CLIMATIC CLASSIFICATION: THE SEMI-ARID TROPICS AND ITS ENVIRONMENT - A REVIEW[1]

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ABSTRACT - This paper analyses the advantages and limitations in using the Troll, Hargreaves and modified Thornthwaite approaches for the demarcation of the semi-arid tropics. Data from India, Africa, Brazil, Australia and Thailand, were used for the comparison of these three methods. The modified Thornthwaite approach provided the most relevant agriculturally oriented demarcation of the semi-arid tropics. This method is not only simple, but uses input data that are available for a global network of stations. Using this method the semi-arid tropics includes major dryland or rainfed agricultural zones with annual rainfall varying from about 500 to 1,250 mm. Major dryland crops are pearl millet, sorghum, pigeonpea and groundnut. This paper also presents the brief description of climate, soils and farming systems of the semi-arid tropics.

Index terms: dryland or rainfed agricultural zone.

CLASSIFICAÇÃO CLIMÁTICA: TRÓPICOS SEMI-ÁRIDOS E SEU MEIO AMBIENTE - REVISÃO

RESUMO - Foram analisadas as vantagens e limitações dos métodos de Troll, Hargreaves e método de Thornthwaite modificado, para demarcar os trópicos semi-áridos. Utilizaram-se dados da Índia, África, Brasil, Austrália e Tailândia para comparação dos três métodos. O método Thornthwaite modificado ofereceu a demarcação dos trópicos semi-áridos mais relevante, orientada agriculturalmente. Este método não só é simples, mas também usa os dados da pesquisa úteis para uma rede global de estações. Com este método, os trópicos semi-áridos abrangem maior número de regiões áridas ou zonas agrícolas úmidas com precipitação anual variando de 500 a 1.250 mm. Os produtos mais comuns nas regiões áridas são o milheto, o sorgo, o feijão-guandu e o amendoim. Este trabalho inclui também uma breve descrição do clima, solos e sistemas de cultivo dos trópicos semi-áridos.

Termos para indexação: regiões áridas, regiões agrícolas úmidas.

INTRODUCTION

The objective of this study is to clarify the usage of the term semi-arid tropics and to develop a more explicit definition. This involves the establishment of relevant physical environmental characters for the identification of homoclimes, zones of comparable climates. The purpose of climatic classification is to identify those aspects of climate which distinguish a region from nearby regions and to derive inferences on the influence of climatic factors on human, animal and plant life. In an environmental context this may allow areas to be characterised and boundaries to be drawn around contiguous areas that can be regarded as homogeneous in certain respects. Under given climatic conditions there are similarities in natural vegetation, soils, crop possibilities etc. Broad areas exist with climatic homogeneity which allows a simple classification to be an aid to study and understand the earth's land and people.

In dividing the world into a number of "climatic types" there is a certain artificiality in the establishment of their boundaries. This is because boundaries are shown as sharp delineations, whereas actually there is a gradual transition in the climate. For a general climatic classification to be realistic, boundaries should at least conform with known plant distribution boundaries (Wilsie & Shaw 1954). Good (1953) states that the facts of plant geography everywhere show that plant distribution is basically dependent on climate. Edaphic factors are secondary, because they are often controlled by climatic factors. Thus, it might be said that climatic factors will determine whether corn shall be a potential occupant of a given area, whereas terrain and soil factors may determine

[1] Accepted for publication on July 13, 1983.

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largely whether corn actually will be grown and in what abundance (Wilsie & Shaw 1954).

Climatic differences between various regions were recognized by the Greeks as early as 600 B.C. (Boyko 1962). The importance of climatic classification was recognized by the world by the middle of the present century. There exists in the literature (Boyko 1962, Burgos 1968) a wide spectrum of approaches for the climatic zonation. However, the suitability of individual methods depends upon the problem that is envisaged and availability of input data. The humid and more favourable rainfall areas have been extensively and intensively cultivated and heavily populated by human beings. The future of the humanity now lies in the semi-arid lands. These lands are mostly confined to tropics and in particular in the under-developed countries with high population pressure. There is a well recognised and urgent need for the development of dry farming technology for increasing agricultural production in these areas to meet the increasing demand placed on these lands with ever increasing population pressure (Kanwar 1975). The traditional crop production systems in these regions do not make full and efficient use of available soil and water resources. Therefore, the purpose of classification in the present context is to identify the semi-arid areas especially in tropics as this will facilitate in the subdivision of these regions into agronomically relevant homogeneous zones that help in the transfer of location-specific dryland technology.

As the interest here is directed towards agriculture in the tropical areas, climates of these regions can be divided into a finite number of groups, such as arid, semi-arid, sub-humid or wet-dry, humid etc. in an orderly fashion on a broader scale (from a drier extreme to wetter extreme) on the basis of natural vegetation types. The arid zone towards the drier extreme of climates representing the grasslands where food crop production is uneconomical under unirrigated conditions; and the other extreme on wetter side of climate representing rain forests is termed as the humid zone. In between these two extremes the major food crop zones of the tropics can be divided into two parts, namely the semi-arid zone towards drier side and the wet-dry zone towards wetter side. On the wetter side dryland or rainfed agriculture is risky due to heavy rains and some of the food crops of this region are paddy (or rice), sugarcane, finger millet etc. The semi-arid lands are the major dryland or rainfed agriculture zone and some of the major food crops of this region are pearl millet, sorghum, pigeonpea and groundnut. For food crop production moisture or water is the limiting factor in the arid and semi-arid zones while excessive rains are the major constraints in wet-dry and humid zones. Hence, the mechanisms and liming factors for agricultural production are different in these two areas.

There is ambiguity both in the usage of the term "semi-arid" and its implied practical application. This ambiguity stems from: 1. the method of defining broad zones; both in terms of the choice of climatic parameters that are used to define an index and the class limits of the index; 2. the association of defined zones with specific natural vegetation formations and/or land use systems.

The literature is rich in papers that present the spatial distribution of single climatic parameters such as rainfall, evaporation, temperature, radiation, wind and humidity. However, no single parameter can reflect the climate of a place. The majority of existing classifications use two primary factors to define climate, namely moisture, that limits the plant growth, and evaporative demand, that expresses the moisture need at a place for optimum plant growth. Only very few used general weather conditions in defining climate. These are not, in fact, in common use. The broad modes of defining semi-arid in terms of moisture and evaporative, demand are seen in literature. They are annual indices and duration of moist or dry period. Some of these are presented in Table 1.

Most of the procedures that are in wider use are annual indices (Köppen 1936, Thornthwaite 1948, Thornthwaite & Mather 1955, Budyko 1956, Papadakis 1975). While the procedures that use the moist or dry period are more common for the sub-division of semi-arid zones (Schreiber 1975, Cocheme & Franquin 1967; Brown & Cocheme 1969, Raman & Murthy 1971). With few exceptions like Troll (1965), Hargreaves (1971) that are used to demarcate the semi-arid zone.

Those approaches with temperature as the

TABLE 1. Climatic classification procedures.

Evaporative demand parameter	Moisture parameters				
	Monthly dependable rainfall	Actual evapotranspiration	Mean monthly rainfall + stored soil moisture	Mean monthy rainfall	Mean annual rainfall
Temperature				x Stefanoff (1930), x Thomas (1932), x Walter (cf. Moreau, 1938), x Aubreville (1949), x Creutzberg (1950), x Bagnauls & Gaussen (1953, 1957), x Gaussen (1955), Troll (1965)*	Köppen (1900, 1918, 1931, 1936*), Herbertson (1905), de Martonne (1908, 1926), Lang (1920), Emberger (1930, 1955), Champion (1945), Popov (1948), Shanbhag (1956), Walter et al. (1960), Meher-Homji (1963, 1965), Schreiber (1975)*
Net radiation					Budyko (1956)*
Relative humidity					Mangenot (1951)
Saturation deficit					Szymickwicz (1925), Meyer (1926), Prescott (1934, 1938, 1943), Trumble (1937), Hosking (1937), Capot-Rey (1951)
Evaporation					Transeau (1905), Penck (1910), Ivanov (1948), Prescott (1949, 1956, 1965), Bharucha & Shanbhag (1957)
Potential evapotranspiration	x Hargreaves (1971)*	x Eagleman (1976)*	Thornthwaite (1931, 1933, 1948*, 1951), Thornthwaite & Mather (1955) Camargo (1965), Mota et al. (1970), Mota (1974)	Reddy (1977x)*	Reddy & Reddy (1973)*

Note: 'x' before the reference represent the methods under duration of moist or dry period and the rest under the annual index.
Except the references with* are given in Table 2.

