others.

Nitosols

Humic Nitosols occur in the tropical highland zones of Ethiopia. The weathering stage of Nitosols makes them more fertile than Ferralsols. These are considered good agricultural soils.

Regosols

Large areas in Ethiopia and Kenya are covered by Calcaric Regosols. These are weakly developed soils on unconsolidated materials. The suitability of these soils for agriculture is extremely limited and they need good management for better crop production.

Cambisols

They are found in the sorghum-growing areas of SAT Africa, mostly in Ethiopia. They are characteristic of a recent stage of soil formation and in the Ethiopian highlands Dystric Cambisols and Humic Cambisols occur in hilly topography. Dystric Cambisols are poor soils. However, the associated Eutric Cambisols in Ethiopia are good soils, rich in nutrients.

Acrisols

These soils are insufficiently weathered to be Ferralsols but more strongly leached than Luvisols (Young 1976). In Tanzania, mostly Ferric Acrisols occur where the ecological conditions are severe. They have a coarse or medium texture, and are considered poor.

Fluvisols

These are alluvial soils developed from recent alluvial deposits in many African valleys; where water is available the soils are amenable to irrigation. They are well endowed with exchangeable bases and with total P_2O_5.

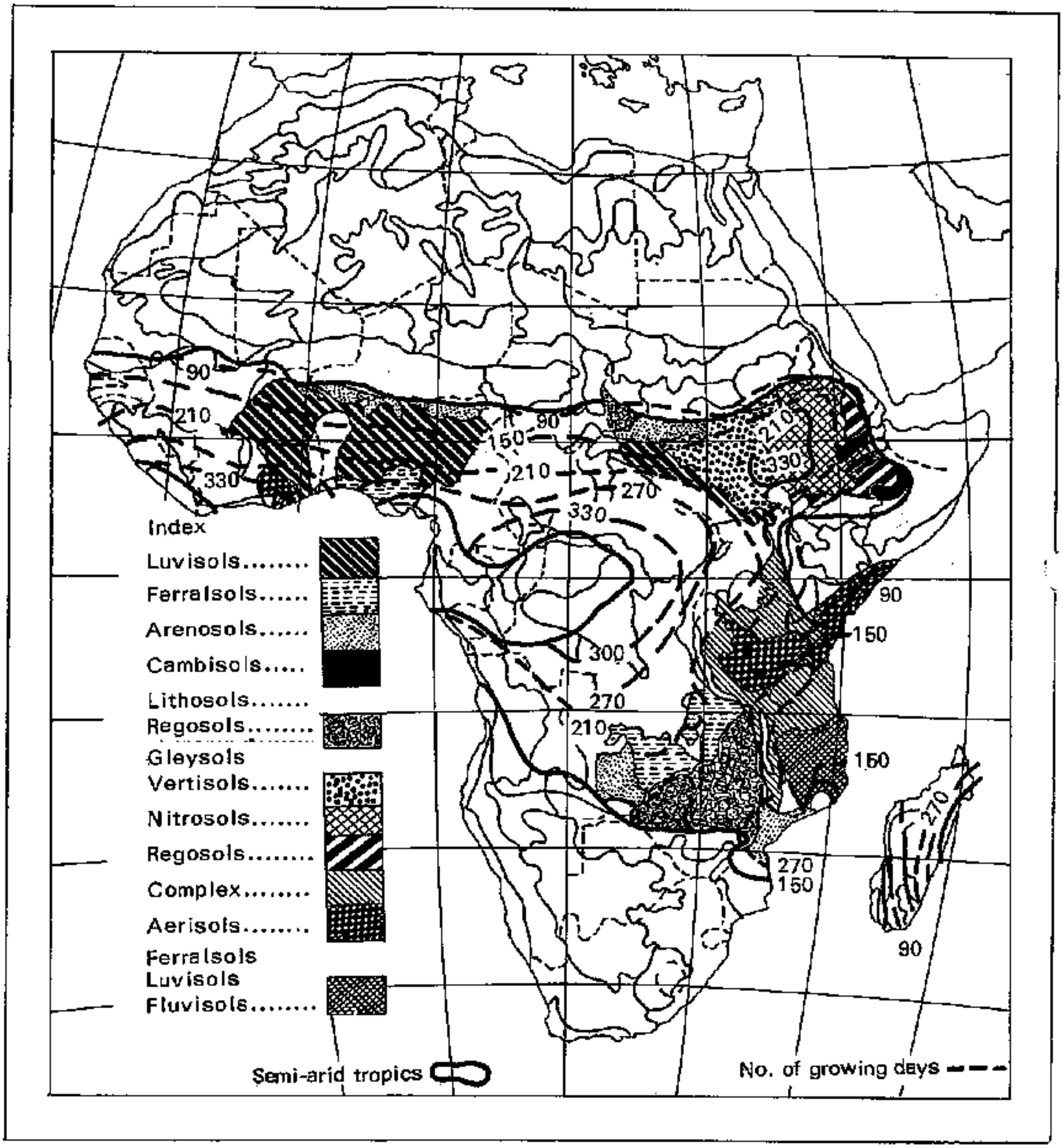
Lithosols

Soils with continuous hard rock at <10 cm depth. Because of dissected topography with steep slopes and of rockiness and stoniness of the substraction, the suitability of these soils for crop production is limited.

Complex of Soils

The soil complex indicated here includes Nitosols, Lithosols, Cambisols, Vertisols, Ferralsols, Acrisols, Gleysols, and Fluvisols in most of Tanzania. In addition the complex of soils in the southeastern Tanzania includes Regosols, Arenosols, and Ferralsols.

From the above description of the broad soil zones in Africa and the length of the growing period it can be concluded that, even where the soil type is favorable, potential yields of sorghum could be limited by the length of the growing period and vice versa. The length of the growing period superimposed on the soil type reveals some interesting features (Fig. 2). In the Arenosols soil region on the northern boundary of SAT Africa, the growing period is between 90 and 150 days, while on the southern boundary the growing period extends up to 210 days. These soils also generally lack adequate nutrient elements. Luvisols in West Africa and Sudan have a richer chemical composition and a better growing period, but they need better erosion control. Ferralsols in southern Ghana and Nigeria have a low natural fertility, but the growing period there is over 270 days. Vertisols and Gleysols in Sudan come under the 150-210 day growing period and



