Physical Environment of Sorghum- and Millet-growing Areas in South Asia

M.V.K. Sivakumar, A.K.S. Huda, and S.M. Virmani*

Abstract

In the semi-arid areas of Asia, rainfed farming of sorghum and millet constitutes the main pattern of land use. About 57% of the world's millet and 38% of the sorghum come from Asia; South Asia contributes 60% of the total Asian production of both crops, with India alone producing 96% of the millet and 98% of the sorghum. However, a major constraint to increasing production is drought, resulting from low and variable rainfall and soils with low water-holding capacity. The wide range of variation in other climatic parameters as well—temperature; radiation, and evapotranspiration—in the sorghum- and millet-growing areas is illustrated and discussed. The broad soil regions in semi-arid Asia are described, and measures suggested for improving and stabilizing yields by matching the crop growth cycle with the growing period. The variability in the phenology, growth, and yield of sorghum is illustrated with examples from a 3-year multilocation sorghum-modeling experiment. It is proposed that data banks be set up to collect—via an interagency network—the information on climate, soils, and crops needed to assess the impact of the physical environment on sorghum and millet production in the semi-arid tropics.

Résumé

Le milieu physique des régions productrices de sorgho et de mil dans le sud de l'Asie : Dans les régions semi-arides d'Asie, la culture pluviale du sorgho et du mil constitue la principale forme d'occupation du sol. Environ 57% et 38% de la production mondiale de mil et de sorgho provient de l'Asie; la majeure partie, 60% de la production asiatique, étant cultivée dans le sud de l'Asie, plus particulièrement en Inde (96% du mil et 98% du sorgho). Cependant, une contrainte majeure à l'augmentation de la production est la sécheresse due à une pluviométrie faible et variable et aux sols ayant une faible capacité de rétention d'eau. Cette communication décrit la grande variation d'autres paramètres climatiques, à savoir, la température, le rayonnement et l'évapotranspiration dans les régions de culture de mil et de sorgho. La description des principales régions pédologiques de l'Asie semi-aride est suivie de recommandations pour l'amélioration et la stabilisation des rendements par le callage de la période végétative des cultures avec la période climatique de croissance. La variabilité de la phénologie, de la croissance et du rendement est illustrée par des exemples pris sur trois ans d'essais multilocaux de modélisation pour le sorgho. Les auteurs proposent l'établissement de banques de données pour collecter, par l'intermédiaire d'un réseau d'agences, de l'information sur le climat, les sols et les cultures, afin de mieux évaluer l'influence du milieu physique sur la production du sorgho et du mil dans les zones tropicales semi-arides.

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* Farming Systems Research Program, ICRISAT, Patancheru, A,P., India.

International Crops Research Institute for the Semi-Arid Tropics. 1984. Agrometeorology of Sorghum and Millet in the Semi-Arid Tropics: Proceedings of the International Symposium, 15-20 Nov 1982, ICRISAT Center, India. Patancheru, A.P. 502324, India: ICRISAT.

Asia, with 58% of the world's population, has only 20% of the world's arable land, 77% of which is already cultivated (Kanwar 1982). It is imperative that the primary strategy for increasing food production in Asia be to improve crop yields on a unit-area basis. This is only possible through an effective understanding and management of available resources, both physical and biological.

In the semi-arid areas of Asia, rainfed farming of sorghum and millet constitutes the main pattern of land use. About 38% of the sorghum and 57% of the millet produced in the world comes from Asia. Burma, India, Pakistan, and Sri Lanka in South Asia cover 79% of the total area and account for 60% of the total production in Asia for both crops. According to the FAO (1981), India contributed 96% of the sorghum and millet produced in South Asia during 1980 (Table 1), but per hectare yields in India are 25% below the Asian average yields. Careful consideration of the physical environment will show, however, that considerable potential exists for raising the yields of these crops far above current averages. For example, research conducted at 15 locations of the All India Coordinated Research Project on Dryland Agriculture (AICRPDA) suggests that across a wide range of rainfall regimes, cereal crop yields could be improved as much as 400% over the yields obtained by the farmers (Fig. 1). The regression coefficients for the relationship between seasonal rainfall and yields of maize, sorghum, and millet suggest that with every 100 mm increase in seasonal rainfall, yields can be increased by 387 kg/ha at the research station, but in the farmers' fields, the expected increase is only 82 kg/ha. This difference could be due to the composite effect of biological and technological innovations adopted at the research stations.

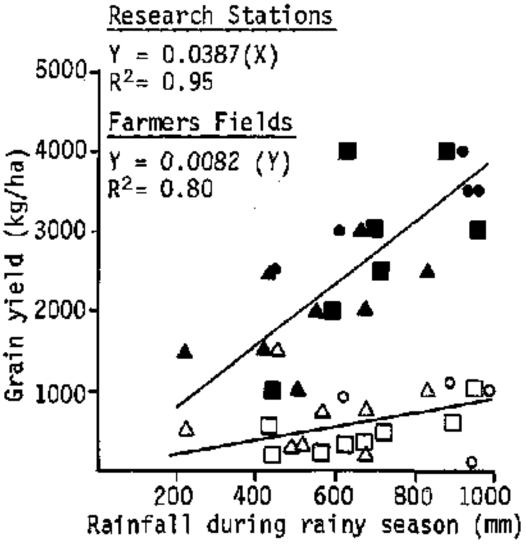


Figure 1. Relationship between rainfall during the rainy season and yield of maize (●), sorghum (■) and millet(▲) grown at research stations (filled-in symbols) and farmers' fields (open symbols) at 15 dryland locations in India.

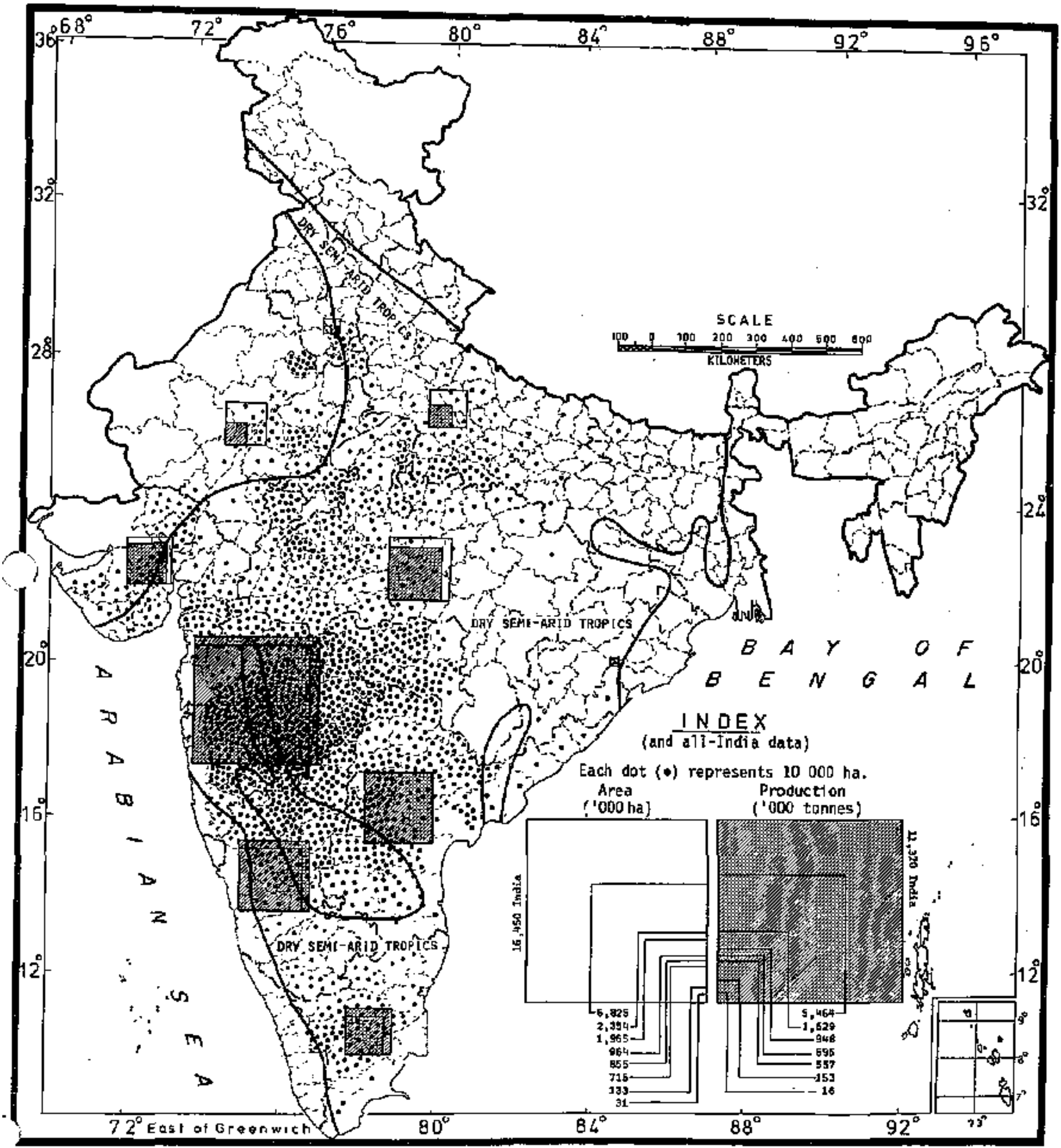
Sorghum- and Millet-growing Regions in South Asia

As shown in Table 1, India contributes about 96% of the sorghum and millet produced in South Asia. Based on data available by district on area and production for 1979/80, maps showing distribution, area, and production of sorghum and millet in India (Figs. 2 and 3) have been prepared (Bose 1981).

Table 1. Sorghum and millet production statistics in South Asia.

	Sorghum			Millet		
Country	Total area (000 ha)	Total production (000 tonnes)	Average yield (kg/ha)	Total area (000 ha)	Total production (000 tonnes)	Average yield (kg/ha)
India	17000	12800	758	17500	9500	543
Burma				180	60	333
Pakistan	480	583	280	641	330	515
Sri Lanka	2	3	1190	35	20	571
Asia	22085	22201	1005	23176	16506	712

Source: FAO (1981).