TABLE 2. Secondary references

Author(s)	Year	Reference
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Bagnouls, F. & Gaussen, H.	1953	Saison sèche et régime xerothermique. Documents pour les cartes des productions végétales, Toulouse, 3, 1.
Bagnouls, F. & Gaussen, H.	1957	Annales de Géographie, 355, 193.
Bharucha, F.R. & Shanbhag, G.Y.	1957	Botanical memoirs Nº3, Univ. of Bombay.
Camargo, A.P. de	1965	Proc. IX Congresso Internacional de Pastagens, São Paulo, pp.17-27
Capot-Rey, R.	1951	Bulletin de l'Association de Géographes Français, pp.73.
Champion, H.G.	1936	Indian Forest Records (N.S., 1).
Creutzberg, N.	1950	Petermanns. Geogr. Mitt., 94, 57.
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de Martonne, E.	1926	Compt. rend., 182, 1395
Emberger, L.	1930	Révue Générale de botanique, 42, 641 & 705.
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Herberton, A.J.	1905	Geographical J., 25, 300.
Hosking, J.S.	1937	Current Sci., 422.
Ivanov, N.N.	1948	Proc. Soviet Geogr. Cong. Vol. 1, Acad Sci., USSR.
Köppen, W.	1900	Geographische Zeitschrift, 6,593 & 657.
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Köppen, W.	1931	Grundriss der Klimakunde, Walter de Gruyter, Berlin.
Lang, R.	1920	Verwitterung und Bodenbildung als Éinführung in die Bodenkunde. Stuttagart: Schweizerbatsche, Verlagsbuchlandlung, pp. 123.
Mangenot, G.	1951	Revue Générale de Botanique, 58, 353.
Meher-Homji, V.M.	1963	Tropical Ecology, 5,17
Meher-Homji, V.M.	1965	Annals of Arid Zone, 4, 152.
Meyer, A.	1926	Chemie der Erde, 2, 209.
Moreau, R.E.	1938	J. Ecol., 26, 467.
Mota, F.S. da, et at.	1970	Pesq. agropec. bras., 5: 1-27.
Mota, F.S. da	1974	Ciência e Cultura. 26(8): 766-774.
Penck, A.	1910	Sitz. ber. Preuss. Akad. Wiss. Physikmath. kl., pp.236.
Popov, V.P.	1948	Sci. Rept. State Univ. Kiev., 7(1).

TABLE 2. Continuação.

Author(s)	Year	Reference
Prescott, J.A.	1934	Trans. Roy. Soc. S. Aust., 58, 48.
Prescott, J.A.	1938	Trans. Roy. Soc. S. Aust., 62, 229.
Prescott, J.A.	1943	Trans. Roy. Soc. S. Aust., 67, 312.
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Shanbhag, G.Y.	1956	Indian Geogr. J., 31, 20.
Stefanoff, B.	1930	Sbornik na bulgarskata akademiya na naukite, 26.
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Thomas, A.S.	1932	J. Ecol.,20, 263.
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Transeau, E.N.	1905	Amer. Naturalist, 39, 875.
Trumble, H.C.	1937	Trans. Roy. Soc. S. Aust., 61, 41.
Trumble, H.C.	1939	Trans. Roy. Soc. S. Aust., 63, 36.
Walter, H., Leith, H. & Rehder, H.	1960	Klimadiagramm. Weltatlas Jena.

threshold limit (Table 1) used natural vegetation as the reference in the demarcation of broader zones. According to Meher-Homji (1962), when some of these approaches are applied to 78 representative stations of the Indian subcontinent none of these methods give entirely satisfactory results in classifying all the stations according to their vegetation types. The approaches with potential evapotranspiration or its equivalents as the threshold limit in the broader zonation food crops or natural vegetation were used as reference. However, the internal homogeneity of the majority of these methods even on broader scale is low (Reddy 1977). This is basically because the procedures lack the objectivity and some are derived based on regional studies or application of already existing model to that environment with minor modifications. For example, the zones were defined with reference to vegetation types of West Africa by Troll (1965) and in terms of food crop production over NE Brazil by Hargreaves (1971).

The past century has witnessed the introduction and evolution of ideas that have successfully brought greater precision and objectivity to climatic classifications. In Köppen's (1936) classification the zones can show vast variations within themselves (Berry et al. 1973, Hashemi et al. 1981). In this method temperature was used as a proxy for evaporation but evaporation is not only a function of temperature but also of several other climatic factors (Penman 1948). With Köppen's monumental study the way was opened for analogue climatic classifications and many others followed as a result. Thornthwaite's (1948) climatic classification introduces the most important term potential evapotranspiration and degree of moisture of climatic units by means of an estimate of soil-water balance. The latter was subsequently modified by Thornthwaite & Mather (1955). While the main emphasis of Köppen's classification is on temperature limits. Thornthwaite's climatic classes are based on the effectiveness of precipitation. This factor bears a close relation to plant growth and hence permits more refined analysis of climatic problems related to vegetation and agriculture than does the Köppen scheme (Berry et al. 1973). In the Thornthwaite approach, while dividing the zones, different arbitrarily chosen intervals were used in the division of humid and dry areas. These limits are not homogeneous with respect to crop production areas. Unequal weightings were given to humid and arid indices in the computation of moisture index which is not justified by the authors. Thornthwaite also introduces the soil moisture factor (which was also used by many later: Papadakis 1975, Eagleman 1976), which is not realistic, as there are wide variations in soil factors even at micro-level. In fact, the moisture index computed with and without soil factor doesn't show any significant difference under dry climates. Hargreaves (1974) states that "a composite index based upon soil and climate might be developed. However, due to the complexity of soils in many areas such combined index might be difficult to use in agroclimatic zonation". Reddy & Reddy (1973) suggested some modifications to Thornthwaite's scheme to develop more homogeneous types - hereafter called as "modified Thornthwaite's approach". The soil term was eliminated in the computation of moisture index; same weights were given both for humid and arid indices; and uniform limits were used on both humid and dry sides of the scale.

From the above discussion the following three methods were found appropriate for the comparison of their suitability to demarcate the SAT. They are:

1. Modified Thornthwaite's annual moisture index;
2. Trolls' himd period;
3. Hargreaves' dependable moist period.

Table 3 presents the details of these three approaches. Montly and annual data from India, Africa, Brazil, Australia and Thailand representing a wide range of climatic regimes were used (Table 4) to test the above three methods.

TROPICS

In order to deliniate the semi-ared tropics we must first define the tropics from sub-tropical and other high latitude regions. The SAT is then a component of the tropical climate.

TABLE 3. Details of different approaches for demarcating the SAT.

Approach	Data requirement	Criteria (attribute)	Limits, Units (for the SAT)
Troll's approach			
Troll (1965)	Average monthly R & T	R > 2T*	2-4.5 months
Gray (1970)	Average monthly R & T	R > 2T*	2-7.0 months
Reddy (1977)	Average monthly R & PE	R > PE	2-4.5 months
Hargreaves appoach			
Hargreaves (1971)	Monthly DP & PE	MAI (DP/PE) > 0.34**	3-4 consecutive months
Modified Thornthwaite's approach			
Reddy & Reddy (1973)	Mean annual R & PE	$I_m = \frac{(R-PE)}{PE} \times 100$	$-25 < I_m < -75\%$

* It appears that Troll (1965) used Gaussen (1954) definition in defining humid month (Walter et al. 1975).

** It is equal to R/PE > 0.50 (Hargreaves 1975), as square root of monthly rainfall generally follow normal or nearly normal distribution. R > 2T can also be represented approximately as R > 0.5 PE. This is half the limit used by Reddy (1977).

R = Rainfall, mm

PE = Potential evapotranspiration, mm

DP = Dependable precipitation estimated using long period rainfall data (75% probability value), mm

T = Temperature, °C

TABLE 4. Data base and data source.