Source: FAO, World Soil Resources Report, 1978.

Figure 2. Length of the growing period on broad soil zones of some of the sorghum-growing areas in semi-arid tropical Africa.

with good management, should be most suitable. The same applies to Humic Nitosols in the Ethiopian highlands, but Calcaric Regosols and Dystric Cambisols in Ethiopia cannot hold enough water in spite of the better growing period.

Environment of Sorghum-growing Areas in India

Nearly 13% of the gross cropped area is devoted to sorghum in SAT India. Karnataka, Andhra

Pradesh, and Maharashtra are the most important sorghum-growing states followed by Gujarat, Madhya Pradesh, and Tamil Nadu. Based on the data available on the sorghum area and production data for 1979-80, it was estimated that of the total area of 16.4 million hectares under sorghum, 60% is under rainy-season sorghum (the *kharif* crop in India) and 40% is under the postrainy season sorghum (termed as *rabi* crop). About 66% of the annual production comes from a rainy season crop while 34% is contributed by the postrainy season. In view of this, we felt the need to distinguish between the climatic characteristics in the two seasons in our discussion.

Bapna et al. (1980) classified the sorghum-growing districts in India into three categories: (a) >15% of sorghum area to district cropped area and >0.5% of sorghum area to all India sorghum area, (b) >15% to district cropped area and < 0.5% to all India or <15% to district cropped area and >0.5% to all India, and (c) <15% to district cropped area and <0.5% to all India. Based on this classification, we defined districts under categories (a) and (b) as core districts and districts under category (c) as satellite districts. Further to emphasize the seasonal production, we define rainy-season sorghum districts as those where the area under sorghum in the rainy season is more than 75% of the total area under sorghum. A similar definition applies to those districts which are classified as postrainy-season sorghum districts. Districts where the area under sorghum in any of the two seasons is less than 75% of the total area under sorghum are termed as rainy- and postrainy-season districts. Therefore we propose six classifications of sorghum-growing areas in India, as shown in Figure 3. Over 99% of the sorghum in India comes from the SAT areas. From this map it is evident that core rainy-season sorghum areas extend from 9°N (Madurai) to 25°N (Hamirpur). On the other hand, the core postrainy-season sorghum-growing areas are restricted to a narrow belt of 14°N (Nellore) to 21°N (Dhule). The reasons for this interesting zoning become more evident when we look at the soils and the length of the growing period.

