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Climatic Approach to Transfer of Farming Systems Technology in the Semi-Arid Tropics

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Abstract

The crop yields in the dry semi-arid tropics are low due to the temporal and spatial variations in rainfall. These areas are characterized by high climatic water demand, and the rainfall exceeds evapotranspiration only from 2 to 4½ months in a year. Due to the wide spatial distribution of the natural endowments, there exists a strong element of location specificity in terms of moisture environment during the crop growing season. Some techniques employed for quantification of rainfall distribution and soil-moisture availability in relation to crop water needs have been described. Examples of the relevance of agroclimatological analysis for the translocation of farming systems technology are discussed.

The tropical semi-arid regions lie to each side of the tropical rain forest climates and at higher latitudes in both hemispheres. Rainfed agriculture, laden with uncertainty and instability in its precipitation patterns, has failed to provide even the minimum food requirements for the rapidly increasing populations of many developing countries in the semi-arid tropics (SAT). The mean annual temperature of the SAT exceeds 18°C. The rainfall exceeds potential evapotranspiration for 2 to 4½ months in the dry SAT and 4½ to 7 months in the wet-dry SAT (Troll 1965). These areas are characterized by a high climatic water demand and by variable and erratic rainfall. It is imperative that any technology for land and water management and crop production in the SAT areas must be aimed at improved resource management that conserves and utilizes rainfall and soil more efficiently and at new crop production systems that maintain productivity and assure dependable harvests (Kampen 1979).

The intimate relationship between the weather and agricultural production systems, especially the complexities associated with vagaries of weather in terms of yield fluctuations, has been a subject of wide concern in national and international crop production planning. In this context, the situation in the SAT areas is even more complex because of the large variations in the weather parameters that affect agricultural production. A proper description and analysis of these weather parameters is an essential element in the application of agrometeorological knowledge for the generation and transfer of farming systems technology in the SAT areas.

Climatic Approach in Farming Systems Technology

Over the past 6 years, a considerable amount of farming systems research at ICRISAT has concentrated on analysis of the agricultural process for identifying the constraints to agricultural production and for evolving suitable production practices in the removal of these constraints. As a useful corollary to this exercise, efforts in the agroclimatology subprogram are aimed at analyzing the meteorological conditions of a region in order to characterize its agricultural potential and identify suitable crops/cropping systems to reap the full benefit of this potential. A systematic climatological approach in this context comprises the following steps:

1. Description of the rainfall regime in a particular area, including studies on the total rainfall, rainfall intensities, and rainfall probabilities.
2. Calculations of potential evapotranspir-

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ation and its relationships with rainfall regimes to identify the water surplus and deficit periods.

3. Evaluation of the soil water-holding capacity and other soil physical characteristics such as texture, structure, infiltration rates.
4. Water-balance calculations using the rainfall and potential evaporation data in conjunction with soil water storage.

Description of Rainfall Regime

Rainfall in the SAT mostly occurs April to October in the Northern Hemisphere and October to April in the Southern Hemisphere; the percentage of seasonal rainfall to annual total often exceeds 90%. Data pertaining to the monthly rainfall, annual total, and seasonal rainfall percentage for six selected locations in the SAT are shown in Table 1. For all the locations the strong seasonality in the rainfall is evident.

Hyderabad, located somewhat in the center of the "heartland" of the SAT, has annual precipitation concentrated in 4 rainy months from mid-June to mid-October. The rainfall is highly erratic; data for the last 78 years show that it may vary from 320 mm (1972) to 1400 mm (1971) with a CV of 26%. Variability is by years as well as by seasons. Rainfall distribution during the last 6 years at ICRISAT Center and the normals (1940–70) for Hyderabad are shown in Table 2. During 1972–73, June was the wettest month, with 107 mm, whereas in 1974–75, October recorded the highest monthly total of 279 mm. In 1978, August received a record amount of rainfall (516 mm), while in 1975 August was the driest of the last 6 years. The reliability of the seasonal rainfall from April to October is indicated by the mean amounts as well as by the low CV.