Region/Country	Data source		Data base (no. of locations)
	Rainfall (R)*	PE	
India	Indian Meteorological Department (Undated)	Rao et al. (1971)	300
NE Brazil	Hargreaves (1973)	Reddy (1981a)	180
Brazil (excluding NE)	Hargreaves (1977)	Hargreaves (1977)	20
West Africa (Senegal, Mali, Upper Volta, Niger, Chad)	Virmani et al. (1980)	Reddy & Virmani (1980a)	300
Africa (excluding West)	FAO**; WMO (1971)	FAO**; WMO (1971)	280
	Griffiths (1971)	Griffiths (1971)	
Thailand	MD (1971)	Reddy (1981b)	49
Australia	Department of Science and Bureau of Meteorological 1975	Nix***	350

* In the case of India, dependable precipitation (DP) data were computed using the long term rainfall data of 50 years for the same 300 locations (Indian Meteorological Department 1967).

** Data has been supplied by Michel Frere, Senior Agrometeorologist, FAO, Rome.

*** H.A. Nix (Personal communication).

In the astronomic sense the tropics refer to the region between 23°27' North and South parallels. However, in climatological and meteorological studies thermic units in terms of mean annual temperature are preferred for defining the tropics (Köppen 1936, Hargreaves 1974). Also, plant species react to temperature rather than to latitude (that define the photoperiod) as such. Photoperiod influences development, but temperature affects both growth as well as development of plants. Although there are many proposed definitions, that of Köppen (1936) is simple and reasonable (Reddy 1977). Accordingly, the tropics are thermally defined as regions with mean annual temperature $\geq$ 18°C. This limit was accepted at a consultant meeting on climatic classification held at ICRISAT during 14-16 April, 1980 (details can be seen from the proceedings).

SEMI-ARID ZONE

Troll's approach (Troll 1965)

As adopted by Gray (1970). ICRISAT adopted Troll's (1965) map (Fig. 1) as a working document to demarcate the semi-arid zone. Gray (1970) identified regions with 2-7 humid months on this map as the semi-arid zone. It appears (Walter et al. 1975) that Troll defined a humid month as any month with mean monthly rainfall (R, mm) exceeding twice the mean monthly average temperature (T, °C) - $R \geq 2T$, following Gaussen (1954). That is, Troll, like Köppen, used temperature as a proxy for evaporation. In the tropics during the rainy season the average monthly temperature is about 30°C. This is equivalent to mean monthly rainfall of about 60 mm or less. During the same period, PE is about 100-150 mm ($R > 2T$ approximately represents the $R > 0.5$ PE). $R > 2T$ for 2-7 months are considered as semi-arid. Hence, large areas with mean annual rainfall less than 200 mm (for example: Northwest India, Southern parts of Sahara desert in North Africa and drier parts of NE Brazil, South Africa and parts of inland Australia) were included under semi-arid. Also, on the wetter side the SAT was extended to the high rainfall regions of West Coast in India etc. With mean annual rainfall exceeding 2,000 mm. This is also evident in the case of Australia and Brazil. This approach is unacceptable as the SAT extends from regions with about 200 mm mean annual rainfall to regions with mean annual rainfall exceeding 2,000 mm and included vegetation formations ranging from shrub steppe and grassland to rainforest.

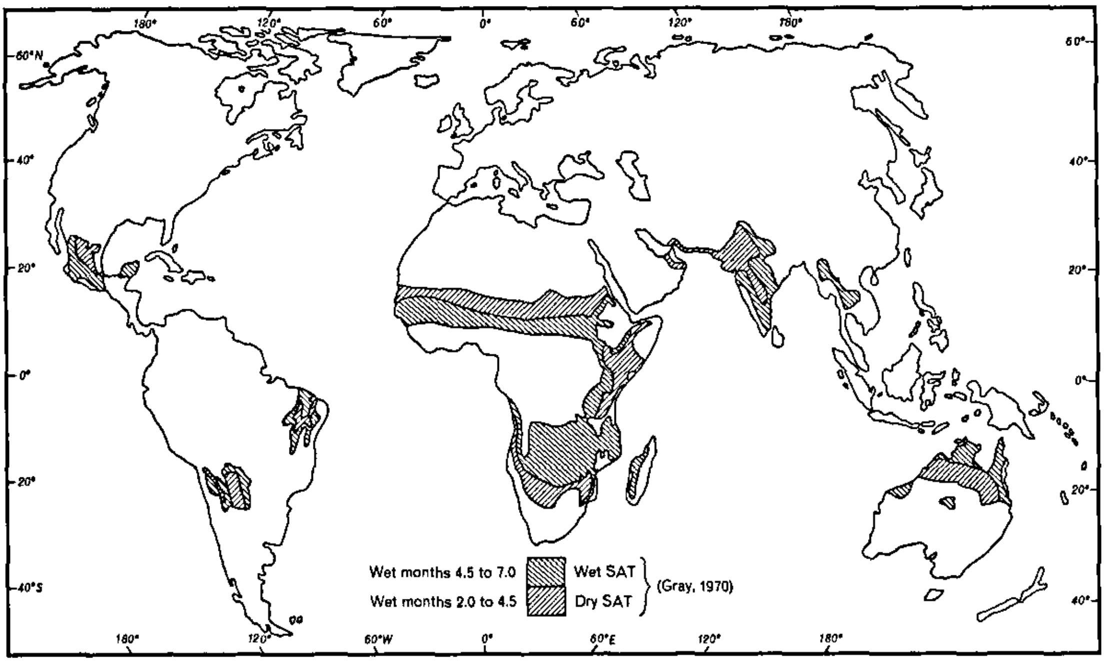

FIG. 1. World semi-arid tropics (Troll, 1965).

To overcome these deficiencies Reddy (1977) modified the method of computing humid period.

As revised by Reddy (1977)

The SAT maps of India, Brazil, Africa, Australia and Thailand (Figs. 2, 4a) were redrawn using PE - potential evapotranspiration data - in place of T - temperature (Troll 1965). A humid month was defined by R > PE (Reddy 1977) and the zone with 2-4.5 humid months was defined as semi-arid. The data used in producing these revised maps, along with data sources, are presented in Table 4.

India. The revised SAT map of India (Fig. 2) is based on data from about 300 locations. The mean monthly rainfall data were taken from a India Meteorological Department (Undated) publication and potential evapotranspiration data were based on data from Rao et al. (1971). However, many scientists have expressed reservations in accepting this map and in particular, the inclusion of high rainfall regions[3] of coastal Maharashtra, Bihar, West Bengal, eastern Madhya Pradesh, Orissa etc.; here paddy (rice) is the major crop (Fig. 3)[4] within the semi-arid tropics (SAT) and for eliminating the major pearl millet[5] (Fig. 3), sorghum (Fig. 3), groundnut, and pigeonpea (Easter & Abel 1973) growing regions from the SAT and including these within the arid zone.

Africa. Figure 2 also depicts the revised SAT map of Africa. Mean monthly rainfall and PE data for 580 locations in Senegal, Mali, Upper Volta, Niger and Chad based on respectively from Virmani et al. (1980) and Reddy & Virmani (1980a). For the rest of Africa the data were partly from FAO (M. Frere, pers. comm.) and partly from Griffiths (1971) and World Meteorological Organization (1971). Although well distributed over West Africa data were sparse over the rest of Africa. Some of

3 At the same consultant meeting (referred to earlier) the majority of the participants expressed a need to modify this approach.