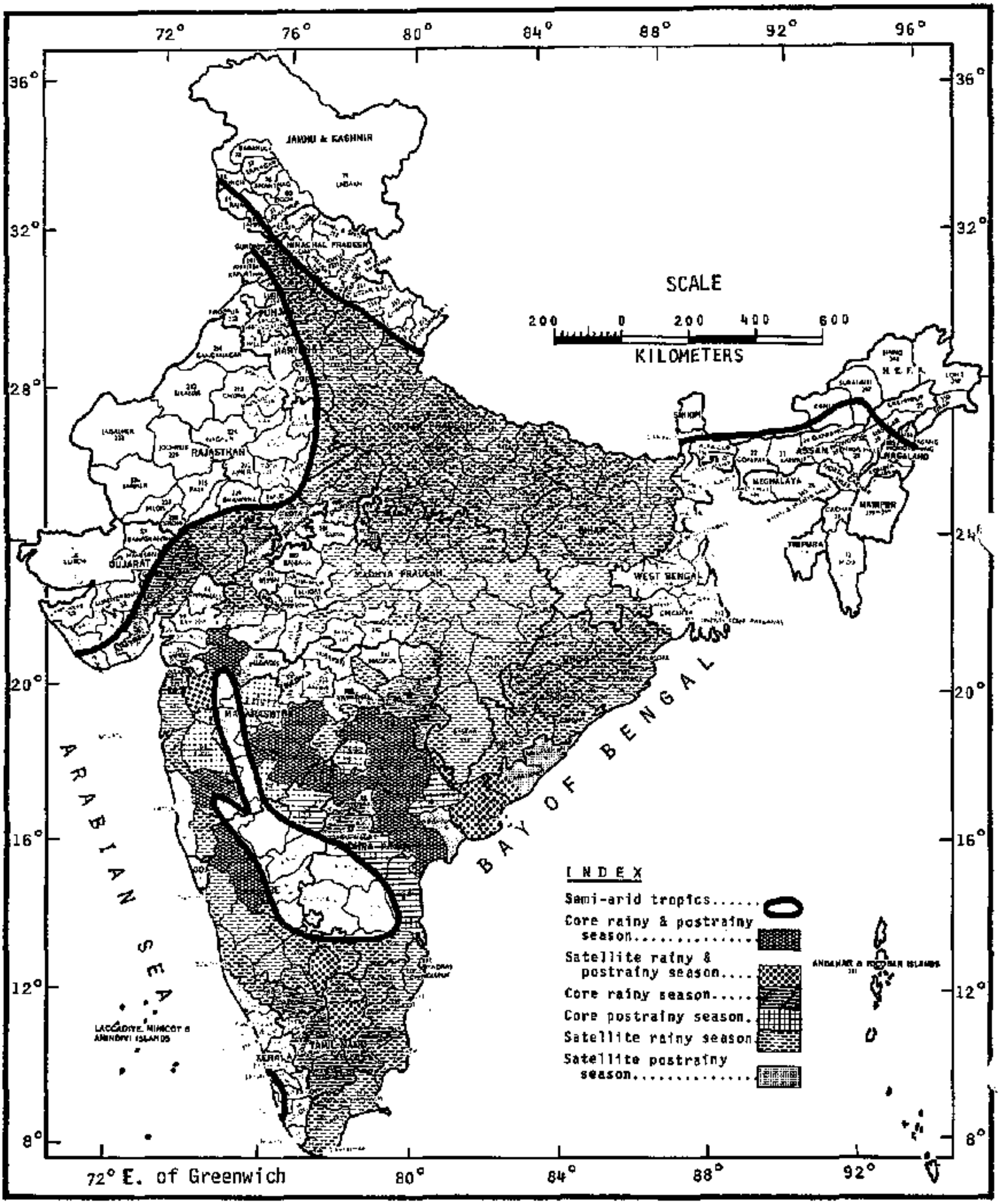
Temperature

The temperature variation between different sorghum growing areas in each of the six zones shown in Figure 3 has to be mainly viewed in terms of the two growing seasons. Based on 30-year normals (IMD 1967), the average, maximum, and minimum air temperatures during the growing season were calculated for the rainy and postrainy seasons. As shown in Table 4, during the rainy season average temperatures vary from 31° in June to 23°C in November. The data are shown for a 6-month period because sowing and harvesting of the rainy- and postrainy-season crops vary in different regions. In the postrainy season, average temperature varies from 22° to 29°C. Average temperatures, however, could be misleading and it is more important to examine maximum and minimum temperatures. The seasonal variation in the average maximum and minimum temperatures calculated from 25 representative stations for each season along with the average dates of anthesis and physiological maturity for CSH-6 (a rainy-season hybrid sorghum) and CSH-8 R (a postrainy-season hybrid sorghum) are shown in Figures 4 and 5. It is evident from the data that the maximum temperature variation during the rainy season is not significant, but the minimum temperatures decrease from 25°C to about 20°C by physiological maturity. In the postrainy season, however, the maximum temperature increases from 30°C at the end of October to 35°C by March. What is relevant in terms of the crop phenology is that the diurnal range in temperature is rather small in the rainy season and the uniformly high temperatures should promote good vegetative growth and grain filling. In the postrainy season, the diurnal range in temperature, especially around flowering, is rather large and the minimum temperatures are consistently low. Implications of these temperatures are discussed in detail by Peacock (1982).