The marked seasonality of the rainfall in the SAT exerts an overall control on the water availability and agricultural systems. The characteristics of individual rainstorms are also of importance, particularly their intensity and duration. In the SAT, a high proportion of rainfall occurs in large storms of high intensity. Hudson (1971) concluded that 40% of the rainfall in the tropics occurs at intensities of at least 25 mm/hr, a figure considered as a threshold value at which rainfall becomes erosive. The highest rainfall intensity observed at ICRISAT Center was 88 mm/hr recorded on 24 September 1975. On 18 August 1976, a rainfall intensity of 60 mm/hr was experienced. These characteristics are of great importance to both soil erosion and the effectiveness of rainfall to agriculture; large storms of high intensity result in considerable loss as surface runoff and as drainage beyond the root zone.

Despite the complexity of the moisture supply, certain generalizations can be made. Use of monthly average to describe seasonal rainfall

Table 1. Average monthly rainfall (mm) for selected SAT locations.

Location	Lat ° '	Long ° '	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Annual*
1. Hyderabad (India)	17 27N	78 28E	2	10	13	23	30	107	165	147	163	71	25	5	761 (93)
2. Dakar (Senegal)	14 44N	17 30W	0	2	0	0	1	15	88	249	163	49	5	6	578 (98)
3. Bamako (Mali)	12 38N	08 02W	1	0	3	15	60	145	251	334	220	58	12	0	1099 (99)
4. Maradi (Niger)	13 28N	07 05E	0	0	0	4	32	60	164	260	110	12	0	0	642 (100)
5. Sokoto (Nigeria)	13 01N	05 15E	0	0	0	13	53	89	165	252	147	15	0	0	734 (100)
6. Ouagadougou (Upper Volta)	12 21N	01 31W	0	3	8	19	84	118	193	265	153	37	2	0	882 (99)

* Percentage of seasonal rainfall (April to October) to annual total is shown in parentheses.

Table 2. Rainfall at ICRISAT Center during 1973–78 and normals (1940–70) for Hyderabad.

Month	Normal Mean (mm)	Normal CV (%)	1973	1974	1975	1976	1977	1978
Jan	5.5	319	0.0	0.0	35.0	0.0	0.0	17.2
Feb	11.0	204	0.0	0.0	0.0	0.0	0.0	20.5
Mar	12.5	199	0.0	0.0	23.9	0.5	0.0	3.8
Apr	24.0	122	0.0	14.8	0.0	91.0	7.5	56.4
May	26.5	95	3.0	15.0	1.7	22.4	36.0	15.0
June	115.5	57	59.8	119.8	98.4	86.0	66.5	181.4
July	171.5	45	161.0	89.3	195.2	219.3	183.5	228.2
Aug	156.0	52	230.8	160.2	139.4	298.7	196.4	515.8
Sept	181.0	57	68.9	185.5	422.3	74.0	40.0	81.5
Oct	67.0	94	216.4	278.6	173.5	0.6	48.9	70.5
Nov	23.5	167	10.6	4.5	15.0	29.7	27.8	10.4
Dec	6.0	254	1.3	0.0	0.0	0.0	2.0	0.9
Annual	800.0		751.8	867.7	1104.4	822.2	608.6	1201.6

regimes is often not sufficiently accurate; at certain times in the crop growing season, the presence or absence of water is not critical, and indications of variability over shorter time periods are of great importance. Many agricultural operations revolve around the probability of receiving given amounts of rainfall. Farm-scale operational planning often requires decision-making with respect to resources, manpower needs, available work days, cropping schemes, and several other factors. A comprehensive idea regarding the probability of rainfall is essential in view of the economic implications of certain weather-sensitive operations — dry seeding, harvesting, etc.

In agronomic terms, once a seed is planted, water is required on a continual basis until the crop matures. We therefore utilized the concept of the Markov Chain to define the probability of rainfall of a given amount during a given week: initial probabilities or P(W); the probability of rain next week if rain was received this week P(W/W); and the probability of next week being wet if the current week has been dry P(W/D). These are called conditional probabilities.