4 The extreme eastern parts below 19°N lat. represents irrigated paddy (see Johnson 1979).

5 The western parts above 21°N lat. represents irrigated pearl millet (see Johnson 1979).

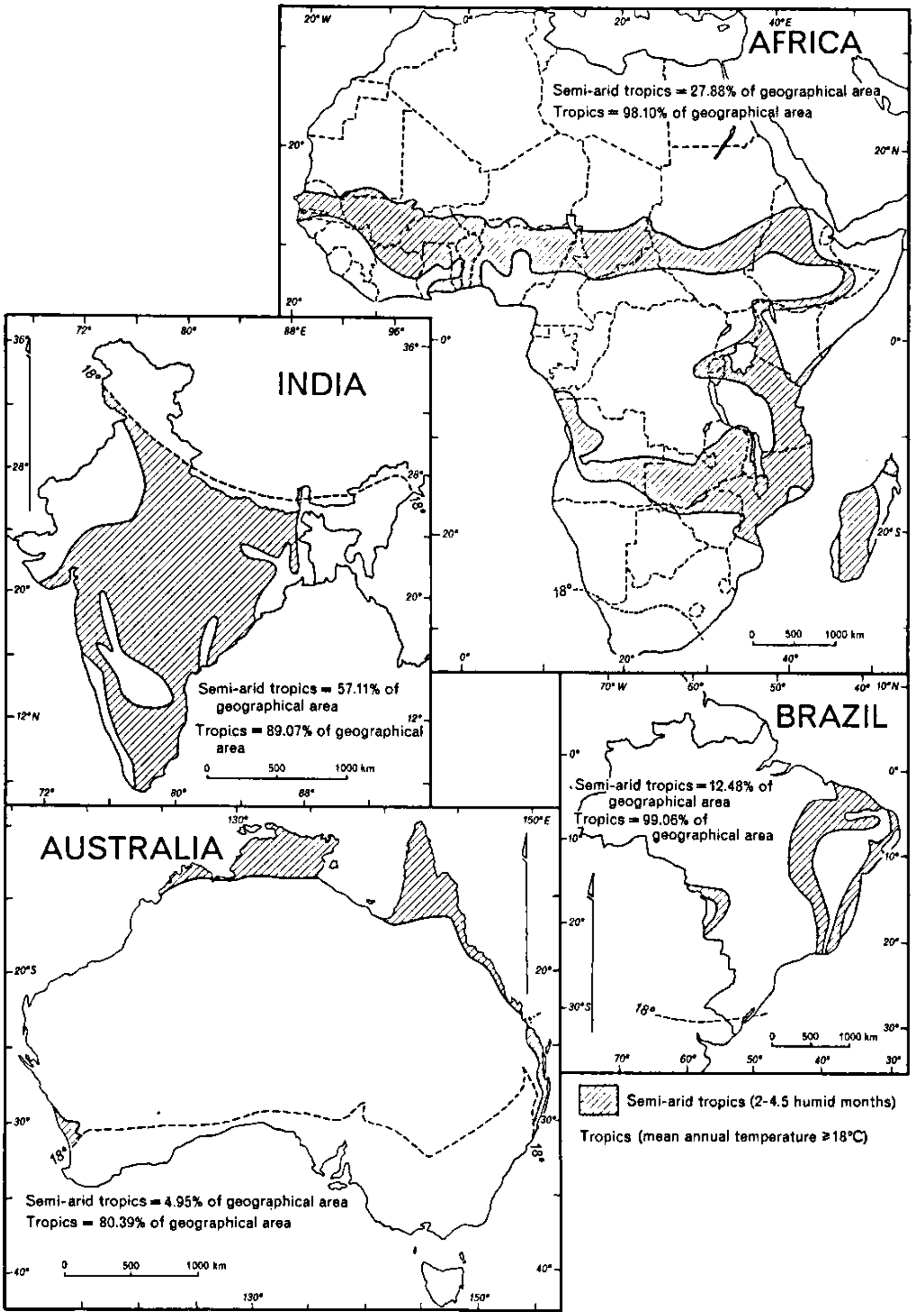

FIG. 2. SAT map of Africa, India, Brazil and Australia (Revised Troll's approach).

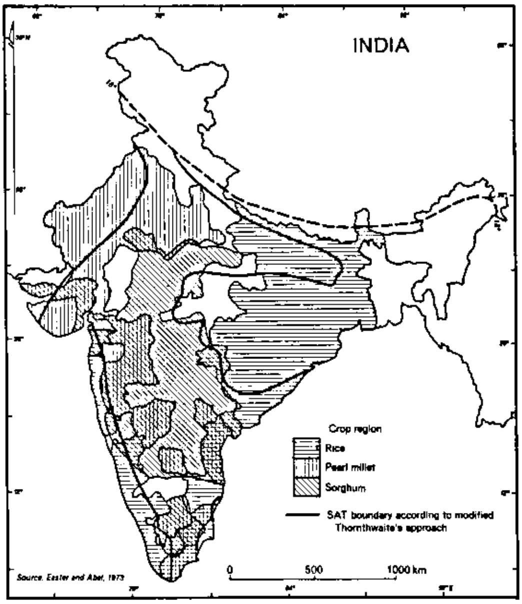

FIG. 3. Rice, pearl millet and sorghum cropping regions in India.

the anomalies reported above in the Indian situation (Fig. 2) are also evident in the case of Africa.

Brazil. Using data (Hargreaves 1973 e 1977, Reddy 1981a) for about 200 locations the SAT areas were demarcated for Brazil (Fig. 2). In this map, not only are high rainfall regions included under the SAT, but regions with more than 900 mm of mean annual rainfall are included within the arid zone.

Australia. Figure 2 depicts the revised SAT map of Australia. This map is based on data for about 350 locations. Mean monthly rainfall and PE data were taken respectively from Department of Science and Bureau of Meteorology (1975) and H. A. Nix (pers. comm.) - PE = 0.85 E, where PE is the potential evapotranspiration and E is the open pan evaporation (Reddy 1979). As in India, the rainfall in the Australia SAT varied from about 740 to 2050 mm (An anomaly occurs in that part of the winter, wet/summer dry zone of South-Western Australia is included because mean temperatures exceed 18^{o}C). In the wet-dry zone the mean annual rainfall varies from 1,100-1,900 mm. Regions with about 800 mm are included under arid while most regions with more than 1,500 mm are or were rainforest areas.

Thailand: The revised SAT map of Thailand (Fig. 4a) is based on 49 locations data (Meteorological Department 1977, Reddy 1981b).

Because of the above presented deficiencies in terms of dryland agriculture, the revised Troll's method is also not acceptable for the demarcation of the SAT.

Hargreaves' approach (Hargreaves 1971)

Hargreaves (1971) classified Brazil on the basis of monthly moisture availability index (MAI = DP/PE, where DP is the dependable rainfall at 75% probability level and PE is the potential evapotranspiration). DP is estimated using rainfall data for a large number of years by fitting an incomplete

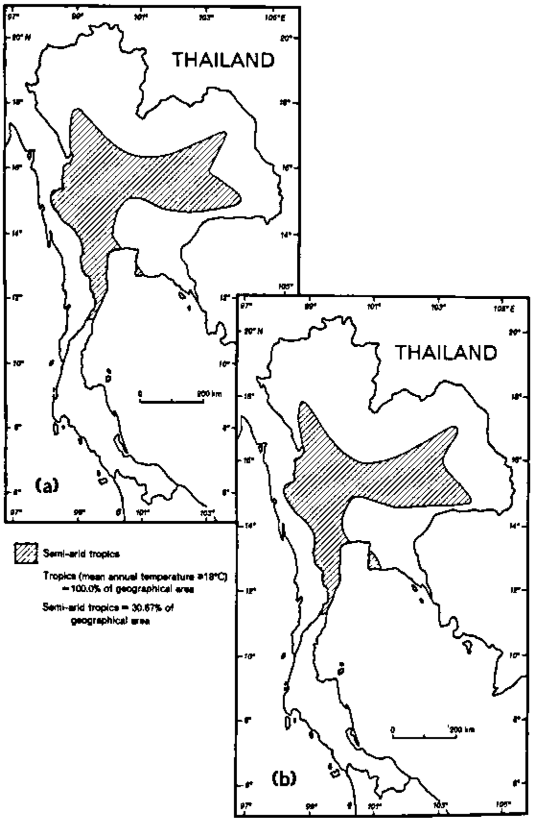

FIG. 4. SAT map of Thailand (a) Revised Troll's approach (b) Modified Thornthwaite's approach.

gamma distribution. Hargreaves (1971) defined the semi-arid zone as the region with MAI > 0.34 for 3 to 4 consecutive months. The limit is equivalent to R/PE > 0.50 (Hargreaves 1975). This is half limit that used to define a humid month by Reddy (1977). Boundaries of the SAT zones according to this approach are shown for India, West Africa and NE Brazil in Fig. 5. In drawing the SAT Map of India according to this approach data from 300 locations were used. Dependable rainfall (DP) values were computed using monthly rainfall data for 1901-1950 (India Meteorological Department, 1967). West Africa used data from 300 locations (Virmani et al. 1980, Reddy & Virmani 1980a) while NE Brazil used data from 700 locations (Hargreaves 1974). It is evident from Fig. 5 - India - that the high rainfall paddy growing areas of eastern Madhya Pradesh and Orissa are included under the SAT and most of the pearl millet and sorghum growing regions are included under arid zone. Indeed an even larger area than that seen in Fig. 2.