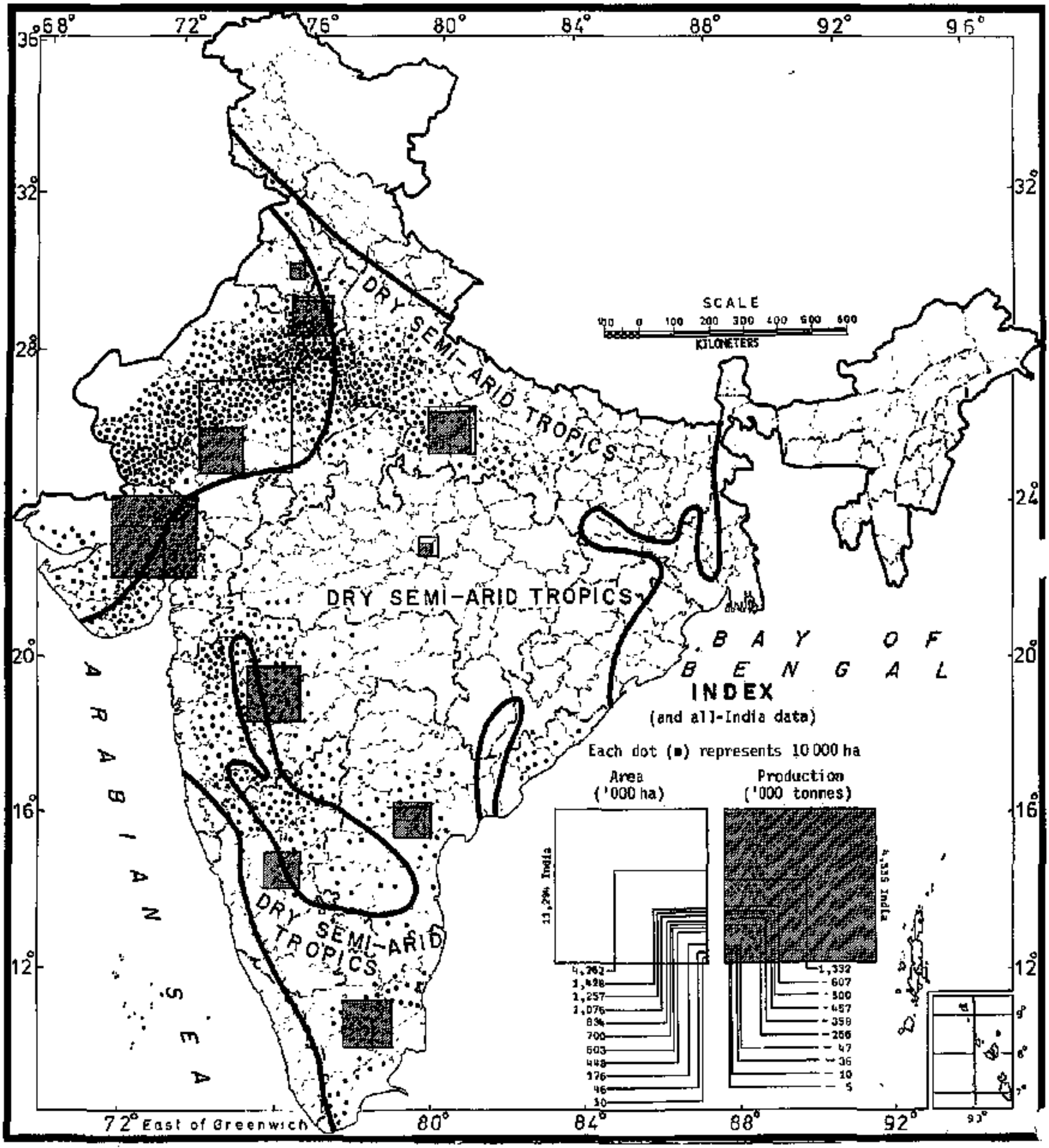


Conical Equal Area Projection with
two Standard Parallels

Sources: Agricultural situation in India (June 1981).
ICRISAT Agroclimatology Subprogram Progress report 5 (1980-81).

Figure 2. Distribution, area, and production of sorghum in India (1979/80).

Maharashtra, Karnataka, and Andhra Pradesh contribute 77% of all the sorghum produced in India; Madhya Pradesh, Tamil Nadu, Gujarat, Uttar Pradesh, and Rajasthan together contribute 22%. In all these states, except Rajasthan and Uttar Pradesh, sorghum is grown during both the rainy and postrainy seasons. About 66% of the total sorghum produced in the country is harvested during the rainy season and the rest during the postrainy season; hence it is important to examine the physical environment of sorghum in India in this context. Other major sorghum-producing countries in South



Conical Equal Area Projection with two Standard Parallels

Sources: Agricultural situation in India (June 1981).
ICRISAT Agroclimatology Subprogram progress report 5 (1980-81).

Figure 3. Distribution, area, and production of pearl millet in India (1979/80).

Asia are Pakistan and Sri Lanka. Sorghum production data are not available by region for these countries.

As with sorghum, about 71% of the total millet crop produced in India is contributed by only four states—Gujarat, Rajasthan, Maharashtra, and Uttar Pradesh. Haryana, Andhra Pradesh, Tamil Nadu, Karnataka, Madhya Pradesh, and Punjab are the other prominent states, producing 28% of the total. Unlike sorghum, however, all the millet crop in

India is produced during the rainy season. Pakistan, Burma, and Sri Lanka together produce 4% of the millet crop in South Asia.

Physical Environment of Sorghum- and Millet-growing Regions in South Asia

The physical environment of South Asia is primarily discussed in terms of atmospheric circulation, climatic elements, and soils, keeping in view the pertinent features of sorghurh and millet crops that are so important to the region.

General Atmospheric Circulation

Rainfall is the most significant climatic element affecting sorghum and millet production in South Asia. Rainfall, temperature, and wind patterns in the region are determined largely by the atmospheric circulation.

The size of the land mass in South Asia—which includes the very high mountains in the north, the plains below them, the peninsula in the south, hill ranges in the northwest and northeast, and a lower range along the west coast—is an important factor in determining the climate of the region. The Himalayas in the north, which form an unbroken range of lofty mountains, block the cold winds from the north and the monsoon winds from the south. By checking the winds from the north, they help the monsoons reach more northerly latitudes than would be possible otherwise. Rao (1981) provided a good description of the atmospheric circulation over South Asia.

In the summer months, March to May, intense heating of the land mass in South Asia leads to increased temperatures and low atmospheric pressure. The heating of land is especially marked over northwestern India and adjoining rainless areas of West Pakistan and a low-pressure zone is well established in the area. The early trade winds change direction on crossing the equator and become southwesterlies and westerlies. After entering the Arabian Sea and the Bay of Bengal, they appear in South Asia as southwest monsoons. On the west coast of Sri Lanka the Arabian Sea branch of the monsoon brings heavy rainfall; it then hits the Western Ghats of India and advances eastward in southern and central India, resulting in moderate rainfall. The Bay of Bengal branch of the monsoon causes heavy precipitation in coastal areas of Burma and parts of northeastern India. These two branches of the monsoon meet north of the low-pressure area and then advance westwards, bringing considerable rainfall to the submontane tract of the Himalayas. Depending on the position and frequency of eastern depressions in northern and central India, the occurrence of rainfall in central and northwestern areas of India varies, which could cause droughts of varying durations and intensities, Rajasthan, southern Punjab, and the Sind plains of Pakistan remain out of the path of the monsoon and get little rain.

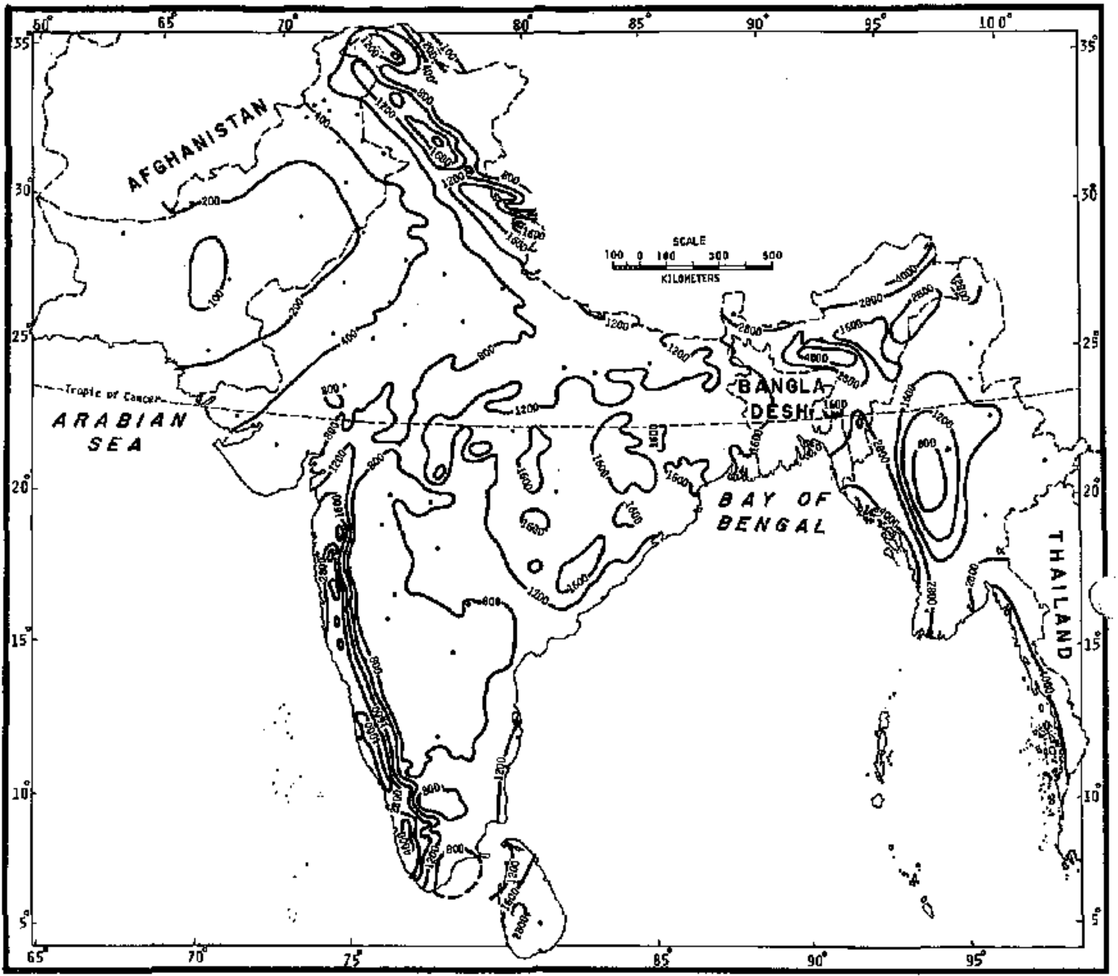
As the southwest monsoon withdraws in September, the northeasterly air currents dominate the area and bring the northeast monsoon rains to Sri Lanka and southeastern and southern India from November to January; they also bring some rain to northern India. Formation of cyclones in the Bay of Bengal and the Arabian Sea also could bring heavy rains inland during October to December. Cyclones over the Atlantic or over regions of the Mediterranean area also bring rain in northwestern Pakistan and India.