Peacock (1982) suggests that the extreme temperatures are as relevant to sorghum growth as the average temperature. The highest and lowest air temperatures recorded in the rainy sorghum-growing season at selected locations are shown in Table 5. Maximum temperatures could reach as high as 45°C, as at Jhansi, while the temperature dip could extend to as low as 8°C in November at Indore. During the postrainy season (Table 6) highest temperatures of up to 40°C could be recorded, while minimum temperatures of 8°C are not uncommon.

Solar Radiation

Average global solar radiation during the rainy season varies from 16.7 to 18.8 MJ/m^2/day while



Source: Agricultural situation in India 1981

Figure 3. Sorghum-growing districts in semi-arid tropical India.

in the postrainy season solar radiation on an average is reduced by 0.4 to 1.7 MJ/m^2/day. As with temperatures, average values could be misleading and the highest and lowest values of solar radiation recorded at any location depend on the cloud cover and the geocoordinates of the region.

Table 4. Average temperatures during rainy and postrainy sorghum-growing seasons in semi-arid India.

Season	June	July	Aug	Sept	Oct	Nov
	Oct*	Nov	Dec	Jan	Feb	Mar
			Mean average temperature (°C)			
Rainy	31.2	27.8	27.0	27.1	26.3	22.9
Postrainy	26.5	23.9	22.2	22.8	25.1	28.5
			Mean maximum temperature (°C)			
Rainy	36.4	31.4	30.5	31.3	32.4	30.1
Postrainy	31.8	30.3	29.4	30.1	32.8	36.2
			Mean minimum temperature (°C)			
Rainy	25.9	24.1	23.4	22.8	20.1	15.7
Postrainy	21.1	17.5	15.0	15.4	17.4	20.8

* Months in the lower column apply to postrainy seasons.

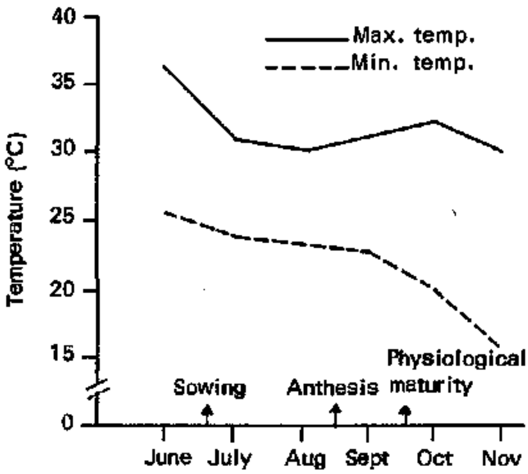


Figure 4. Seasonal changes in maximum and minimum air temperatures during the rainy season in India.

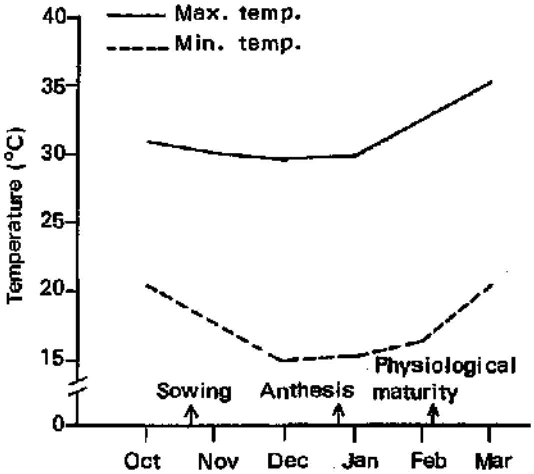


Figure 5. Seasonal changes in maximum and minimum air temperatures during the postrainy season in India.

Rainfall

The success of sorghum as a rainy or postrainy crop depends to a large extent on the available soil moisture which is largely modulated by the rainfall and the soil type. The rainfall isohyets superimposed on the sorghum-growing areas show that the annual rainfall varies from 700 mm to 1400 mm (Fig. 6). It is also interesting to note that almost all the core rainy-season sorghum-growing areas are located between the 800 and 1000 mm/yr rainfall isohyets. The core postrainy-season sorghum-growing areas are mostly located in the belt with low and undependable rainfall areas with 800 mm/yr. Based on a moisture index defined as $\frac{(P-PE) \times 100}{PE}$, Where P is the precipitation, and PE is the potential evapotranspiration, Krishnan (1972) showed that the moisture deficiency during the rainy season is accentuated from east to west. In southern India, deficiency exists in Andhra Pradesh, interior Maharashtra, Karnataka, and Tamil Nadu. During the postrainy season

Table 5. Highest and lowest air temperature (°C) recorded in the rainy sorghum-growing season at selected locations in semi-arid India.