Potential Evapotranspiration or Evaporative Demand

Another significant feature of the tropical environment is the high climatic water demand. The meteorological factors affecting evaporation include solar radiation, temperature of the evaporating surface, vapor pressure gradient, and wind and air turbulence. Solar radiation is the dominant source of energy and sets the broad limits of evaporation. Values of solar radiation tend to be high in the tropics, modified by cloud cover, making the evaporative demand of the atmosphere considerable (Jackson 1977). The annual values of potential evapotranspiration (PE) often exceed 1750 mm. During the growing season these values are of the order of 8 to 10 mm/day on clear nonrainy days and usually are around 3 mm/day on cloudy or rainy days.

When rainfall exceeds PE, soil moisture reserves are recharged. When rainfall is less than PE, soil moisture reserves are utilized. Most of the time in the SAT areas, rainfall is less than PE and actual evapotranspiration (AE) may equal rainfall. As shown in Figure 1, all six selected locations show only 2 to 3 months when rainfall exceeds PE, allowing some soil moisture recharge followed by utilization in the succeeding months

Denmead and Shaw (1962), working with corn in Iowa, reported that on a clear day, when the potential transpiration was as high as 6 to 7 mm/day, the decline in the transpiration rate occurred at a very low moisture tension, close to field capacity (Fig. 2). On a heavily overcast

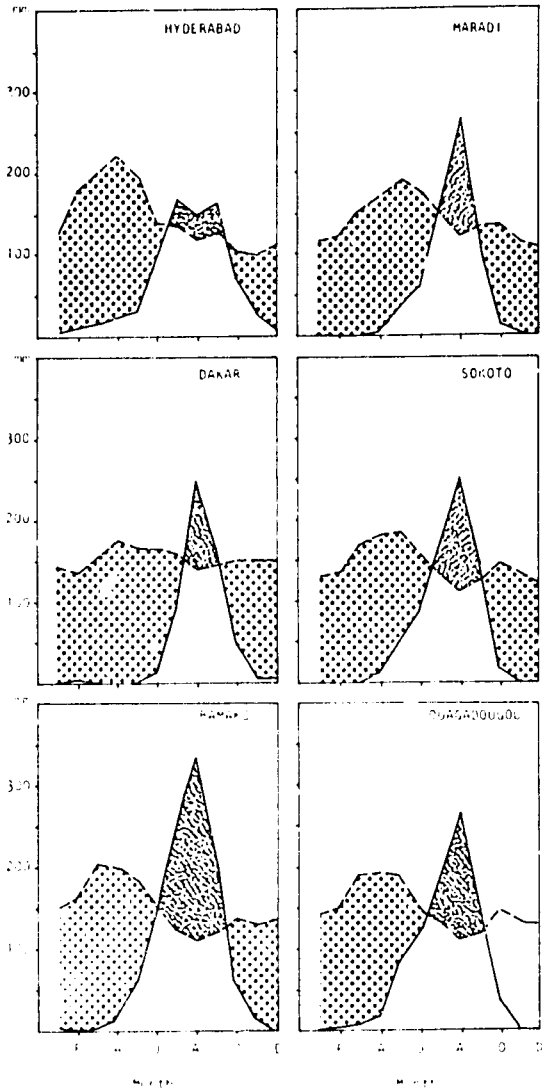

Figure 1. Monthly variation in rainfall (——) and potential evapotranspiration (----) at six selected locations in the SAT. Water deficiency soil moisture recharge.

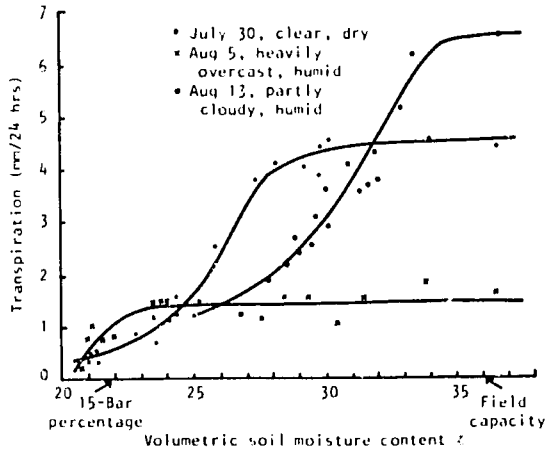

Figure 2. Actual transpiration rate as a function of soil moisture content (Source: Denmead and Shaw 1962).