Because of these features in the general atmospheric circulation, northeastern India, the west coasts of India and Sri Lanka, coastal Burma/and submontane areas of the Himalayas receive considerable rainfall. The general decrease in rainfall is from east to west and north to south.

Rainfall

Since both sorghum and millet are rainfed, the optimum time of sowing, establishment, and survival of these crops in South Asia depend to a large extent on the fluctuations in the onset of the southwest monsoon, the duration of its influence over South Asia, and its subsequent withdrawal from the area. Isochrones of the onset of the monsoon have been published by the India Meteorological Department (IMD 1978), The normal date of onset of the southwest monsoon is 25 May in Sri Lanka and Burma, 5 June over the southern peninsula, and 1 July in the major millet-growing areas in northwestern India, The monsoon reaches Pakistan around 15 July. The withdrawal also commences in Pakistan by 1 September and progresses steadily into north and central India; by 15 October it withdraws from the upper half of the southern peninsula and Burma.

Mean annual rainfall over South Asia is shown in Figure 4. The orography in the region causes signif-



Conical Orthomorphic Projection. Origin 27½° N.
Standard Parallels 16° & 38°

SOURCE: World Survey of Climatology Volume 9, 1981.

Figure 4. Mean annual rainfall (mm) over South Asia-Pakistan, India, Burma, and Sri Lanka.

icant differences in the rainfall received over the whole area. The highest annual rainfall, exceeding 1500 mm, is recorded on the southern slopes of the Khasi-Jaintia Hills in West Bengal, on the slopes of the Western Ghats, in the sub-Himalayan region, over the hill ranges of Tripura, Manipur, Nagaland, and the Mizo Hills, on the western coast of Burma, and on the Colombo-Jaffna belt on the west coast of Sri Lanka. From the east coast rainfall decreases inland up to the eastern side of the Western Ghats in the peninsula, south of 17°N. To the east of the Western Ghats, between 14 and 18°N, is a region of low rainfall (less than 700 mm) covering parts of Andhra Pradesh, Karnataka, and Maharashtra, where a significant quantity of sorghum and millet are produced. North of 24°N, the rainfall decreases from east to west, from 1500 mm in Uttar Pradesh to less than 100 mm in the Thar desert of Pakistan.

When the rainfall isohyets shown in Figure 4 are superimposed on the distribution, area, and production maps for sorghum and millet (Figs. 2 and 3), reasons for the preferential cultivation of these two crops in certain states become obvious. For example, almost all the millet crop in India is grown in areas where the mean annual rainfall is below 800 mm, most of it under 600 mm. Sorghum-growing areas in India, however, are extended up to the 1200 mm mean annual rainfall isohyet, but the majority of the sorghum-growing regions are located in the annual rainfall isohyet range of 600 to 1000 mm.

It is of interest to note that the rainy-season sorghum-growing areas are located between the 800 and 1000 mm rainfall isohyets. The postrainy-season sorghum areas are located in the belt with low and independable rainfall areas, with less than 800 mm rain. Based on a moisture index defined as

$$p - \frac{PET \times 100}{PET}$$

where P is the precipitation and PET the potential evapotranspiration, Krishnan (1972) showed that the moisture deficiency during the rainy season is accentuated from east to west. During the postrainy season, moisture deficiency extends over the entire country, except for a small belt in eastern Tamil Nadu. The deficiency increases from south to north in peninsular India and from east to west in north India.

Over 75% of the mean annual rainfall is received during the southwest monsoon period from June to September, except in the eastern coastal belt of the southern peninsula and most of Sri Lanka in the south, and Kashmir in the north. From October to December, Sri Lanka, the southern peninsula, the east coast, Assam, and parts of Kashmir receive good rain from the northeast monsoon.

Rainfall Variability

Russell (1959) pointed out that even in regions with annual water surplus, water deficiencies could occur in specific localities because of deviation of annual rainfall from average values. To illustrate such variability in rainfall, we chose a sample of 169 locations in the rainfed areas of India from available records of the India Meteorological Department (IMD 1967). The mean annual rainfall at these locations varies from 550 to 1700 mm. Mean monthly rainfall and annua! rainfall averaged over all the locations showed a coefficient of variation ranging from 39 to 225% for monthly rainfall and 32% for annual rainfall (Table 2). Minimum variability in the monthly rainfall was recorded during June to October, influenced by the predominant southwest monsoon over India.

Monthly precipitation data for 177 locations in Burma, 85 locations in Sri Lanka, and 123 locations in Pakistan have been published by Wernstedt (1972). Coefficients of variation in the monthly and annual rainfall for Burma, Sri Lanka, and Pakistan, respectively, are shown in Tables 3, 4, and 5. All areas in Burma receive high rainfall—except for a small central zone—and the mean annual rainfall is 2185 mm (Table 3). However, the coefficient of variation in annual rainfall is 66%, because of the wide differences in rainfall received over different regions of Burma, and the wide range between the maximum and minimum rainfall received during the year.

Table 2. Monthly and annual rainfall at 169 locations in rainfed areas of India.

Month	Mean rainfall (mm)	Coefficient of variation **(%)**	Maximum (mm)	Minimum (mm)	Range (mm)
January	17	115	92	0	92
February	14	92	72	0.2	72
March	15	91	104	0.1	104
April	22	119	166	0	166
May	40	103	249	0.4	249
June	122	53	238	6	332
July	256	47	519	7	512
August	240	47	508	12	496
September	170	39	341	16	325
October	93	74	307	2	305
November	40	181	458	1	457
December	15	225	239	0	239
Annual	1042	32	1689	305	1384

Table 3. Monthly and annual rainfall at 177 locations in rainfed areas of Burma.

Month	Mean rainfall (mm)	Coefficient of variation (%)	Maximum (mm)	Minimum (mm)	Range (mm)
January	2.9	136.0	22.9	0	22.9
February	7.2	174.2	105.4	0	105.4
March	12.4	144.9	129.5	0.2	129.3
April	39.5	74.3	179.3	0	179.3
May	229.7	54.7	645.4	48.8	596.6
June	419.9	76.7	1237.2	87.1	1150.1
July	467.6.	87.8	1594.1	42,4	1551.7
August	449.4	78.1	1274.8	59.4	1215.4
September	316.0	60.1	968.5	96.8	871.7
October	170.4	35.4	546.9	47.0	499.9
November	57.7	44.5	171.7	18.8	152.9
December	12.7	827	110.5	0	110.5
Annual	2185.4	65.8	5741.2	527.6	5213.6

Table 4. Monthly and annual rainfall at 85 locations in rainfed areas of Sri Lanka.

Month	Mean rainfall (mm)	Coefficient of variation (%)	Maximum (mm)	Minimum (mm)	Range (mm)
January	166.4	56.5	497.1	59.2	437.9
February	111.2	51.0	238.0	25.1	212.8
March	142.3	52.6	312.4	24.6	287.8
April	219.6	42.8	413.3	54.1	359.2
May	242.8	73.2	718.0	25.6	692.4
June	185.5	105.3	910.6	3.6	907.0
July	144.7	94.9	712.7	7.1	705.6
August	150.8	84.4	655.0	7.4	648.5
September	151.5	72.8	535.7	15.2	520.4
October	308.9	41.7	685.0	87.9	597.1
November	322.7	22.2	468.4	185.4	283.0
December	254.3	37.6	557.3	109.7	447,5
Annual	2400.7	43.3	5457,4	967.5	4490.0

Rainfall statistics for Sri Lanka also present a similar picture (Table 4), with a mean annual rainfall of 2401 mm averaged over the 85 locations and a wide range in the monthly and annual rainfall; however, the coefficient of variation (43%) is lower. The predominant influence is that of the northeast monsoon; mean rainfall from October to December exceeds the mean from June to September, and the coefficient of variation in monthly rainfall during the northeast monsoon period is also lower than during the southwest monsoon.

Except for a small region north of 32°N, most of Pakistan is dry, and the rainfall is low. The average annual rainfall over 123 locations is 331 mm (Table 5), with a coefficient of variation of 78%. Maximum annual rainfall recorded over the entire country is 1640 mm; the minimum, 39 mm; and the range, 1601 mm.

Solar Radiation

Direct measurements of global solar radiation have been made in India for 16 stations for periods ranging from 8 to 21 years (Mani and Rangarajan 1982). Daily sums of global and diffuse solar radiation for 145 stations in India have been computed by Anna Mani and Rangarajan (1982) using regression relationships between solar radiation and sunshine.

Table 5. Monthly and annual rainfall at 123 locations in rainfed areas of Pakistan.

Month	Mean rainfall (mm)	Coefficient of variation (%)	Maximum (mm)	Minimum (mm)	Range (mm)
January	25.2	92.8	120.4	0.8	119.6
February	25.8	85.0	111.8	2.5	109.2
March	28.2	107.3	154.9	0.5	154.4
April	19.3	119.1	111.0	0.2	110.7
May	12.9	98.9	64.3	0.2	64.0
June	19.8	92.0	106.7	0	106.7
July	76.5	77.7	362.2	1.3	360.9
August	72.9	93.1	358.1	0	358.1
September	27.7	96.9	134.4	0	134.4
October	5.9	138.3	53.3	0	53.3
November	4.2	104.3	22.3	0.4	22.3
December	12.5	87.8	53.8	0.5	53.3
Annual	330.7	77.5	1640.1	39.4	1600.7

The mean daily global solar radiation on an annual basis over India ranges from 4.6 KWh/m^2 per day in the northeast to 6.4 KWh/m^2 per day in the northwest. During the rainyseason, solar radiation per day in northern India decreases from 6.0 to 8.0 KWh/m^2 in June to 5.2 to 6.8 KWh/m^2 in September. In peninsular India, however, the solar radiation shows a slight increase, from 4.4 to 5.8 KWh/m^2 in June to 5.0 to 6.0 KWh/m^2 per day in September.

During the postrainy season, solar radiation per day in sorghum-growing areas ranges from 5.0 to 6.0 KWh/m^2 in October to 5.8 to 6.6 KWh/m^2 in February. The lowest values are recorded in December. In the semi-arid tropics of India, therefore, solar radiation should be quite adequate for sorghum and millet production.