Mean annual rainfall at Agra and Sholapur is comparable, yet crop production is stable at Agra but unstable at Sholapur (stable and unstable are defined on the basis of variability in crop production potential over years, see for details Indian Council Agricultural Research 1982). Moreover, Agra is included within the arid and Sholapur within the semi-arid zone (Table 5). Similarly, Indore and Bangalore present anomalies. Indore, with stable agricultural production is included within the semi-arid zone, while Bangalore with unstable crop production (Indian Council Agricultural Research 1982) is included within the wet-dry zone. Thus. locations with comparable mean annual rainfall amounts but with stable agricultural production are included within drier zones than locations with unstable crop production. The basic explanation is that stations like Bangalore and Sholapur have less dependable rainfall in that the onset and withdrawal of rainfall shows wide year to year variation (Reddy 1975). In these cases moist period yields misleading results.

Thus, it seems that the only significant difference between the Troll (1965) and Hargreaves (1971) approaches lies in the time limit chosen for the demarcation of SAT: Hargreaves used 3 to 4 consecutive months and Troll as reported by Gray (1970) used 2 to 7 humid months. Because of this more arid regions are included within the SAT in the case of Troll (1965) compared to the Hargreaves approach. Even though the Hargreaves method is simple, the computation of dependable precipitation requires long term rainfall record. Also, a computer facility may be needed to fit the data to the incomplete gamma distribution where large data sets are involved. In addition this procedure presents anomalies in terms of dryland agriculture. Because of these, this method is also not acceptable for the demarcation of the SAT.

Modified Thornthwaite's approach (Reddy & Reddy 1973)

According to the modified Thornthwaite's approach (Reddy & Reddy 1973) the semi-arid zone is defined by mean annual rainfall (R) exceeding 25 to 75% of the mean annual PE. ($-25 < I_m = \frac{R-PE}{PE} \times 100 < -75\%$) This method is simple and the input data readily available. Using this approach, the SAT boundaries for India are shown in Fig. 6. At the upper ($I_m = -25\%$) and lower ($I_m = -75\%$) boundaries of the SAT, the range in mean rainfall amount is very low. For example, at the lower limit it is 480-520 mm, at the upper limit it is 1,200-1,250 mm. In addition, there is a much better correspondence with crop zone boundaries than was obtained with methods previously described. Important dryland crops, such as sorghum, pearl millet, groundnut, pigeonpea and chickpea are limited mainly to the defined zone (Fig. 3 and Easter & Abel 1973) and it includes the major dry farming or rainfed farming tracts of India. Also shown in Fig. 6 are the SAT boundaries, as defined by this approach, for Africa, Brazil, Australia. Boundaries for Thailand are presented in Fig. 4b. Data sources are as shown in Table 4.

Because of its simplicity and that it best fits the existing pattern, this method is used to demarcate the SAT as relevant to dryland agriculture.

The percentage areas that fall within the SAT for individual countries have been estimated for both the Troll (Fig. 1) and modified Thornth-

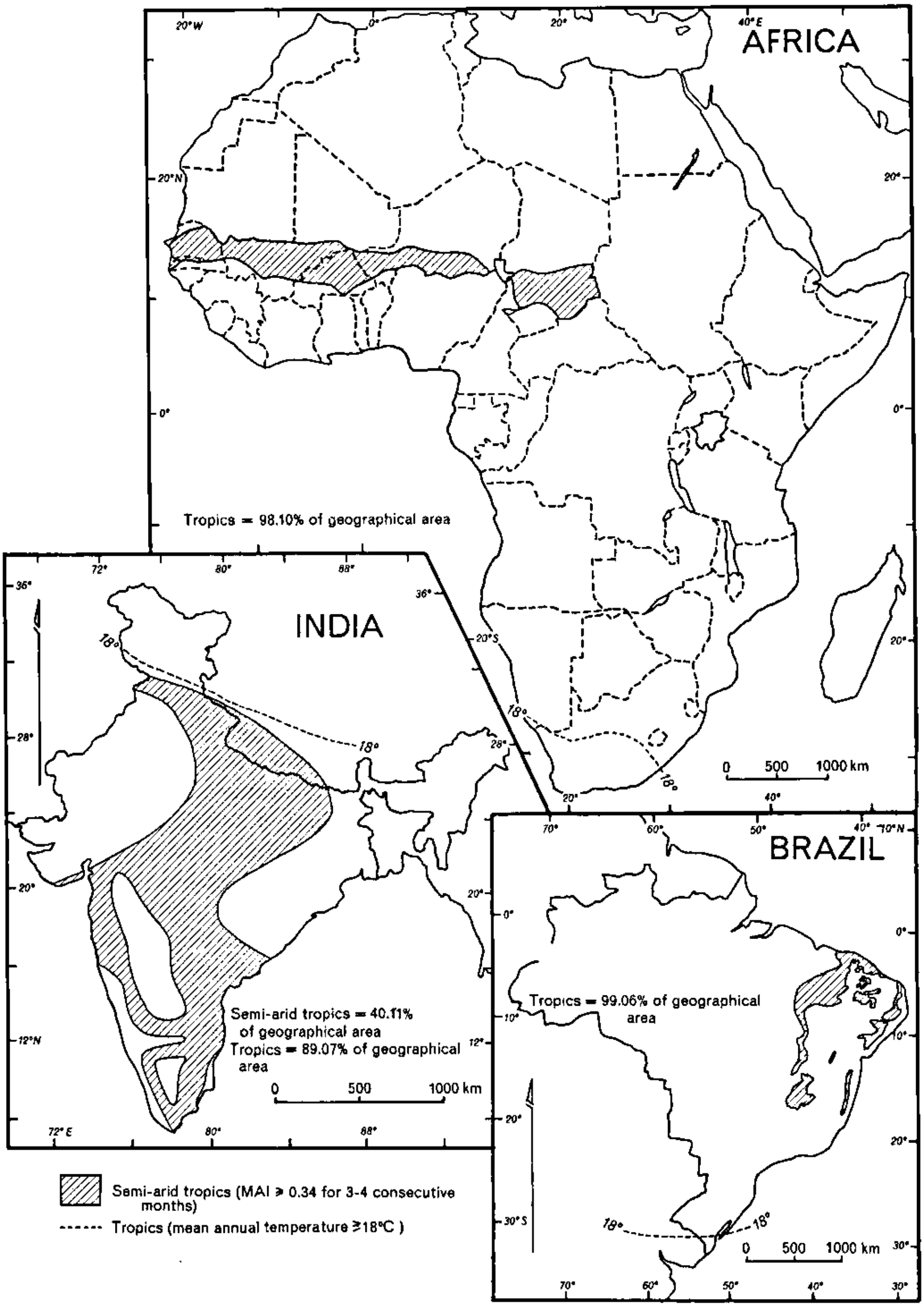

FIG. 5. SAT map of Africa, India and Brazil (Hargreaves' approach).

TABLE 5. Rainfall characteristics at four Indian locations.

Location	Mean annual rainfall (mm)	MAI ≥ 0.34 (No. of months)	Zone	Crop production
Agra	765	2	Arid	Stable
Sholapur	724	3	Semi-arid	Unstable
Bangalore	924	6	Wet-dry	Unstable
Indore	1.053	4	Semi-arid	Stable

waite's approach (Table 6). Although some countries have much the same percentage area within the SAT by either method, these do not represent the same geographical regions.

The environment of the semi-arid tropics (SAT)

Before attempting to sub-divide the SAT into agronomically relevant homogeneous zones, it is important to know the SAT environment in terms of climate, soil and farming systems that influence the dryland agriculture in the SAT. This section, therefore, attempts to describe briefly the SAT environment in terms of the above three factors.