day, when the potential transpiration rate was only 1 to 4 mm/day, the transpiration rate did not decline until the soil moisture reached 12 bars, not much above the permanent wilting point. Since the rainfall distribution in the SAT is highly erratic, and rainy spells are interspersed with unpredictable droughts, the crops are exposed to considerable stress at different stages of growth. Since the crop yields are proportional to moisture availability, the semi-arid tropical environment introduces a strong element of risk to high and stable crop yields.

Soil Moisture Storage

The soils of the SAT show great diversity in texture, structure, type of clay, organic matter content, and depth. Among other things, the precipitation actually entering the soil depends upon the type, surface conditions, and moisture status of the soil.

As shown in Figure 3, the moisture depletion from a given soil varies with the soil type (Holmes 1961). The idealized curves show that in the case of sandy soils, the low moisture-holding capacity and the low colloid content permit a rapid removal of much of the soil moisture. The depletion rate remains at a high level almost to the wilting point. For a heavy clay soil, on the other hand, the moisture cannot be removed rapidly.

The average values of changes in the profile moisture on the weekly basis in three typical soils of the Hyderabad region are plotted in Figure 4. These curves are based on the 1901–70 rainfall records. It is apparent that in the shallow Alfisols there is very little soil moisture storage for use over extended drought periods. In deep

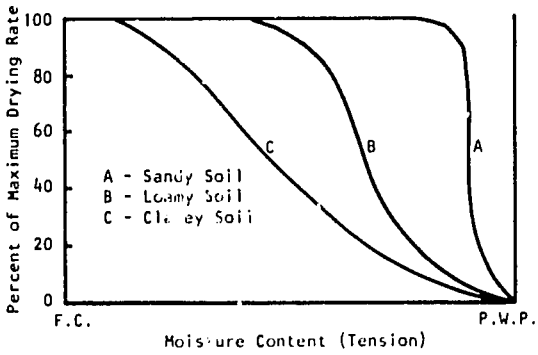

Figure 3. Drying rates of three types of soils as a function of soil moisture content (Source: Holmes 1961).

Alfisols, medium deep Vertisols, and in deep Vertisols, there is a fair degree of moisture storage for a substantially longer time during the growing season compared with shallow Alfisols. Thus, under identical rainfall conditions, the effects of short-term intraseasonal droughts on crop moisture status will differ in different soil types. The amounts of water lost by runoff would be much higher in the shallow Alfisols compared with the other two soil types, and the potential benefits derived from supplemental applications of water would vary with the soil type. Our experience has shown

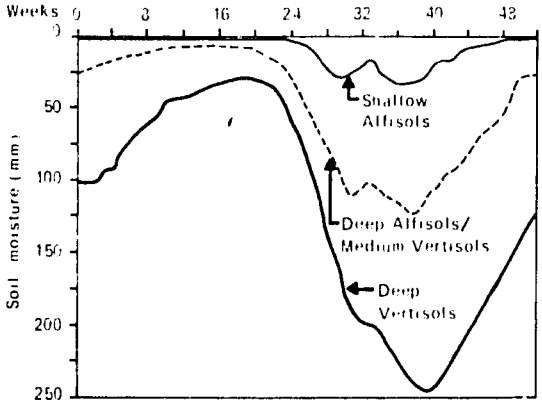

Figure 4. Weekly soil-moisture storage in three soils (based on Hyderabad data, 1901–1970).

that it is on the shallow Alfisols that reuse of runoff is usually profitable under Hyderabad conditions.

Water Balance Calculations

It is possible to calculate the water balance for a given region for any given crop from the actual rainfall evapotranspiration and soil moisture characteristics over a series of years. The use of computers for fast and accurate calculation of water balance using various simulation models has made this task relatively easy. Water-balance results find useful application in the determination of the length of the growing season and the optimum sowing date; maximum water use of a crop and maximum water availability can be matched for optimal use of available resources.