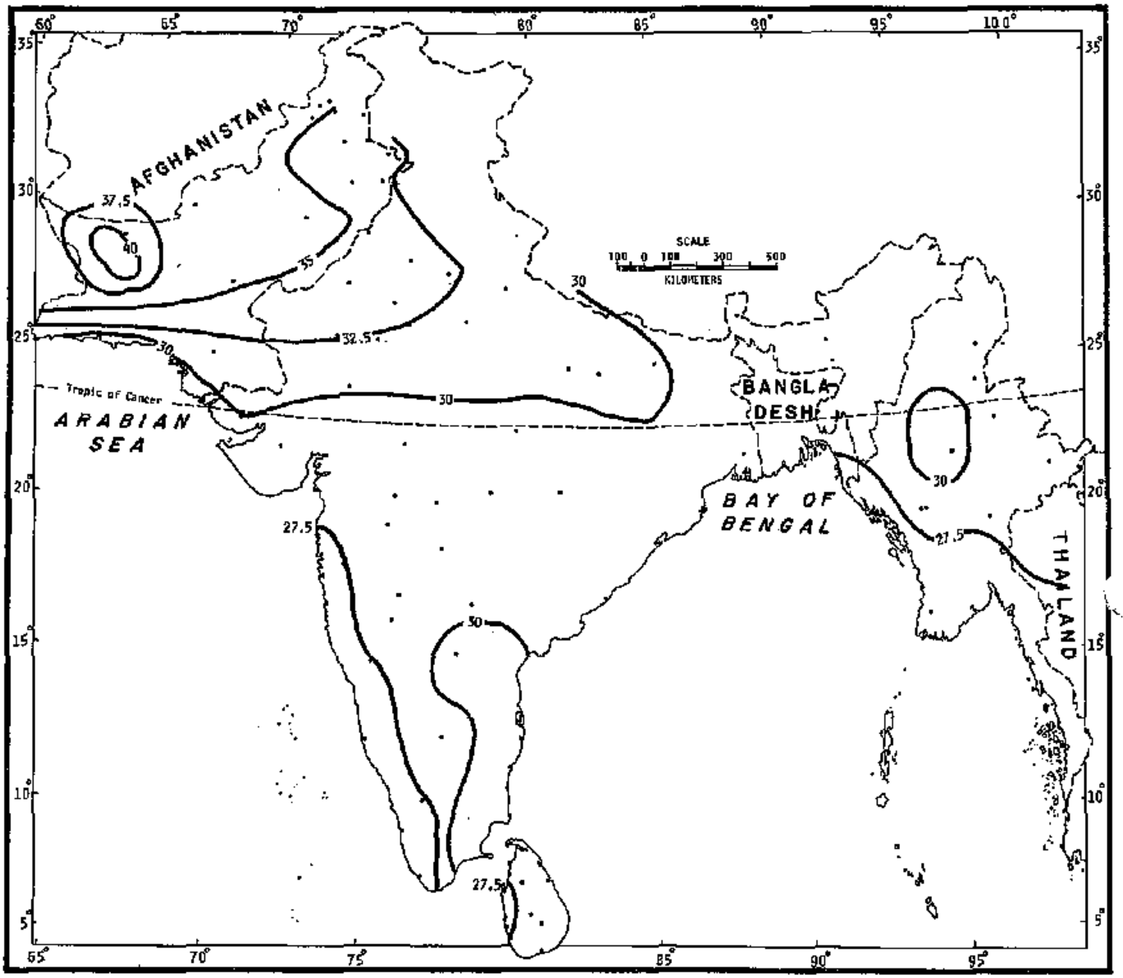
Temperature

In general, temperature determines the rate of crop growth and development. The effects of temperature stress on each critical stage of development of sorghum are discussed by Peacock and Heinrich (these Proceedings) and the response of millet to temperature is described by Ong and Monteith (these Proceedings). We briefly describe here the range of temperatures under which sorghum and millet are grown in South Asia.

Mean daily temperatures (average of the mean daily maximum and the mean daily minimum) over South Asia in July are shown in Figure 5. During July, when both sorghum and millet are usually in the rapid vegetative growth stage over most of India (except in the northwestern regions), the mean daily temperatures range between 28 and 32°C. In Rajasthan and the adjoining areas in Pakistan, the mean daily temperatures exceed 32.5°C; in Baluchistan, they exceed 40°C. In central Burma—which receives the lowest seasonal rainfall in the country—mean daily temperatures exceed 30°C. In southern Burma, July mean temperatures are below 27°C. By October, throughout South Asia the mean daily temperatures generally range from 27 to 29°C. Almost all of the postrainy-season (*rabi*) sorghum in India is grown south of 25°N latitude, where the mean daily temperatures exceed 17.5°C. Figure 6, showing mean daily temperatures for January, indicates the temperatures prevailing in rabi sorghum areas during the postrainy season.

In the major postrainy-season sorghum belt of Maharashtra, Karnataka, and Andhra Pradesh, mean daily temperatures in January exceed 22.5°C.

Average or mean temperatures, however, could be misleading; it is more important to examine the maximum and minimum temperatures. Mean daily maximum temperatures over South Asia in July {Fig. 7) show some interesting features. In the major sorghum-growing regions of India (Fig. 7) the mean maximum temperatures are less than 35°C. However in western Rajasthan, an important millet-growing region, mean maximum temperatures range from 35 to 40°C, and in Pakistan maximum temperatures reach up to 45°C. In the drier regions

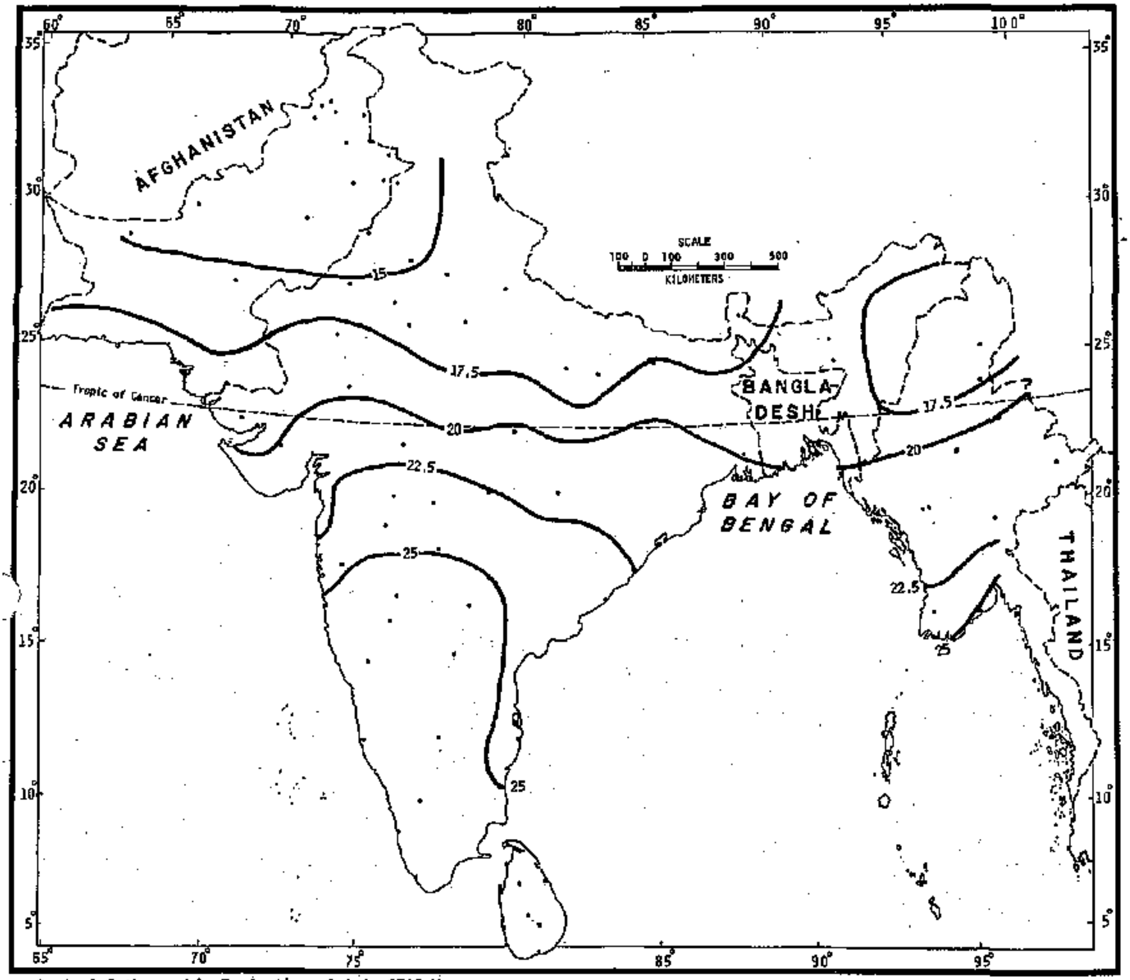


Conical Orthomorphic Projection. Origin 27½° N.
Standard Parallels 16° & 38°

Figure 5. Mean daily temperature (°C) in July over South Asia—Pakistan, India, Burma, and Sri Lanka.

of central Burma, maximum temperatures in July exceed 32.5°C. By October, however, the temperatures in the northwest are lower. The highest temperatures in South Asia are over Baluchistan. Mean maximum air temperatures in January (Fig. 8) exceed 25°C in the postrainy-season sorghum-growing areas, and in the major states of Maharashtra, Karnataka, and Andhra Pradesh, maximum air temperatures are over 30°C.