Location	June	July	Aug	Sept	Oct	Nov
Akola	42.2	36.2	31.4	35.0	35.6	33.6
	22.5	21.8	21.7	21.1	14.7	10.6
Hyderabad	39.9	34.0	33.0	32.8	33.3	31.5
	21.2	21.0	20.9	20.3	15.8	11.8
Indore	40.0	34.1	31.5	32.6	33.2	31.2
	21.4	21.0	20.4	18.9	13.0	8.2
Jhansi	44.9	39 6	35.5	35.6	36.0	33.4
	23.8	23.1	22.7	21.6	14.7	8.8

Table 6. Highest and lowest air temperatures (°C) recorded during the postrainy sorghum-growing season at selected locations in semi-arid India.

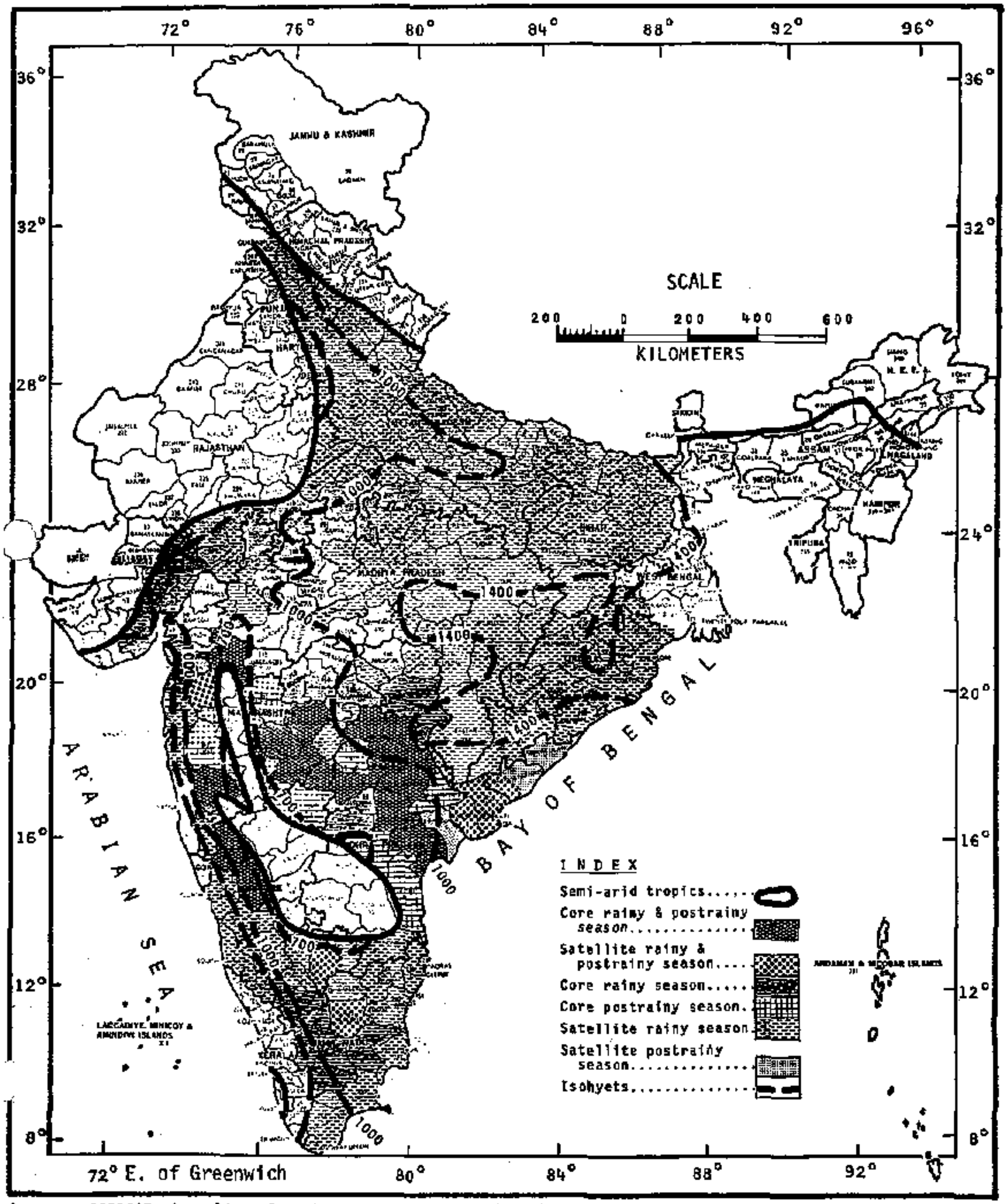
Location	Oct	Nov	Dec	Jan	Feb	Mar
Bijapur	33.6	31.8	31.4	32.7	35.8	38.5
	17.0	12.9	11.1	12.0	14.1	17.3
Gulbarga	34.4	32.8	31.5	32.7	36.1	39.4
	16.8	12.9	10.5	11.7	14.3	17.4
Sholapur	34.7	32.2	31.9	33.3	36.4	39.7
	16.6	12.9	10.7	11.3	13.1	16.7
Ahmednagar	33.5	32.2	31.1	32.0	34.4	38.5
	14.5	10.5	8.0	8.0	9.6	13.0