Transfer of Farming Systems Technology: Some Case Studies

For over 2 decades agricultural research has focused its major attention on improved crop yields under irrigated agricultural systems. Recent crop failures and widespread famines in the arid and semi-arid areas have brought to the attention of researchers the need for improved technologies for greater yields and production stability in these areas. The geographical diversity and the distance between SAT locations impose definite limitations on the technical and financial resources for intensive investigations over large areas in the SAT. Hence, research conducted at a few important locations for the generation of improved technology will have to find application over large areas.

The climatic approaches for the transfer of agrotechnology have been described earlier. A few case studies are presented here to show the application of these approaches for some practical problems. These case studies are by no means exhaustive but can serve as useful examples to illustrate the idea behind these exercises.

Location Specificity of Moisture Environment

The distinctive characteristics of the SAT

influence the distribution of natural endowments — soils, rainfall, and climate — introducing a strong element of location specificity in terms of the agricultural environment. This is exemplified by a comparison of two locations — Hyderabad and Sholapur, India — situated about 500 km apart at similar latitude and altitude. They seem agroclimatologically, ecologically, and edaphically similar (Virmani et al. 1978). At both locations, soils are deep to medium deep Vertisols. The mean annual rainfall at both the locations is about the same (764 mm at Hyderabad and 742 mm at Sholapur) and, on an average, more than 75% of their precipitation is received between June and September. Krishnan (1974) computed the annual PE at 1757 and 1802 mm, respectively, for Hyderabad and Sholapur; the actual length of the growing season was estimated to be 130 and 148 days, respectively. The CV of the annual rainfall is 26.1% for Hyderabad and 28.6% for Sholapur. Rao et al. (1971) computed Thornthwaite's moisture index at −56.4 and −58.7, respectively.

With this information, one could expect similar agricultural potentials at these two locations. However, research has shown that this is not true. At Hyderabad, on Vertisols, yields in excess of 5000 kg/ha are common in pigeonpea/maize intercropping and in maize/chickpea sequential cropping; rainfall-use efficiencies of the order of 6 to 10 kg/mm can be obtained regularly. However, at Sholapur, rainy-season cropping is undependable with sorghum or maize; a short-duration crop of pearl millet or a grain legume followed by sorghum grown on conserved moisture is somewhat successful. Furthermore, yields from year to year are highly variable, ranging from 1000 to 2000 kg/ha; the rainfall-use efficiencies are quite low.

Hargreaves (1975) reported extensive rainfall analyses for defining the agricultural potentialities for rainfed agriculture of semi-arid tropical northeastern Brazil. He found that if the amount of rainfall was sufficient to meet one-third of the potential demand (R/PE = 0.33), it was sufficient to meet water requirements of dryland crops in soils with a fair amount of available water-holding capacity. The rainfall is defined as "dependable precipitation" when the probability of its receipt is at least 75%. In such a scheme of evaluation, consideration is given both to the adequacy of rainfall in relation to crop water needs and the dependability of its occurrence.

An analysis for initial and conditional probabilities of R/PE≥0.33 explains most of the differences between Hyderabad and Sholapur (Fig. 5). The rainfall distribution is highly erratic; few of the initial probabilities P(W) exceed the 70% threshold level and the (P(W/W) follows a similar pattern. In comparison, the rainfall analysis for Hyderabad shows that rainfall is dependable (as defined at 70% probability) between 18 June and the end of July, and from about mid-August to mid-September. Thus, rainfall characterization based on short-term periods can be particularly effective in explaining differences in agricultural climate and crop yield potentialities.

The illustration of location specificity, as exemplified by the rainfall analysis of Hyderabad and Sholapur, clearly brings out that quantification of the moisture environment would be essential for identifying isoclimes and for the transfer of different elements of the farming systems technology.