Mean daily minimum temperatures in July in the sorghum-growing regions of India vary from 25 to 27°C, while in western Rajasthan and Pakistan, minimum temperatures exceed 28°C (Fig. 9). By October in this region, temperatures drop below 20°C, while in central and peninsular India minimum temperatures range from 23 to 25°C. In the postrainy sorghum-growing season, the minimum temperatures are lower and, as shown in Figure 10, in January the mean daily minimum temperatures north of 25°N latitude are lower than 10°C. In central and peninsular India the temperatures range from 12 to 22°C. Minimum temperatures measured at the screen height are often considered to be higher than those actually experienced in the crop canopy. Data published by IMD (1978) show that north of 20°N latitude, the gross minimum temperatures are lower than 7.5°C. Such low air temperatures hamper the growth of sorghum, which is



Conical Orthomorphic Projection. Origin 27½° N.
Standard Parallels 16° & 38°

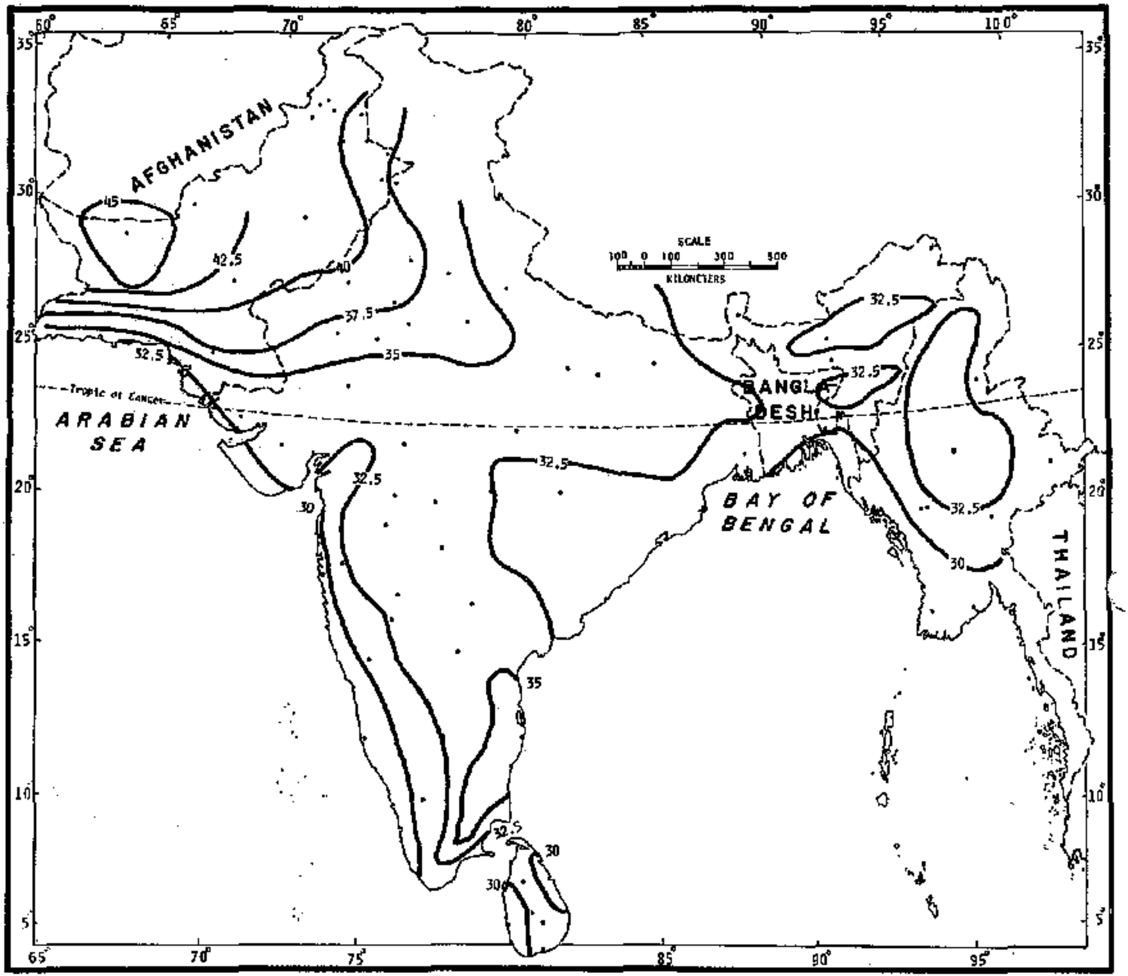
Figure 6. Mean daily temperature (°C) in January over South Asia—Pakistan, India, Burma, and Sri Lanka.

probably why postrainy-season sorghum is primarily limited to peninsular India.

The temperature data discussed above suggest that in more marginal areas suitable for growing millet but not sorghum, the air temperatures are higher by 4 or 5°C. In terms of the relevance of the observed temperatures to the phenology of sorghum grown in the rainy and postrainy seasons, the diurnal range in temperature is small in the rainy season, and the uniformly high temperatures should promote good vegetative growth and grain filling. In the postrainy season, however, the diurnal range in temperature, especially around the time when the sorghum crop reaches flowering, is rather large, and the minimum temperatures are consistently low. The implications of these temperatures are discussed in detail by Peacock and Heinrich (these Proceedings).

Potential Evapotranspiration

Although the rainfall at two locations is similar, if the degree of atmospheric demand for water between the locations is different, it can make a significant difference in the water requirement of the crop. Rao et al. (1971), using a modified Penman's formula, have calculated the potential evapotranspiration (PET) for 300 stations in India, Burma, Pakistan,



Conical Orthomorphic Projection. Origin 27½° N.
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Figure 7. Mean daily maximum temperatures (°C) in July over South Asia—Pakistan, India, Burma, and Sri Lanka.

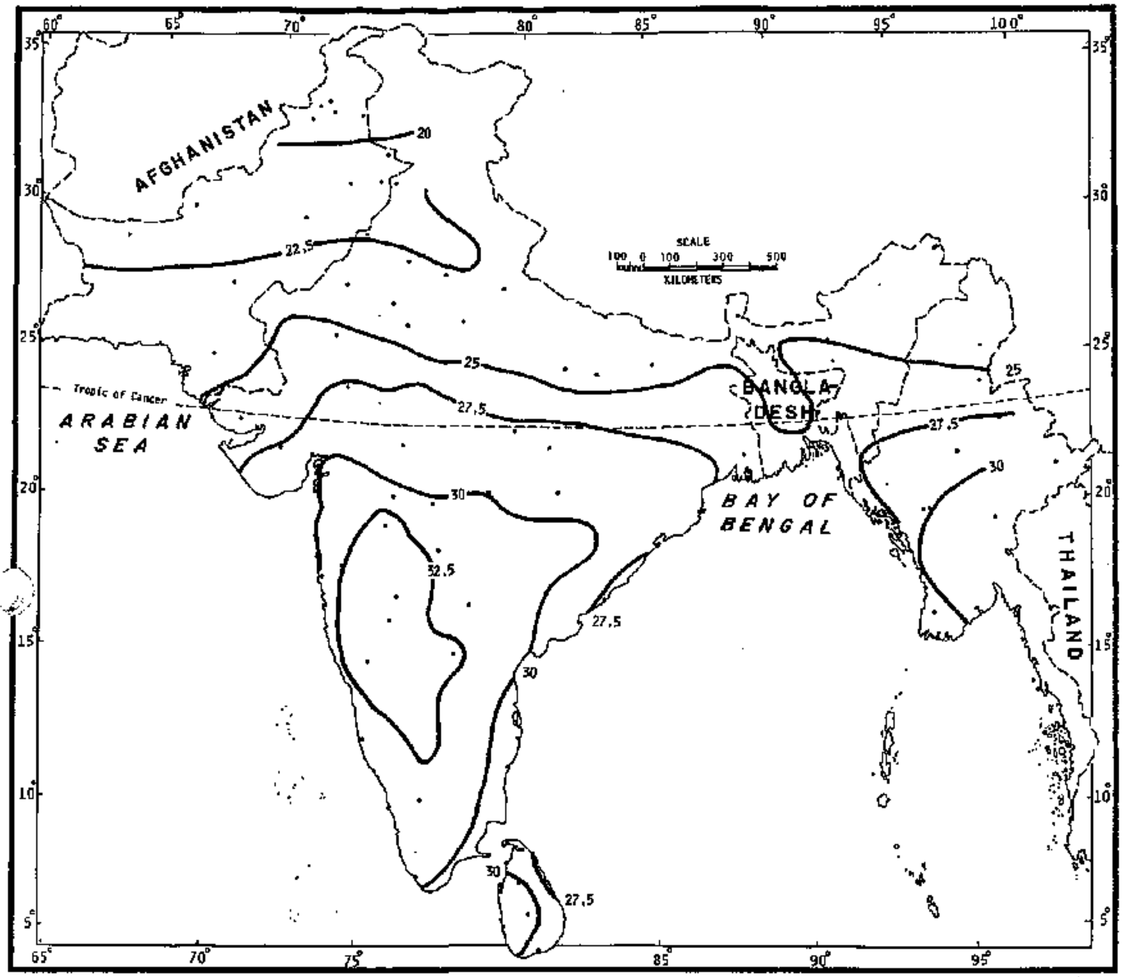
and Sri Lanka from climatological data of temperature, vapor pressure, cloudiness, etc. Mean potential evapotranspiration over South Asia from June to September is shown in Figure 11. In southwestern peninsular India and in Burma, because of the active monsoon and cloudy skies, the PET is low (about 400-500 mm) and in northwestern India and Pakistan, PET exceeds 600 mm. On an annual basis, PET over the sorghum- and millet-growing regions varies from 1400 to 2000 mm, with the higher PET values predominating in the major millet-growing regions of Gujarat and Rajasthan.

During the postrainy season, PET ranges from 80 to 140 mm/month in the sorghum-growing areas of Andhra Pradesh, Karnataka, Maharashtra, Tamil Nadu, and Gujarat.

Mean monthly and annual PET, averaged over 169 locations in India (Table 6), show that the variability in PET is much lower than in rainfall and that the atmospheric demand is high.

Moisture Availability

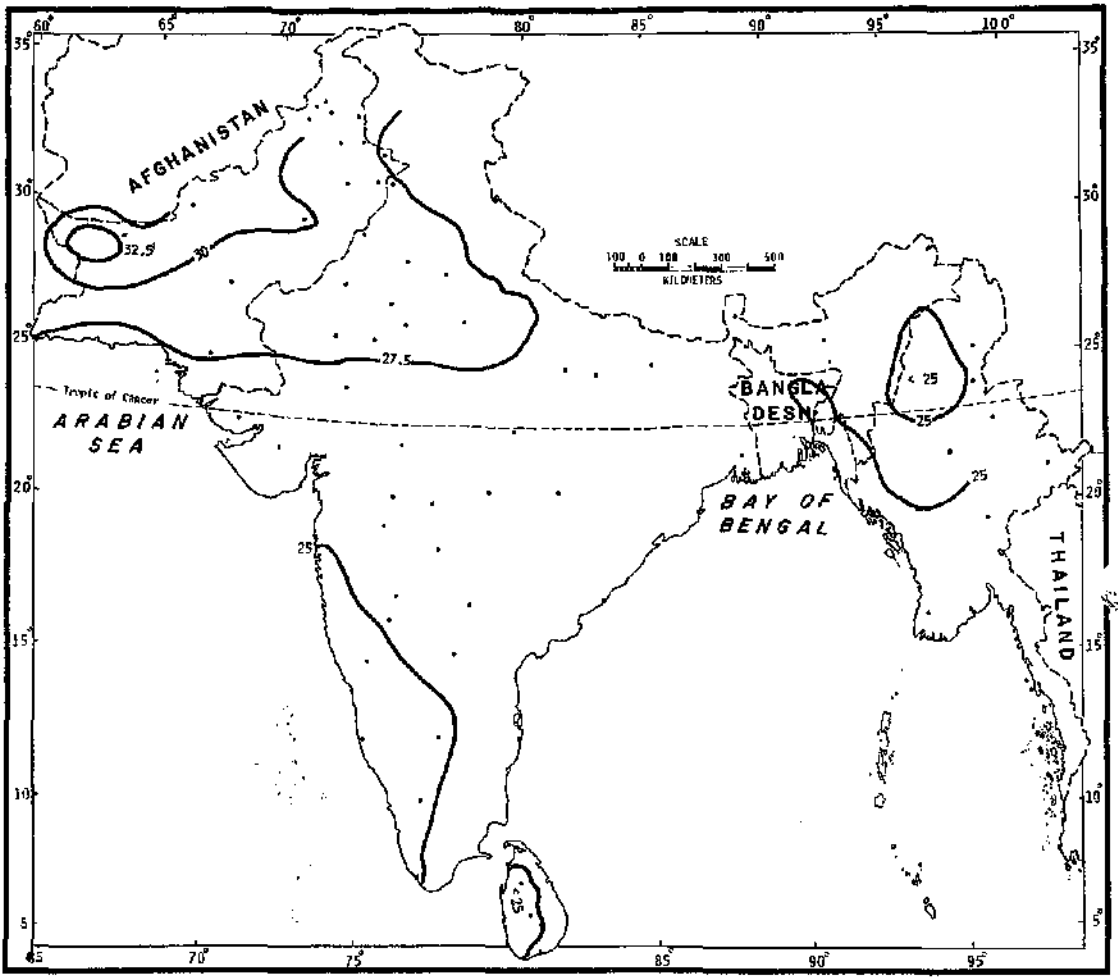
Average rainfall figures do not yield information on the dependability of precipitation. Hargreaves (1975) has defined dependable precipitation (DP) as the amount of rainfall that could be received at