Climate

General

The climate in the tropics is largely controlled by the movement of Intertropical Convergence Zone (ITCZ), which is the zone of convergence of winds from the high pressure belts of the two hemispheres. The displacement of the ITCZ over the area of its influence tends to follow the zenithal position of the sun with a time lag of four to six weeks and hence follow a north-south displacement with summer and winter alternatively. Area south of Sahel in West Africa, this is an important agroclimatic feature that is directly associated with the rainfall. In other parts of the semi-arid tropics the rainy periods are associated with ITCZ movement, but the rain causing mechanisms are different particularly in southeast Asia. In these parts of the SAT the rainfall patterns are drastically modified by orography, mountains and land-sea contrasts etc. These variations in the global circulation patterns and their modification due to regional or local scale factors have a bearing on agricultural production. Characterization of these mesoscale features can be of immense value to rainfed agriculture.

Rainfall

Rainfall in the SAT is summer dominant (April to October in the northern hemisphere and October to April in the southern hemisphere) with few exceptions. A few regions, e.g. southeastern parts of India and eastern parts of Queensland in Australia, also receive rains in winter (Krishnan 1975). Some typical rainfall patterns in the SAT are shown in Fig. 7. Indore (India), Tambacounde (Senegal), Niamey (Niger), Asmara (Ethiopia), Inhambane (Mozambique), Pretoria (South Africa), Campos Sales and Aracati (NE Brazil) present a single peak (unimodal distribution); Ahmednagar (India) has a double peak while Voi (Kenya) has two separate rainfall pulses (bimodal distribution). Madurai (India) has a unimodal pattern under winter rainfall and Anantapur (India) has a long rainfall season influenced by both summer and winter rainfall. The prevailing marked seasonality of rainfall is basically linked with sun-controlled shifts in the latitudinal position to the high pressure belts. Where rainfall distribution is more complex this is because of varying contributions of summer and winter mechanisms. In addition to these global controls, rainfall patterns are modified substantially by local (orography or vegetation) and/or regional (landsea contrast etc.) factors. The rainfall at any given location has both long-term and short-term variations. Long-term rainfall trends and fluctuations (Parthasarathy & Dhar 1974; 1978, Tyson 1978) differ significantly over different continents and also over different regions within the same continent. Seasonal and annual rainfall totals follow the normal distribution (Rao et al. 1972; Griffiths 1967). The square root of monthly rainfall also shows normality (Griffiths 1967). In general the SAT is characterized by short rainy

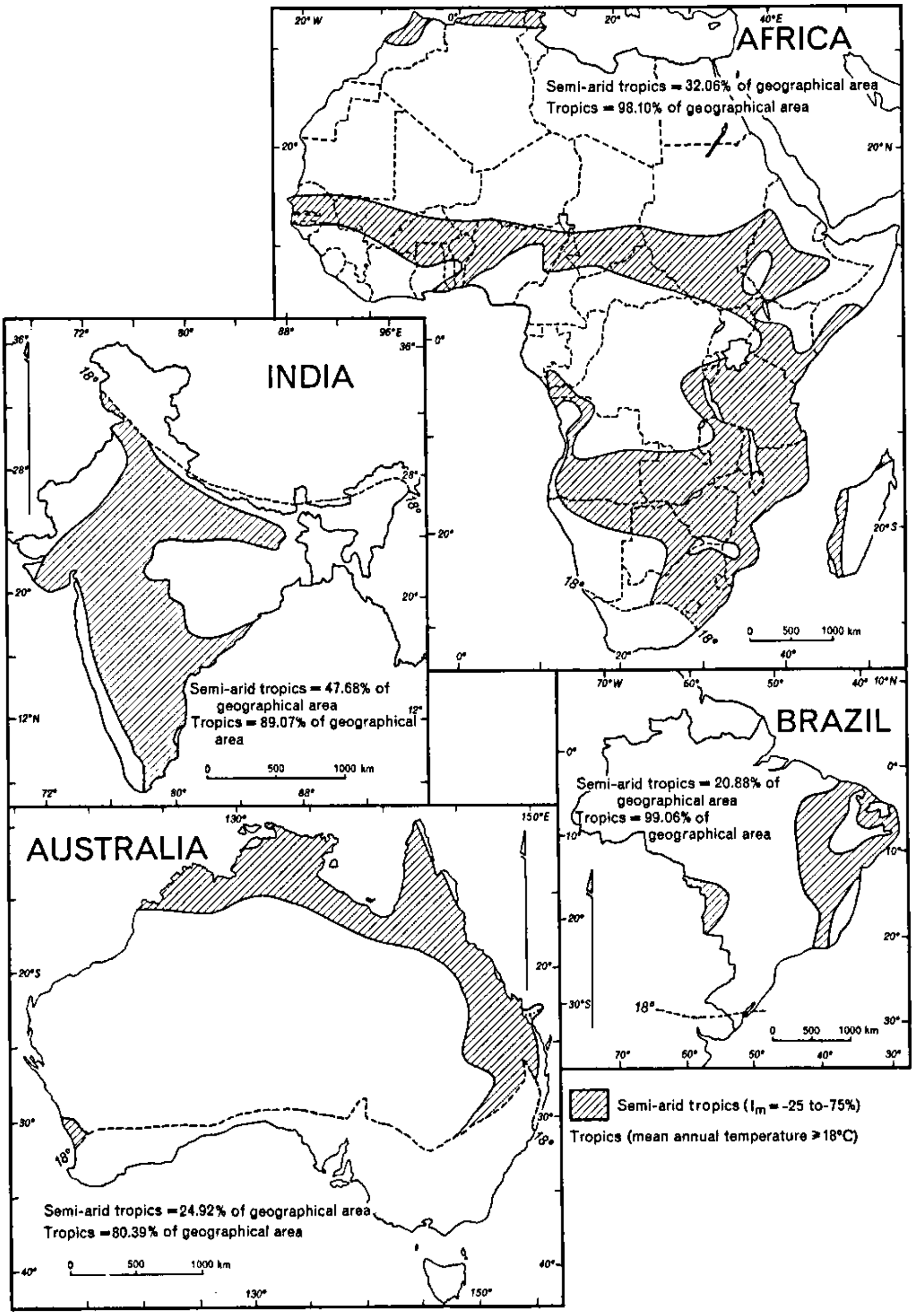

FIG. 6. SAT map of Africa, India, Brazil and Australia (Modified Thornthwaite's approach).

TABLE 6. Percentage area under the SAT according to modified Thornthwaite's and Troll's approaches.

Region	Country	Area (% of geographical area)		
		Tropics*	SAT	
			Method-1	Method-2**
SE Asia	India	89.07	47.68	54
	Thailand	100.00	30.67	60
Oceania	Australia	80.39	24.92	25
Southern & Central America	Brazil	98.76	20.88	12
Africa		98.10	32.06	64.83
	Algeria		5	-
	Angola		64	60
	Botswana		55	100
	Cameroon		17	25
	Central African Republic		34	50
	Chad		27	40
	Dahomey (Benin)		85	80
	Ethiopia (Afars + Issas)		39	50
	Gambia		100	100
	Ghana		43	50
	Guinea		100	70
	Kenya		56	90
	Madagascar		23	50
	Malawi		100	75
	Mali		27	60
	Mauritania		.08	25
	Morocco		28	-
	Mozambique		96	50
	Namibia		25	30
	Niger		07	40
	Nigeria		52	75
	Port of Guinea		-	100
	Rhodesia (Zimbabve)		92	100
	Senegal		81	100
	Somalia		21	50
	Sudan		38	60
	Tanzania		100	60
	Togo		50	80
	Tunisia		34	-
	Upper Volta		89	100
	Zaire (Rwanda & Barundi)		11	10
	Zambia		93	100
	Uganda		16	-
	South Africa (Swaziland & Lestho)		46	-

* Tropics = Mean annual temperature 18°C.

** Method-1: Modified Thornthwaite's approach (Fig. 6 & 4b);
Method-2: Troll (1965) approach (Figure 1 · values are according to Ryan et al. 1975).