Possibilities of Dry Seeding on Vertisols in India

The methodology of rainfall probabilities could be used for assessing the risk associated with dry seeding of rainy-season crops in the SAT. From our experience, we have observed that the dry seeding period of the crops will be a couple of weeks ahead of the onset of the rainy season. At Hyderabad, the onset of seasonal rainfall is abrupt at the commencement of the rainy season and the probabilities of continuance of rain are fairly dependable. Therefore, this location offers an excellent scope for dry seeding. At Sholapur, on the contrary, the onset of rains at the commencement of the season is not abrupt and the probabilities of the continuity of rainfall after onset are not high; such locations are prone to considerable risk in dry seeding. Based on rainfall probabilities of more than 90 locations in India, the areas offering possibilities of dry seeding on Vertisols are mapped in Figure 6. The technology for dry seeding of crops generated at ICRISAT Center could be translated with a fair degree of success to Akola, Jabalpur, Indore, and Udaipur; whereas at Sholapur, Dharwar, Jalgaon, and Ahmedabad the likely success of dry seeding is

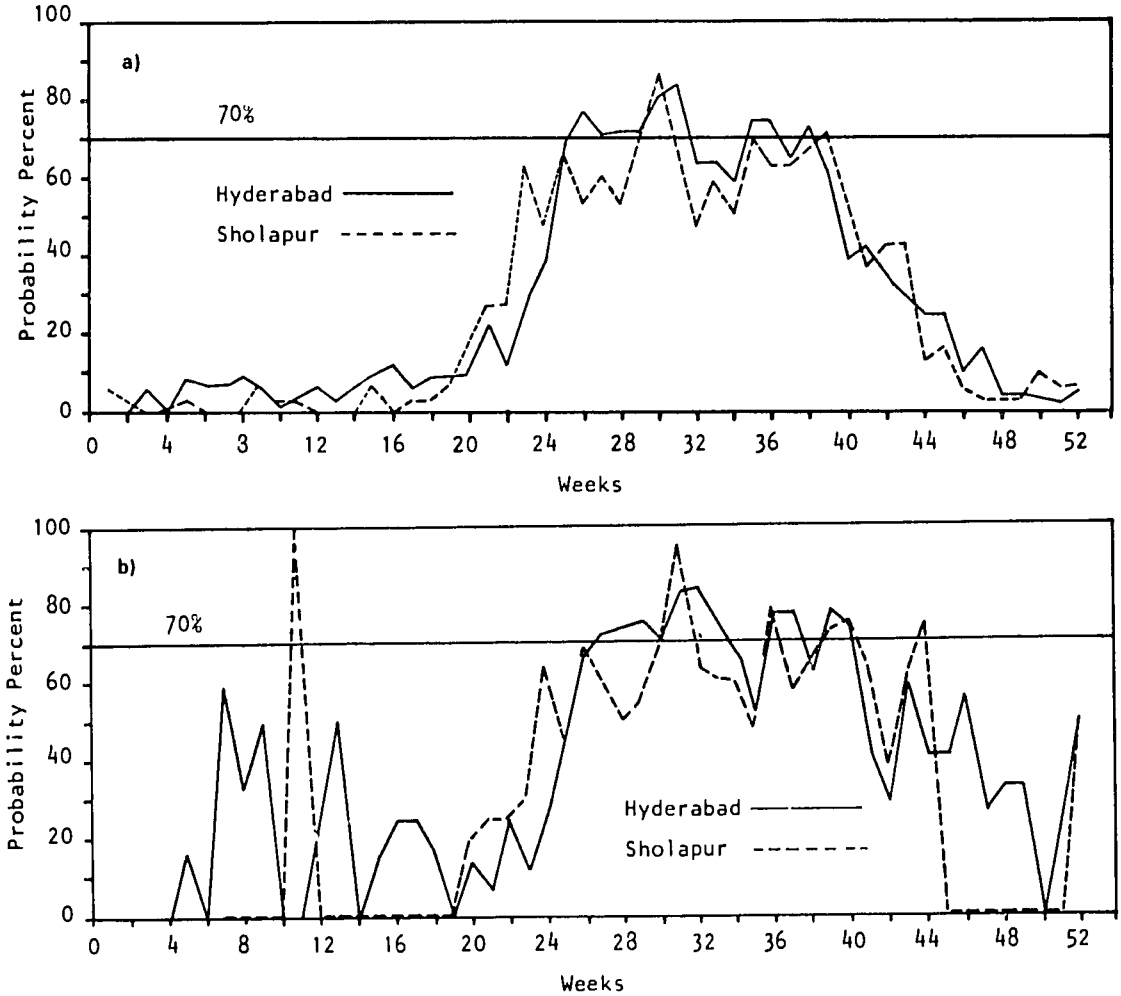

Figure 5. Comparison of probabilities of R/PE≥0.33 at Hyderabad and Sholapur.
a. Initial probabilities (P[W])
b. Conditional probabilities (P[W/W])

low due to the high risk associated with this practice. In such cases it would probably be best to build up some moisture in the upper horizons of the soil profile prior to seeding.

Length and Characteristics of the Growing Season

Thus far our discussion has been mainly on the probabilities of rainfall and the methodologies that may be used to employ this information in the planning of agricultural strategies/operations. The length of the growing season depends upon the pattern of rainfall and also upon the type of the soil, particularly its moisture-holding characteristics.

The soil-moisture availability characterization could have implications in crop planning and selection of crop cultivars, at least as a first approximation. The length of the growing season in the three soils is shown in Table 3. At the