Conical Orthomorphic Projection. Origin 27½° N.
Standard Parallels 16° & 38°

Figure 8. Mean daily maximum temperature (°C) in January over South Asia—Pakistan, India, Burma, and Sri Lanka.

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 rainy season at selected locations in South Asia are shown in Table 7. In Sri Lanka, since the predominant rains occur during the northeast monsoon season, MAI at Hambantota and Mannar from June to October is very low, indicating low potential for sorghum and millet production during this period. In peninsular India, the MAI for Hyderabad, Bangalore, and Pune is indicative of adequate moisture availability for sorghum and millet crop production. In central and northern India, the MAI values show a more favorable moisture environment. In northwestern India, data for Jodhpur and Bikaner indicate that the moisture availability is very low and that both sorghum and millet are likely to suffer from periods of moisture stress during the growing season. In Pakistan, the region around Lahore shows promise for growing millet, and that around Murree shows promise for growing both sorghum and millet. In fact, the high MAI values in July and August suggest the need to provide drainage. Peshawar, however, is very dry, and the rest of Pakistan south of Multan has little or no moisture availability for the growth of sorghum and millet.

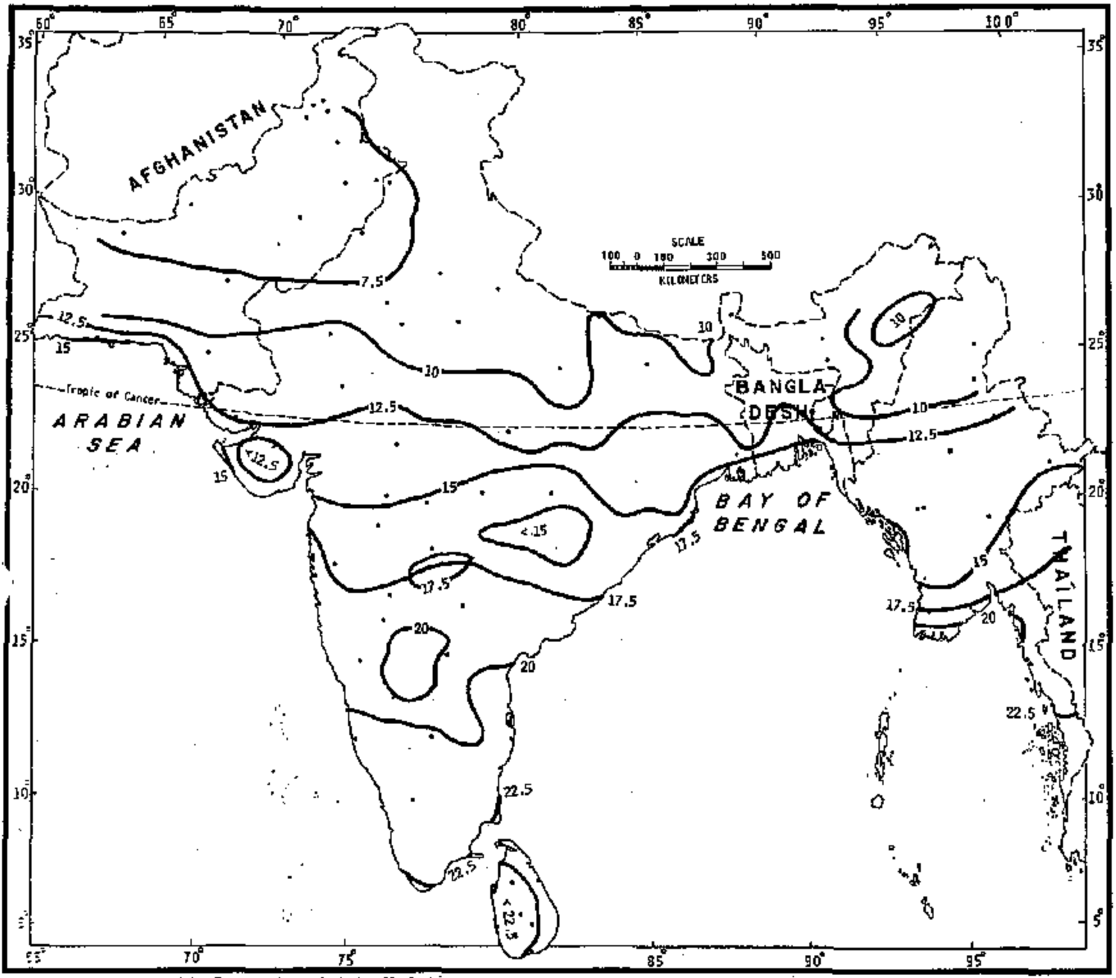


Conical Orthomorphic Projection. Origin 27½° N.
Standard Parallels 16° & 38°

Figure 9. Mean daily minimum temperature (°C) in July over South Asia—Pakistan, India, Burma, and Sri Lanka.

Length of the Moisture Availability Period

For rainfed crops like sorghum and millet to be successful, their growth cycles should be of such a length that they are comfortably contained within the moisture availability period. Failure to match these characteristics does not completely exclude the cultivation of the crop, but can result in reduction of yield and quality, Moisture availability period or length of the growing period has been computed by the Agroecological Zones Project of the FAO (see Frere, these Proceedings) for India. 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. Length of the growing period computed for India is shown in Figure 12. For most of the millet-growing areas in India, the length of the growing period extends from 60 to 90 days. It is notable that sorghum-growing areas show a more favorable length of growing period, 90 to 150 days.



Conical Orthomorphic Projection. Origin 27½° N.
Standard Parallels 16° & 38°

Figure 10. Mean daily minimum temperature (°C) in January over South Asia—Pakistan, India, Burma, and Sri Lanka.

Soils of South Asia

The growing period described above for South Asia takes 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. In the soil map of South Asia published by UNESCO (1977), nine major soil zones were identified in the region covering Sri Lanka, India, Pakistan, and Burma (Fig. 13).

Lithosol-Regosol-Yermosol association in Pakistan. These soils cover the arid parts of Pakistan. The climate is extremely arid, with the mean annual rainfall less than 300 mm, and in most places does not exceed 150 mm. The main soils are Lithosols on hill slopes, stony Regosols on colluvial slopes, and Yermosols on piedmont plains. Lithosols are poor, shallow soils with little potential for improved agricultural production. Regosols are generally poor soils because of low moisture- and nutrient-holding capacity. Yermosols without irrigation are suitable only for grazing; where they are irrigated, drainage and salinity are great problems.

Yermosol-Xerosol association of Pakistan and northwestern India. This soil region covers

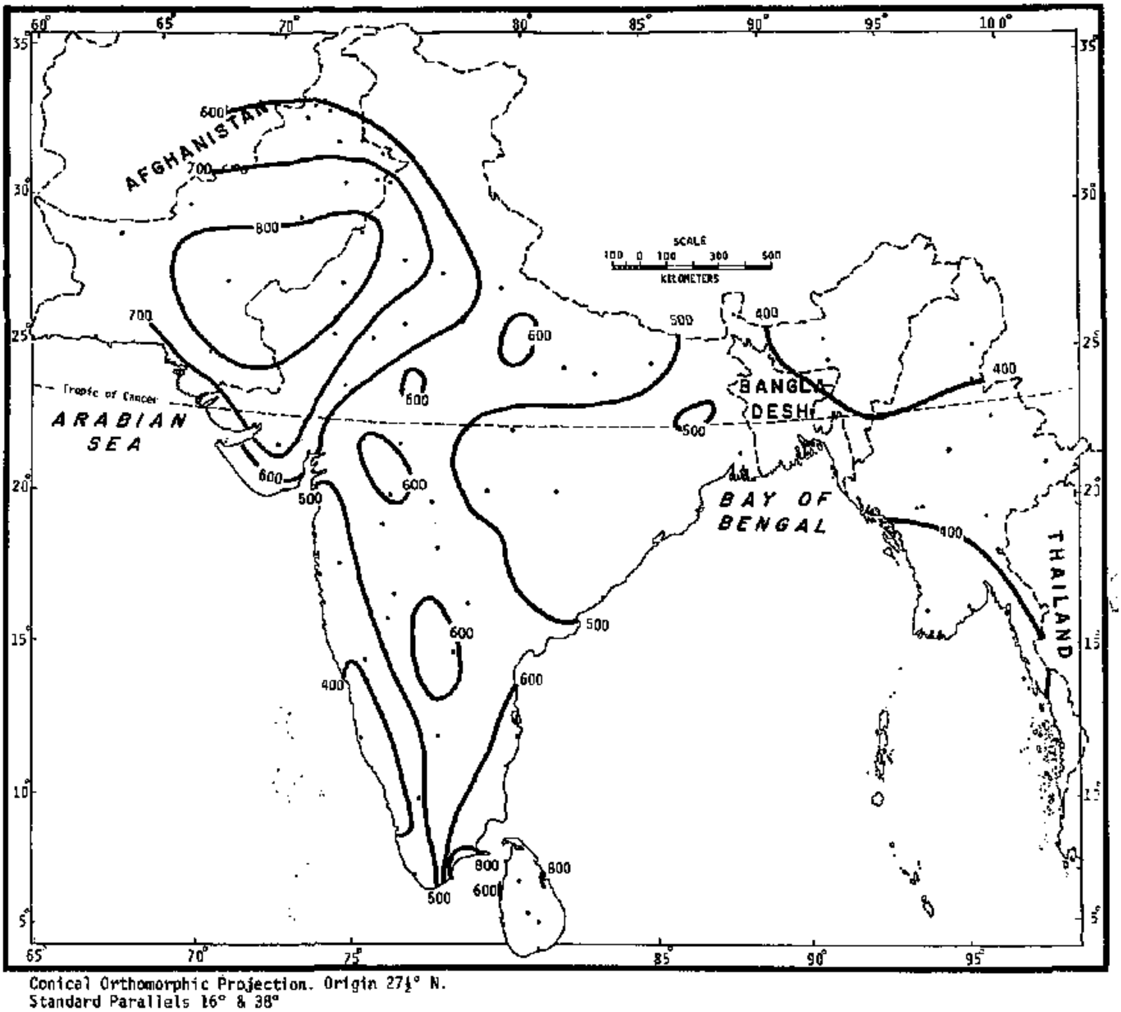


Figure 11. Mean potential evapotranspiration (mm) during June to September over South Asia.