Table 7. Moisture availability index (MAI) in the rainy months of sorghum-growing areas at selected locations in semi-arid India.

Season	Location	June	July	Aug	Sept	Oct
Rainy	Hyderabad	0.31	0.76	0.66	0.88	0.15
	Akola	0.38	1.10	0.60	0.60	0.03
	Nagpur	0.74	2.54	1.64	0.73	0.07
	Indore	0.25	1.44	1.13	0.67	0.03
Postrainy	Sholapur	0.38	0.41	0.41	0.72	0.13
	Ahmednagar	0.40	0.34	0.23	0.67	0.13
	Chitradurga	0.24	0.37	0.34	0.47	0.40

moisture deficiency extends over the entire country except for a small belt in eastern Tamil Nadu. The deficiency accentuates from south to north in peninsular India and from east to west in north India.

As described earlier, a measure of the dependability of the annual rainfall in meeting crop water needs could be given by comparing the potential evapotranspiration (PE) with dependable rainfall. Moisture availability index (MAI), as defined ear-



Source:- ICRISAT, Agroclimatology Progress Report - 2 (1978)

Figure 6. Mean annual rainfall in the sorghum-growing districts of semi-arid tropical India.

lier, for the rainy months at selected locations in the rainy- and postrainy-season sorghum-growing areas (Table 7) shows that MAI in the rainy-season sorghum-growing areas is consistently high in comparison with those areas where sorghum is grown only in the postrainy-season. The low MAI values at Sholapur, Ahmednagar, and Chitradurga bear ample evidence of the farmers' preference to crop these areas only in the postrainy season.

Length of the Growing Period

Length of the growing period calculated by the agroecological zones project of FAO (Frere 1980, personal communication) for the sorghum-growing areas in semi-arid India is shown in Figure 7. Most of the core rainy-season sorghum-growing areas show growing periods between 120 and 180 days.

Soils

Murthy and Pandey (1978) prepared a soil map of India. A superimposition of the soil map of India over the sorghum-growing areas shows (Fig. 8) that the core sorghum-growing areas are in the black soil and red sandy soil belts.

The black soils are usually poorly drained and possess a low hydraulic conductivity. The texture of the topsoil is always clayey (40 - 60%) which leads to pronounced shrinking of the soil during drying. Black soils are hard in the dry season, but muddy and sticky in the wet season. The soil depth varies usually between 1 and 2 m and the available water-holding capacity ranges from 150 to 300 mm.

The red soils or Alfisols are relatively shallow, well-drained, and have a reasonable hydraulic conductivity. The texture of the surface soil ranges from sandy in Andhra Pradesh, Tamil Nadu, and Karnataka states to loamy soil in Madhya Pradesh and Orissa. The water-holding capacity of the soil is variable, depending on the depth, but ranges usually between 100 and 150 mm. In the dry season the soils are difficult to cultivate because of surface hardness.

The alluvial soils, or Entisols, are usually deep, possess good physical qualities, and are moderately permeable. The available water-holding capacity is lower than that of Vertisols, and varies from 150 to 200 mm. The texture of the surface soil may range from drift sands to loams and from silts to heavy clays.

The sorghum-growing area under laterite soils or Oxisols is fairly limited. The surface soil texture is loamy or clayey. The topsoil is of varying depth underlain by ferruginous deposits which harden on exposure.