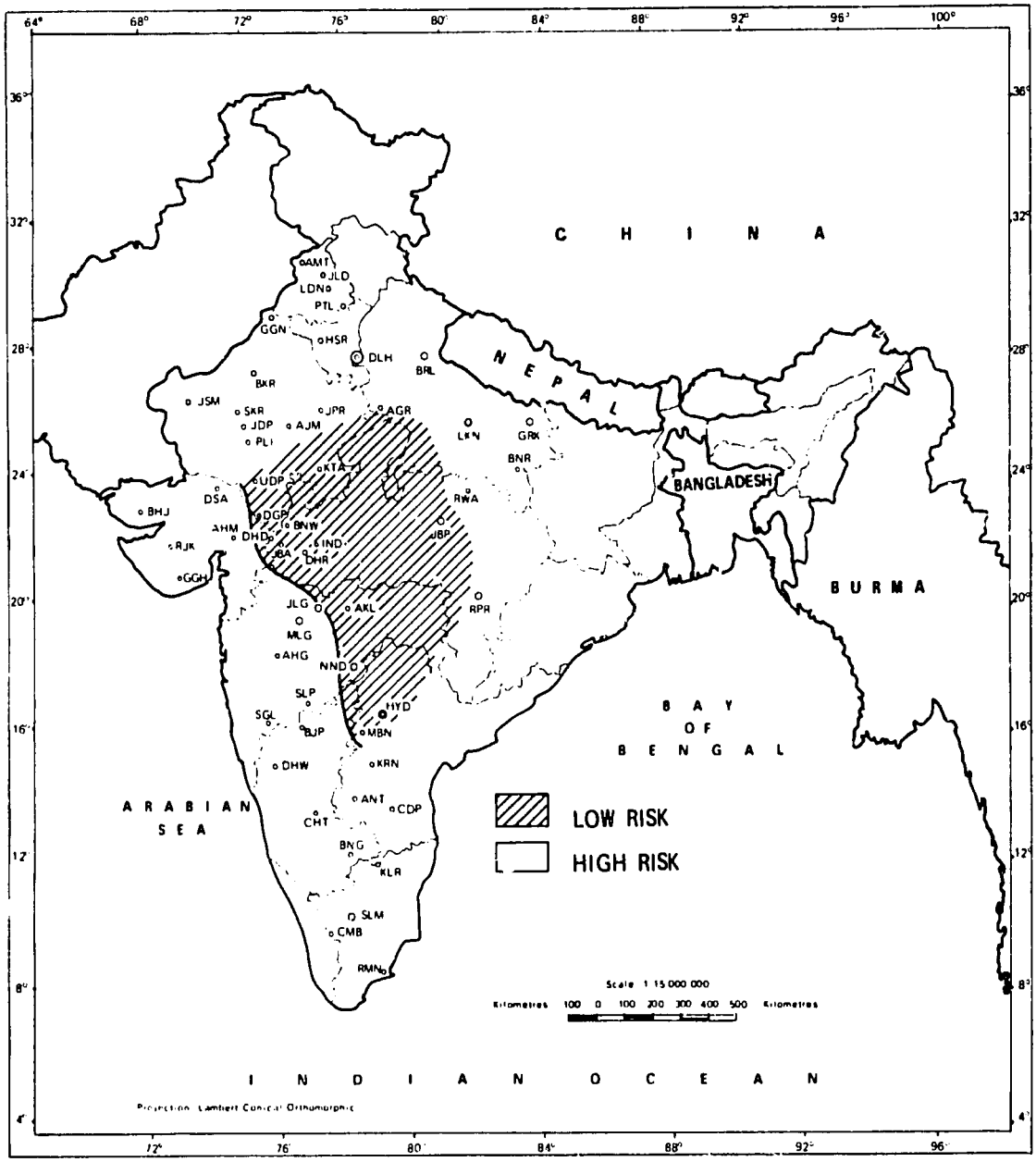

Figure 6. Possibilities of dry seeding on Vertisol.

75% probability level, the length of the growing season in shallow Alfisols would be about 15 weeks, while in the Vertisols it extends to about 23 weeks. This would mean that — depending upon the soil water-storage capacity — one could grow a medium- to long-duration crop at the Hyderabad location on a deeper soil, as opposed to a short-duration crop on a low water-holding capacity soil. Since soil types and rainfall patterns in the SAT show considerable variations over short distances, such analyses will assist considerably in deriving estimates of

Table 3. Length of the growing season (in weeks)[a] for three soil conditions.[b]

Rainfall probability	Available water-storage capacity		
	Low (50 mm)	Medium (150 mm)	High (300 mm)
Mean	18	21	26
75%	15	19	23
25%	20	24	30

a. From seed-germinating rains (25 June) to end of season (time when profile moisture reduces EA/PE to 0.5).
b. Low: shallow Alfisol; medium: shallow to medium-deep Vertisols; high: deep Vertisol.

the crop growing periods and suitable crops, and in delineating isoclimes for the transfer of technology.

References

DENMEAD, O. T., and SHAW, R. H. 1962. Availability of water to plants as affected by soil moisture content and meteorological conditions. Agronomy Journal 54:385–390.