nearly all of the Indus plains and the semi-arid part of northwestern India, In the Indus plains, because of the strong influence of the regular floods on the soil water regimes, the soils are well developed. In the southeast, Xerosols are formed in alluvium. Low and sporadic rainfall on the Xerosols makes crop production risky. Xerosols are not fertile and need nitrogen and phosphorus application for sustained crop production.

Arenosols and Regosols of the Thar Desert. These are sand dunes and ridges of various shapes and heights. The soils are mainly Cambic Arenosols. Calcaric Regosols occur in the south, where the rainfall is less than 200 mm. The gravelly or stony Arenosols have a low moisture-holding capacity. In the uplands erosion is a problem.

Cambisol-Luvisol association of the northern Indo-Gangetic plains. The main soils in this region at the foot of the Himalayas are the Eutric Cambisols, which developed in calcareous alluvium. Locally there are areas of clayey Gleysols occupying strips of low-lying land. These soils are useful for rainfed cultivation of sorghum and millet. But water erosion is a major problem, and proper soil conservation strategies are essential. They are quite fertile soils and need only nitrogen and phos-

Table 6. Potential evapotranspiration (PET) for 169 locations in rainfed areas of India.

	PET			
Month	Mean (mm)	Standard deviation (mm)	Coefficient of variation **(%)**	Mean rainfall (mm)
January	85	27	32	17
February	103	24	23	14
March	151	23	15	15
April	177	21	14	22
May	207	33	16	40
June	174	34	19	122
July	132	27	20	256
August	122	21	18	240
September	122	18	15	170
October	119	15	12	93
November	90	19	21	40
December	78	25	32	15
Annual	1556	196	13	1042

Table 7. Moisture availability index (MAI) for selected locations in South Asia.

	Moisture availability index (MAI)				
Station	June	July	Aug	Sept	Oct
Hambantota	0.16	0.07	0.09	0.10	0.37
Mannar	0.00	0.00	0.00	0.00	0.56
Hyderabad	0.32	0.75	0.55	0.65	0.21
Indore	0.33	1.59	0.94	0,84	0.03
Jodhpur	0.04	0.24	0.29	0.02	0.00
Lahore	0.03	0.38	0.25	0.04	0.00
Peshawar	0.00	0.02	0.03	0.02	0.00
Quetta	0.00	0.00	0.00	0.00	0.00

phorus to produce high yields. Organic matter is usually sufficient, and soils are easily worked to good tilth.

Vertisol-Cambisol association of peninsular India. Covering the northwestern part of peninsular India, this region includes extensive areas of Vertisols intercepted by strips of Cambisols. The soil depth of Vertisols in low-lying areas exceeds 150 cm and in higher terrain it ranges from 100 to 150 cm. Within the nearly continuous Vertisol area are strips of Vertic Cambisols, which occur on high undulating ground. They are slightly to moderately calcareous. Rainfed sorghum and millet can be grown successfully on these soils; however, because they are heavy soils, the drainage is poor, and ridging or making shallow surface drains is essential to provide better drainage. Phosphorus and nitrogen application is essential for higher yields.

Luvisol-Nitosol association of Sri Lanka and peninsular India. These soils cover eastern and southern parts of peninsular India and all of Sri Lanka. Hers Chromic Luvisols predominate while Ferric Luvisols are common in the northeast. Nitosols occur in the high-rainfall areas along the west coast, in northeastern India, and in Sri Lanka. Rainfed sorghum and millet are commonly grown on these soils, which are shallow and sometimes on steep slopes, but have a good structure and are easily worked to a good tilth. Intensive soil-conservation measures are needed to protect these soils from erosion on steep slopes. Nitosols on gentle slopes or level areas have no erosion problems; however, low fertility, low available phosphorus, and excessive wetness from low permeability are their limiting factors.

Cambisols of Burma. Humic Cambisols on the higher elevations and Dystric Cambisols on the lower elevations are the major soils. These soils are sandy and are rapidly permeable. Dystric Cambisols in western Burma are subject to erosion and are poor in phosphates and bases. Because the organic matter is sufficient for good physical condition, they respond well to fertilizer and management.

Acrisol-Fluvisol association of the irrawaddy basin In Burma. Extending from the coast to the center of Burma in the north, this region occupies a 150- to 200-km belt. Acrisols and Luvisols in the undulating to rolling and hilly areas and Eutric Fluvisols in the floodplains of rivers are common. Acrisols, having reached an advanced stage of weathering, are highly acid and low in bases as well as phosphate. Eutric Fluvisols in the floodplains have maintained continuous crop production with low levels of nutrient application. Under good management they respond well to fertilizer use.

Nitosol-Acrisol association of eastern Burma. Dystric and Humic Nitosols and Orthic Acrisols are the common soils here. Excessively drained Orthic Acrisols on high sites in Burma often suffer from drought. The soils have a low natural fertility and

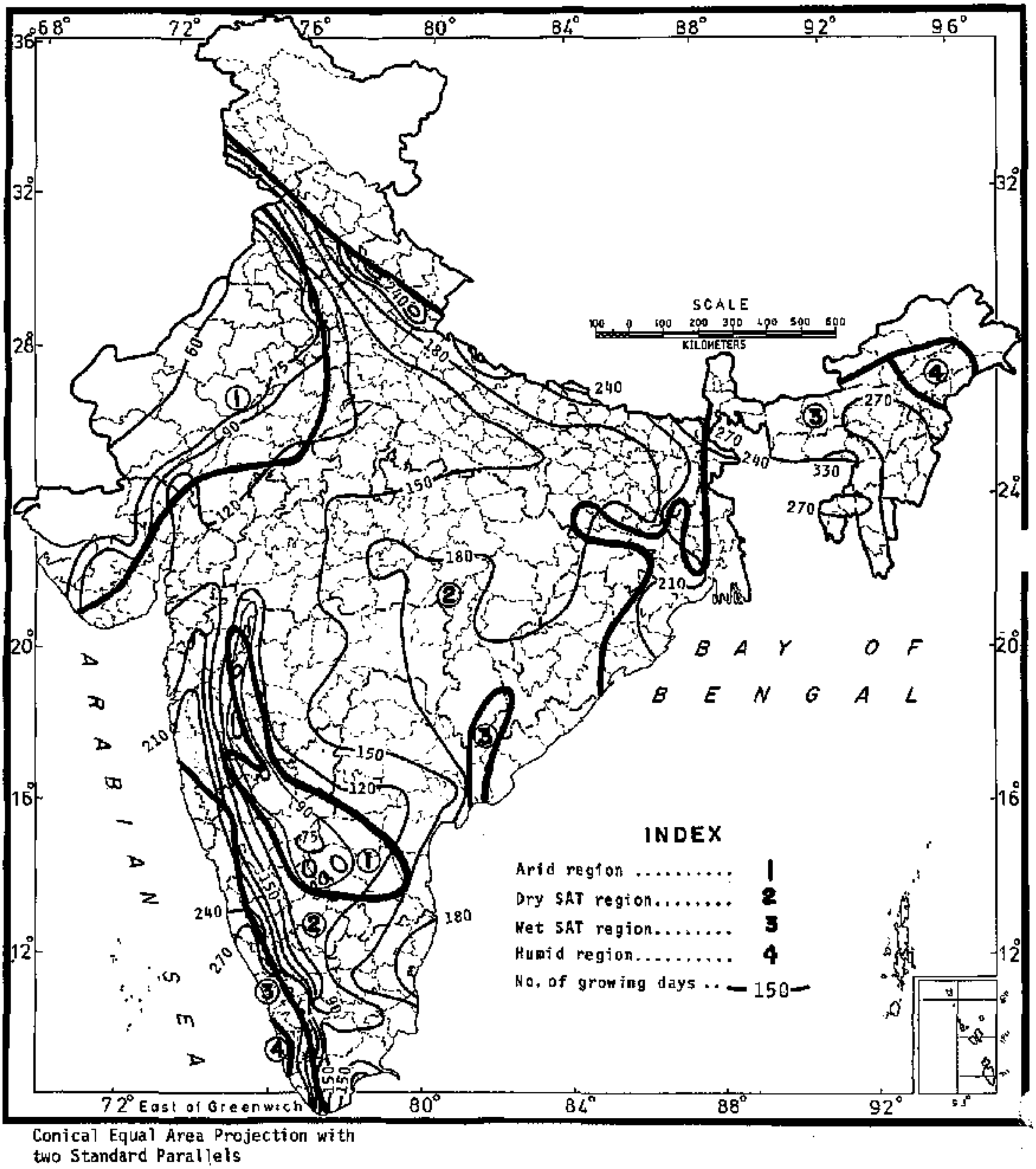
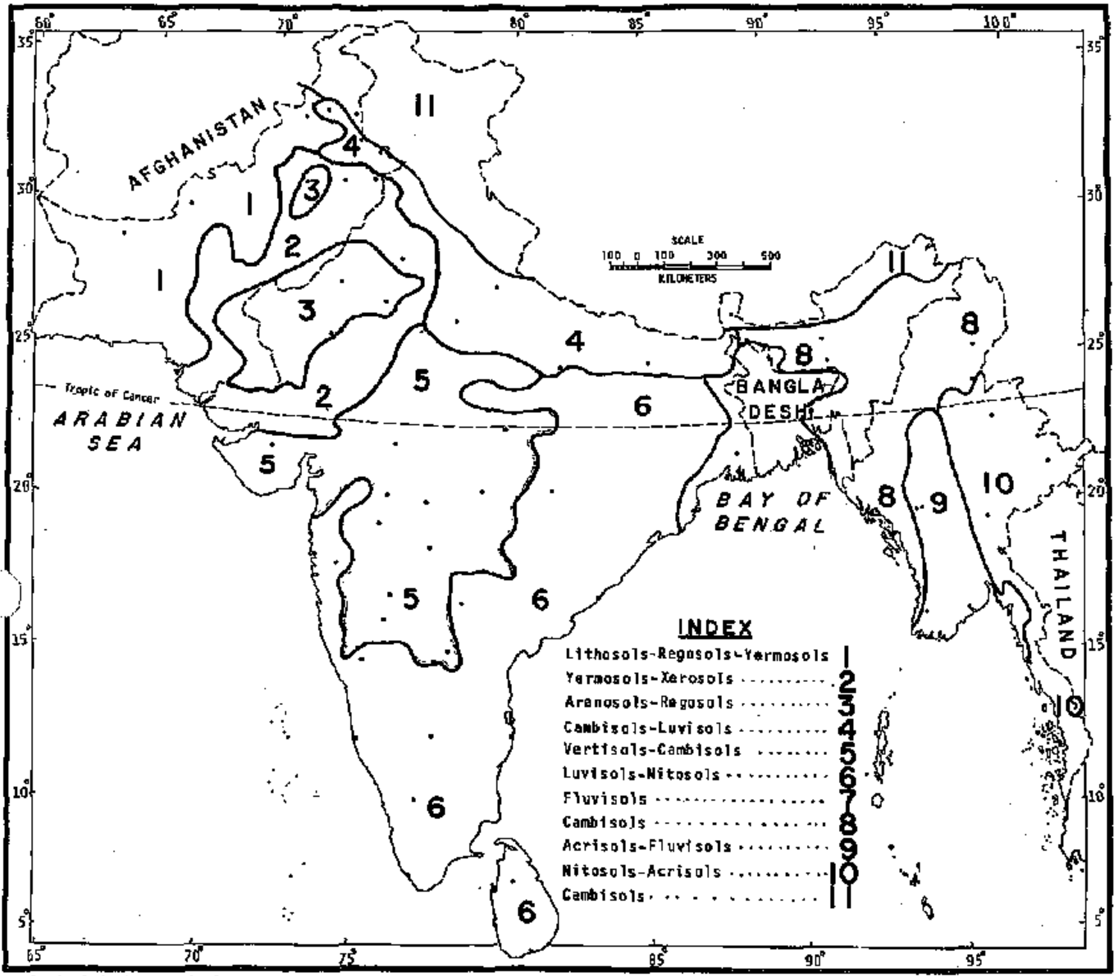