As mentioned earlier, the soil profile characteristics play an important role in the plant-water relations. Using a water balance model to give estimates of weekly changes in available soil water for the shallow, medium, and deep soils, with 50, 150, and 300 mm water-holding capacities respectively, Virmani et al. (1978) showed that available soil moisture contents (mm) at the commencement of the rainy season for the three soil types are 16, 66, and 72 mm, respectively. At the commencement of the postrainy season the available soil moisture is 7, 80, and 204 mm for the shallow, medium, and deep soils. These data emphasize the need to consider the soil characteristics rather carefully in analyzing crop productivity over different seasons.

Based on soil climatic zonation, Kanwar (1972) pointed out that the most efficient sorghum regions are in the peninsular region or the central and south Indian states. This area lies in the climatic belts where the precipitation deficit (when compared with the potential evapotranspiration) could extend up to 40%, and on black soils that have higher moisture retention capacity.

Summary

The physical environment of the sorghum growing areas in semi-arid Africa and India has been evaluated by examining the temperature, radiation, and rainfall regimes with respect to soils of these areas. Analysis of the sorghum-growing areas in Africa showed that considerable potential exists in terms of the climatic suitability of the areas growing sorghum. Considering the differences in the two major sorghum-growing seasons in India, i.e., the rainy and postrainy seasons, emphasis was placed on describing the physical environment in the two seasons and the cropping potential that exists, particularly in the black soil areas of India.