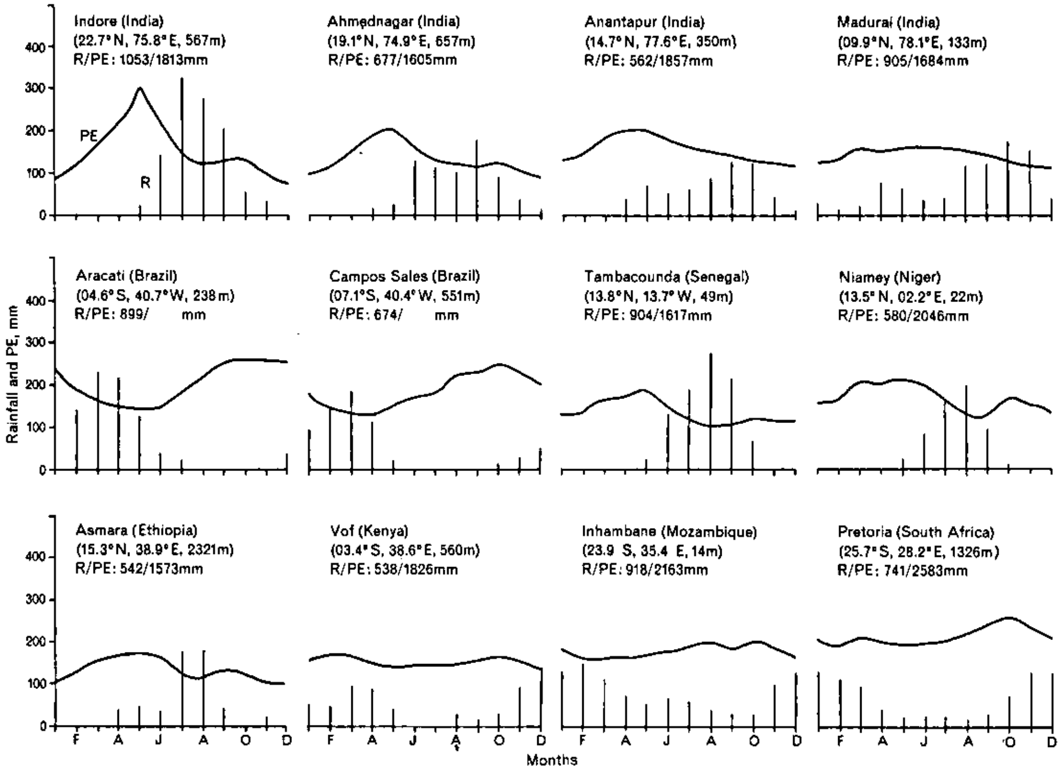

FIG. 7. Seasonal distribution of rainfall and PE for 12 selected locations in the SAT.

season; erratic rainfall distribution; frequent droughts and high intensity storms of varying duration; wide variations over regions and seasons; and wide variations in arrival and withdrawal of rains (Reddy 1975, Reddy & Singh 1981) see Fig. 8.

Radiation, Temperature and Relative Humidity

Direct measurements of solar radiation is restricted to a limited network of stations, but application of empirical relationships based upon sunshine hours or cloud has permitted calculation of solar radiation at a much larger number of locations (Reddy 1971a, b, Reddy & Rao 1973, Reddy 1973, 1981c). Solar radiation is a conservative element that shows only moderate year to year variation. Annual global solar radiation can vary between 400 and 550 ly/day (Landsberg et al. 1963, Thompson 1965, Reddy & Rao 1976, Reddy & Virmani 1980b). However, on a daily basis this may vary from as low as 100 ly/day on an overcast day to as high as 750 ly/day on a clear day. Variation in temperature among the SAT countries is low compared to other climatic regimes (Table 7, Krishnan 1975). The West African SAT show little variation even over seasons. Variation in temperature with season and latitude is systematic (Reddy & Virmani 1980b). Relative humidity is high in Asian SAT and northeastern parts of Australia compared to other SAT regions.

Potential Evapotranspiration

PE is generally high (> 1,800 mm) in most parts of the SAT except Asian SAT (< 1,800 mm). The high PE particularly in the post-rainy season in Africa (Reddy & Virmani 1980b; FAO-Mitchel Frere, Pers. Comm.) and NE Brazil (Reddy 1981a) limits double cropping or rainy season fallowed

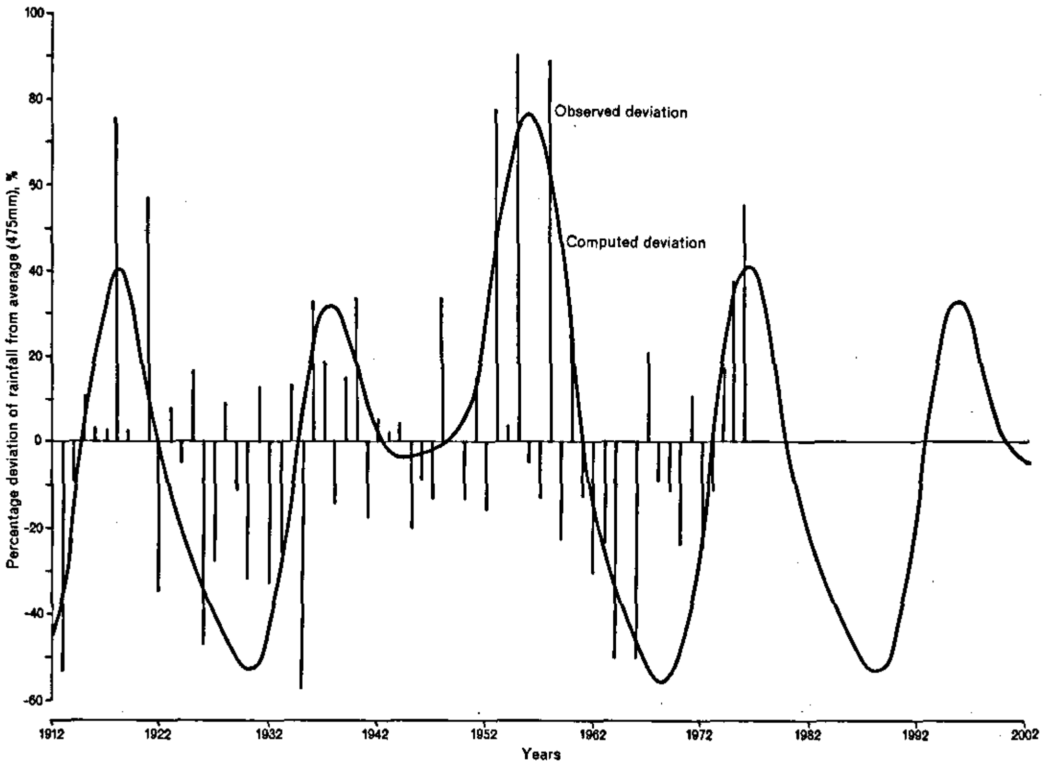

FIG. 8. Observed and estimated seasonal trend in mean annual rainfall (Mahalapye, Botswana).

TABLE 7. Seasonal variation of temperature and relative humidity in world SAT.

SAT region	Element*	Seasons**			
		Winter (Dec-Feb)	Summer (Mar-May)	Monsoon (Rainy) (Jun-Sep)	Postmonsoon (Postrainy) (Oct-Nov)
North Africa	T	25.3	29.4	26.7	26.9
	RH	40	48	76	63
South Africa**	T	20.1	24.7	24.5	23.1
	RH	58	59	77	67
Australia**	T	20.8	27.8	29.5	25.2
	RH	43	45	60	39
India-9 to 15°C	T	25.6	30.2	28.6	26.5
	RH	63	57	65	72
-15 to 25°C	T	22.4	30.4	27.9	25.2
	RH	48	41	72	56

(Source: Krishnan 1975).
T = Average temperature, °C;
RH = Average relative humidity, %
** = For Southern Hemisphere areas the seasons are reversed (on months to that effect).

post-rainy season cropping compared to Asia (Rao et al. 1971, Reddy 1981b). Fig. 7 presents PE patterns over few selected locations in the SAT.

Agriculture in the SAT is a gamble on rainfall. Water surplus and water deficit and their duration are of great important in evaluating water and land management systems for better crop production. While it is important to consider the water receipts over a given area, from the point of effective use, one is also concerned with the loss of water. Hence, in agroclimatic studies, the predominant meteorological factors to be considered are precipitation and potential evapotranspiration (PE) as they respectively represent the water supply and potential water need. The average distribution of rainfall when studied along with the variations about the average both in frequency and extent with respect to PE gives better insight into its agronomic importance in different regions.