HARGREAVES, G. H. 1975. Water requirements manual for irrigated crops and rainfed agriculture. EMBRAPA and Utah State University Publication No. 75–D158.

HOLMES, R. M. 1961. Estimation of soil moisture content using evaporation data. *In* Proceedings, Hydrology Symposium: No. 2, Evaporation. Toronto: Department of Northern Affairs and National Resources, Water Resources Branch.

HUDSON, N. W. 1971. Soil conservation. London: Batsford.

JACKSON, I. J. 1977. Climate, water and agriculture in the tropics. London and New York: Longmans.

KAMPEN, J. 1979. Watershed management and technology transfer in the semi arid tropics. This symposium.

KRISHNAN, A. 1974. Some climatological features of the semi-arid tropical regions of the world. Pages 53–91 *in* Proceedings, International Workshop on Farming Systems. ICRISAT, 18–21 Nov 1974, Hyderabad, India.

RAO, K. N., GEORGE, C. J., and RAMASASTRI, K. S. 1971. Climatic classification of India. Scientific report no. 158. Pune, India: Indian Meteorology Department.

TROLL, D. 1965. Seasonal climates of the earth. Page 28 *in* World maps of climatology, eds. E. Rodenwaldt and H. Jusatz. Berlin: Springer-Verlag.

VIRMANI, S. M., SIVAKUMAR, M. V. K., and Reddy, S. J. 1978. Comparison of some methods of characterizing rainfall pattern in semi-arid tropics in relation to crop planning. Presented at the Seminar on Dry Farming, College of Agriculture, Pune, India.