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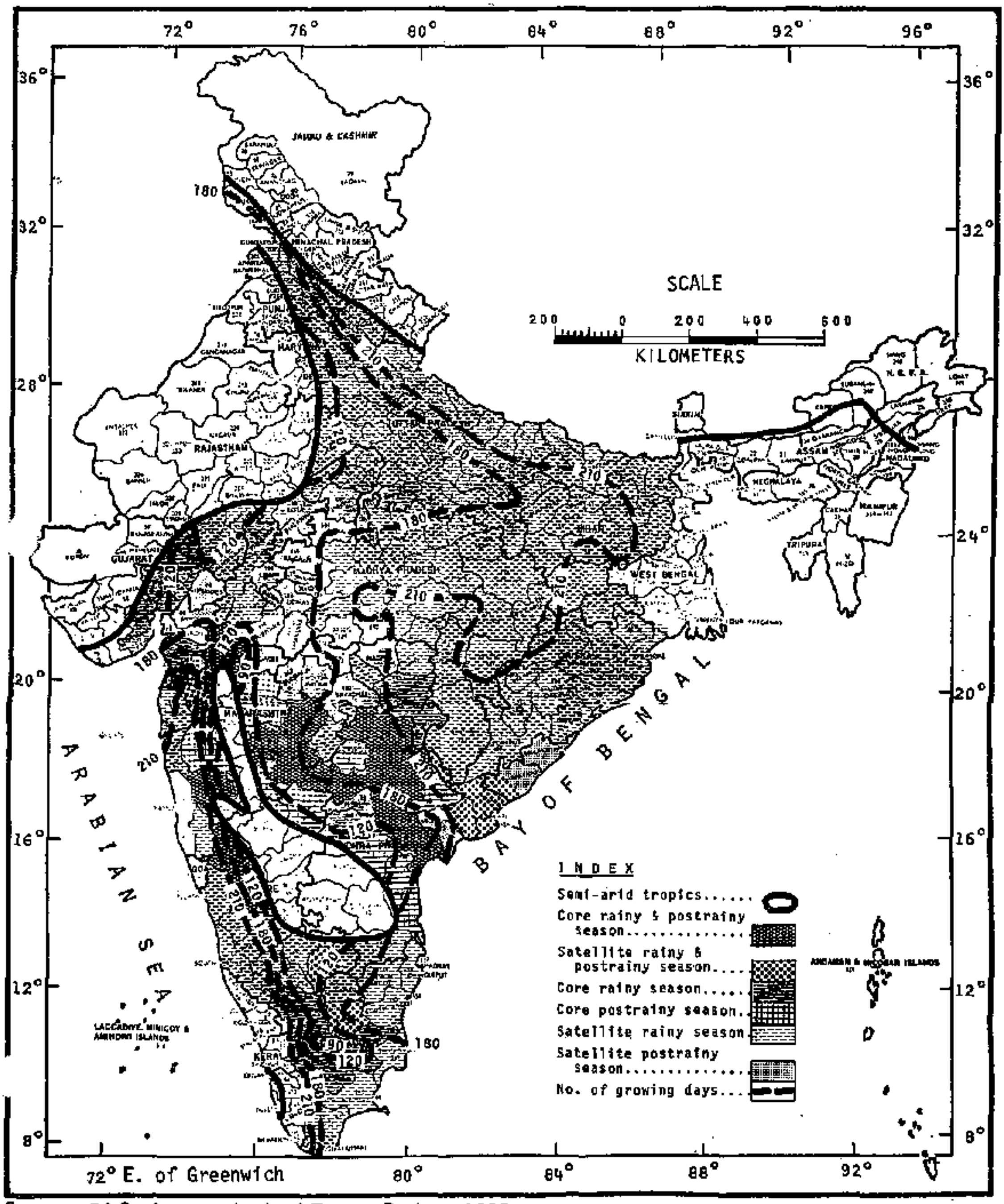
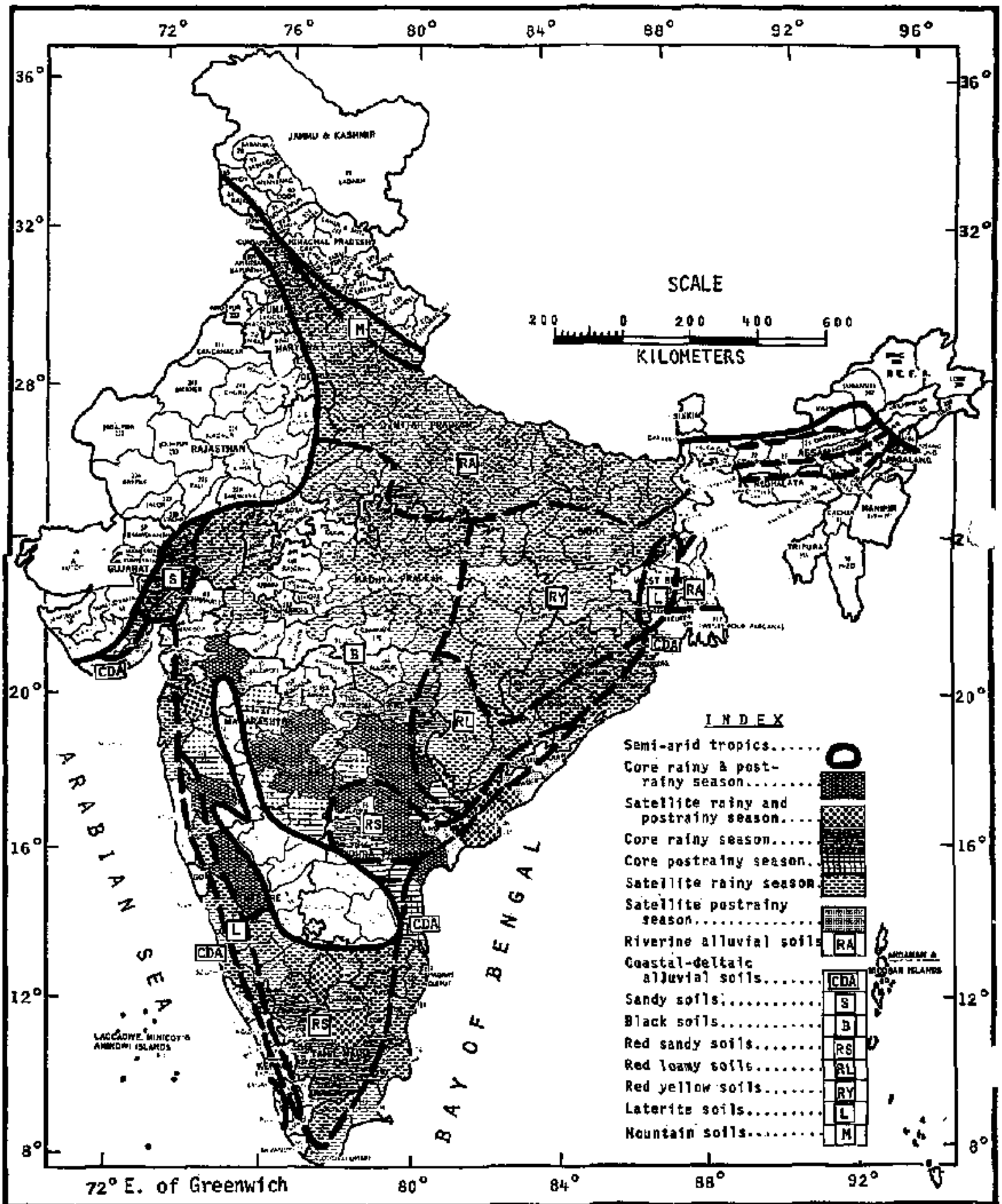


Source: FAO, Agroecological Zones Project 1980.

Figure 7. Length of the growing period in the sorghum-growing districts of semi-arid tropical India.



Source :- Murthy and Pandey (1978) Delineation of Agro-Ecological Regions of India

Figure 8. Soil regions in the sorghum-growing districts of semi-arid tropical India.

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