Figure 12. Length of the growing season in India.

are low in phosphate. Dystric and Humic Nitosols with similar low-fertility problems, however, are good deep soils and respond to management. The periodically wet subsoil with the restricted internal drainage may become a restricting factor.

Physical Environment and the Performance of Sorghum

The description of the physical environment in South Asia shows the diversity of agroclimatic con-



Conical Orthomorphic Projection. Origin 27½° N.
Standard Parallels 16° & 38°

SOURCE: FAO-Unesco Soil Map of the World Vol. VII-1977.

Figure 13. Broad soil regions in South Asia—Pakistan, India, Burma, and Sri Lanka.

ditions under which sorghum and millet are grown in this region. For improving production of sorghum and millet, it is important to integrate the crop, soil, and climatic information into usable and practicable region-specific recommendations. The growth and development of sorghum over a heterogeneous region such as India always show a lot of variability, depending on the nature of the soil and of the season in which the crop is grown. An example of this variability is available from the data collected on the phenology, growth, and yield of sorghum grown under good management in a collaborative multilocation experiment on sorghum modeling conducted at 10 locations in India over a 3-year period, 1979 to 1981. A detailed report of these experiments is given by Huda et al. (these Proceedings). Observed variability in the phenology, dry matter, and grain yield of sorghum hybrid CSH-6 at 10 locations in India is shown in Table 8.

Table 8. Variability in phenology, dry matter, and grain yield of sorghum hybrid CSH-6 at ten locations in India.

Year	Days to anthesis	Total dry matter (t/ha)	Grain yield (t/ha)
1979	50-62	9.5-17.1	3.4-4.5
1980	49-64	8.2-13.0	2.1 -5.6
1981	53-65	8.9-14.0	2.0-6.3

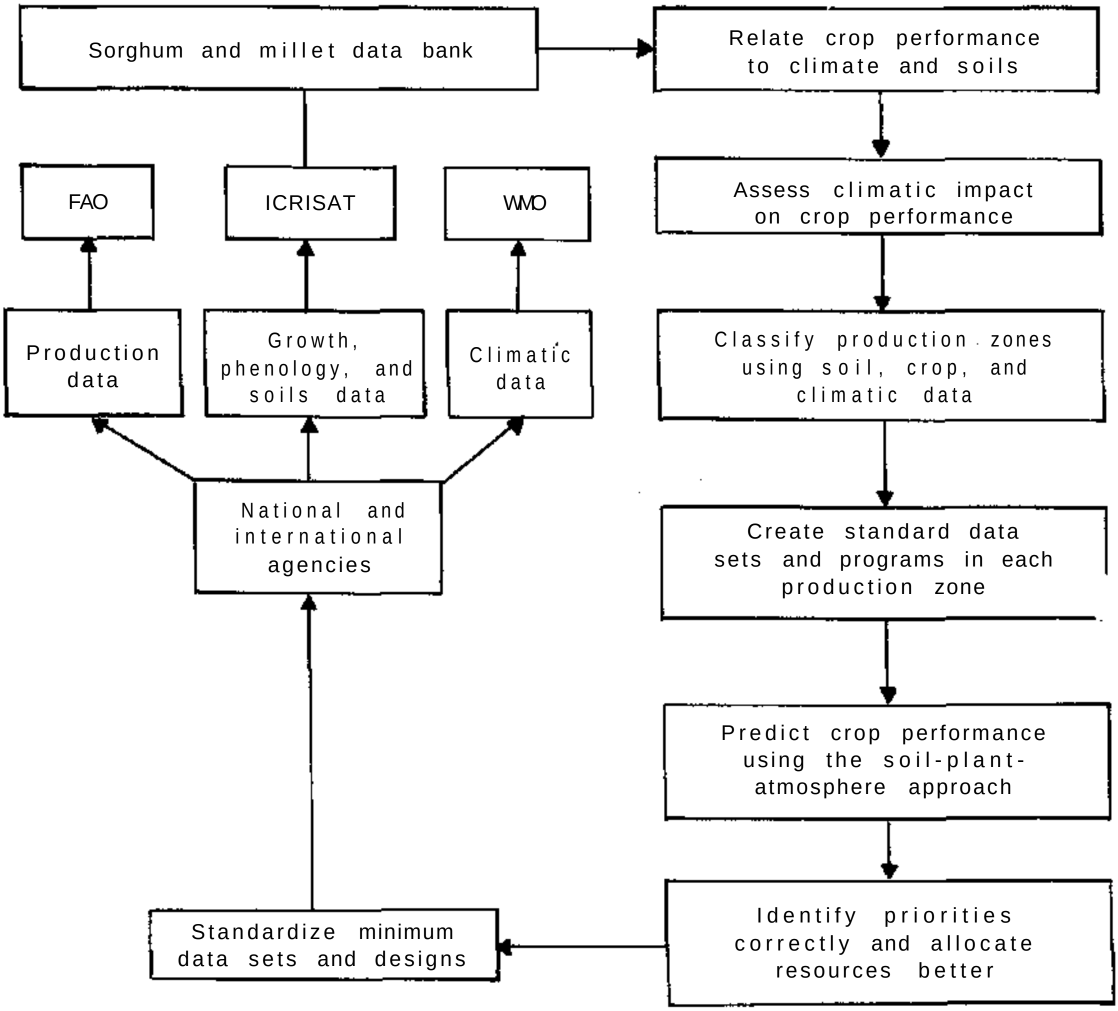


Figure 14. Proposal for an interagency sorghum and millet data bank.

Across the 3-year period, the duration to anthesis varied from 49 to 65 days. Dry-matter production ranged from 8.2 to 17.1 tonnes/ha; grain yields, from 2 to 6.3 tonnes/ha. Because detailed crop, soil, and climatic information was available from these experiments, it was possible to interpret the nature of the sorghum performance at these locations.

However, one difficulty in applying today's results to present problems or relating them to previous experiments is that some or all necessary climate, plant, and soil information is not available. Often experiments involving one or two treatments give excellent single-factor response functions, but with the addition of a few essential variables could give a holistic explanation. It is imperative that a minimum set of data on the site, climate, crop management, and soils be collected to characterize adequately the sorghum and millet response across diverse environments. Climatic data should include daily maximum and minimum temperatures, on-site precipitation, wind speed, and solar radiation if possible. Crop information should be collected on phenology (sowing, emergence, floral initiation, anthesis, and physiological maturity), plant population, and yield components. The management data should include details on the application of fertilizer, herbicides, and insecticides;

genotype; and irrigation dates and amounts (if applicable). Information on extractable water or available water-holding capacity of soils should also be collected.

Proposal for an Interagency Sorghum and Millet Data Bank

Generation of a suitable crop-product ion technology for increased and stabilized production of sorghum and millet in the semi-arid tropics-spread over large areas characterized by a variety of agroclimatic conditions—needs a thorough understanding of the soil-plant-atmosphere continuum. Data necessary to generate such understanding are obviously available, but scattered, and very often not published. The research needs of the 1980s call for a much more efficient and concerted Effort of the international community of scientists and policy-makers. Hence," a proposal for an interagency sorghum and millet data bank is put forth for the consideration of the participants in this symposium (Fig. 14). We believe that such a bank will serve as a repository of the data on production, growth, phenology, soils, and climate for global sorghum- and millet-growing regions. It is suggested that international agencies such as the FAO, WMO, and ICRISAT, in cooperation with the national and other international agencies, can undertake to' collect the necessary minimum data sets. Use of these data should enable the assessment of climatic impact on crop performance and the classification of production zones. For each production zone standard data sets could be made available for predicting the crop performance using the soil-plant-atmosphere approach.

We believe that in the long run such an approach would lead to correct identification of research priorities and better resource allocation, This should enable the national agencies to plan the strategies to improve production of sorghum and millet and, ultimately, to help the farmer.

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