Soils

As with climate, wide variations are seen in soil types both at micro and macro-scale. The diversity of the SAT soils is illustrated by the map of Aubert & Tavernier (1972). This shows four major soil types:

a. alfisols (which constitutes the major part of the SAT soils);
b. vertisols;
c. entisols; and
d. aridisols (for the sake of clarity, the US Soil Taxonomy system of classification is used).

The details on SAT soils according to Troll's approach were presented by Kampen & Burford (1979) and, according to revised Troll's approach (Reddy 1977) by Swindale (1982). Sanchez (1976) presented some general characteristics of these soils (Reddy & Singh 1981).

Alfisols (red and gray soils)

These soils are fairly shallow (< 100 cm) and are moderately well drained. The agricultural value of these soils is usually rated poor to average. Structural stability is generally poor and results in surface compaction and crusting. This increases soil and water losses in runoff and makes erosion hazards high.

Vertisols (black soils)

These are dark cracking, clay soils of low permeability and poor internal drainage. The clay fraction contains a high portion of 2:1 lattice clays which swell on wetting and shrink on drying. Commonly, these soils are deficient in nitrogen, phosphorous and sometimes zinc but sometimes are very fertile. The agricultural potential is rated as high. The poor internal drainage creates excess water problems.

Entisols (Alluvial soils)

As the name implies they are found in present or former river valleys and are recent deposits that have been little affected by soils forming processes. Because these soils have not undergone the adverse action of tropical weathering and leaching they can be among the most productive soils of the world.

Aridisols (Sandy soils)

Aridisols are found primarily along the border regions of arid and semi-arid zones. They are very sandy soils, hold little water, are easily workable, but are subject to wind erosion.

The last paragraphs provide an indication only of the diversity of the major SAT soils. Some important characteristics influencing crop growth can be identified as:

Soil depth

Soils vary a great deal in depth from a few centimeters (< 50 cm) to several meters, (> 2 m) thus affecting the rooting depth as well as water holding capacity. Compact zones like the lateritic plinths in Africa and Latin America may also impede water and root penetration.

Soil moisture storage capacity

The available water storage capacity within the profile is the crucial factor for crop survival and production. Soils show great variability in ability to store water - ranging from coarse sandy soils having limited water holding capacity (even less than 50 mm) to heavy clayey soils having appreciable water holding capacity (even more than 250 mm).

Soil erosion

Kinetic energy associated with high rainfall intensity is the prime cause of serious erosion (Greenland 1977). In Africa and Latin America where bush fallow or swidden agriculture is practiced, a major erosion threat is posed by decreasing fallow periods and thus decreased protection of the soil surface.

Soil fertility

Most SAT soils have low fertility (Jones & Wild 1975; Sanchez 1976). The mode of formation of most soils in the SAT environment has resulted in their being well endowed with bases but they are deficient in nitrogen and phosphorus. Sulphur deficiency is common in Africa. Marginal zinc deficiency appears to be also common.

Crusting and drainage are the other constraints.

Farming Systems

Cultivation Systems

Cultivation systems are multitudinous but three main forms may be recognized (Nye & Greenland 1960, Morgan & Pugh 1969, Ruthenberg 1971). They are:

a. shifting cultivation — a more or less haphazard movement of cultivation from place to place as fertility is exhausted or weeds become uncontrolable;
b. rotation bush fallowing — a deliberate alternation between cropping and bush regeneration. The duration of each cycle depends on soil fertility, weeds and population pressure;
c. continuous cultivation — associated with high population density and in the vicinity of large towns.

The former two systems are prevalent in Latin America and African SAT while the latter is seen in the Asian SAT. As the demand for food with increasing population increases, agricultural systems are shifting more towards the latter form mostly using artificial fertilizers.

Crop/cropping systems

Several forms of cropping are practiced in the SAT. These range from single cropping through inter-cropping to double cropping. Intercropping is the practice of growing 2 or more crops together on the same piece of land, the crops being planted at the same time in various geometric patterns but harvested at the same time or different times.

Where seed of mixed crops is simply broadcast with no geometric pattern, this is termed mixed cropping. Relay cropping refers to the practice of planting a second crop 2-4 weeks before harvest of the standing crop. In double or sequential cropping the second crop is planted after the harvest of the first crop (Rao & Natarajan 1981).

Subsistance food crops are millet, sorghum and groundnut in the drier zones and maize, cassava and various legumes in the wetter. Intercropping is common and many crop combinations are used (Norman 1975, Patrick 1972, Rao & Natarajan 1981). About 44% of the world's sorghum, 55% of the pearl millet, 90% of chickpea, 96% of the pigeonpea, and 67% of the groundnut are produced and consumed in the SAT. These crops are the main source of calories, protein and fat for people living in the SAT (Kanwar 1979).

Agricultural systems in the African SAT differ markedly from those of India, not so much due to the crops involved but, because of differences in soils, different rainfall patterns and socio-economic conditions. There is little use of animal power and most of the operations are performed by hand using hoe and cutlass. Crop yields are low, cereals average 500-600 kg/ha; legumes such as cowpea and soybean produce 250/300 kg/ha; and groundnut yields about 700 kg/ha. In the case of West Africa crops are grown entirely rainfed and the major ones, sorghum, millet, groundnut, cowpea and cotton occupying about 60-80 of the cultivated land. Others such as root crops, vegetables, maize, tobacco, sugarcane and rice cover about 15% of the cultivated area (Kassam 1976). In the case of Nigeria sorghum/millet, cotton/cowpea are the most common 2-crop mixtures. Other mixtures are sorghum/groundnut, pearl millet/sorghum/groundnut, cotton/sweet potato/cowpea and pearl millet/sorghum/cowpea/groundnut (Norman 1975). In the case of Upper Volta pearl millet is prominent in the northern zone; sorghum and pearl millet in the central zone; and sorghum and maize in the southern zone. With respect to soil types, pearl millet is found on relatively shallow soils, sorghum and maize on deep sandy loam and rice on more water capacity soils (Stoop & Pattanayak 1979). In the case of Senegal, groundnut and pearl millet in the north and central zone with lesser extent sorghum and cowpea are practiced; cotton, maize and rainfed rice in central eastern parts; and groundnut, maize/cowpea; sorghum/maize, maize/cowpea in the southern parts (Charreau 1974). In NE Brazil double cropping is not practiced because the short rainy season with high PE rates and low moisture holding capacity of the soils. The most important cropping systems is intercrop. In areas where the rainfall is too erratic and soils are poor for normal agriculture with food crops, perennial cotton is grown either sole or intercropped with cactus or on better soils intercropped with food crops (maize, maize/cowpea, maize/beans) - Lima & Queiroz (1981). Mafra et al. (1979) indicated that maize can be replaced by sorghum in maize/legume systems without damage to the legume yield, because sorghum is less affected by drought than maize.

As yet, most of northern Australia is used for extensive cattle grazing. Lack of infra structure, markets and suitable mechanized technologies for commercial cropping has hindered development. Nix (1978) estimates that only 3 million hectares might ultimately be cropped because of terrain and soil constraints. Perhaps ten times this area might be suited to improved pasture development.

On the deep black soils in India farmers traditionally leave the land fallow during the rainy season and crop it only during the post-rainy season on the residual soil moisture (International Crop Research Institute for the Semi-Arid Tropics 1981). The farmer has long recognized that trying rainy season is less assured than growing a post-rainy season crop on conserved soil moisture in the profile. But, this is not advisable on shallow Vertisols and Alfisols as insufficient water can be retained in the soil to grow a postrainy season crop.

Land and Water Management

Where rainfall is moderately high to high and dependable, the montmorillonitic clay of deep and medium deep Vertisols makes them very difficult to manage. Thus, they are very hard when dry and extremely sticky when wet, and can be cultivated easily only within a limited range of moisture conditions. Once the rains have started, the soil rapidly becomes too sticky for cultivation and sowing. If the rains are heavy, crop water-logging may occur, and opportunity for timely weed control is restricted. To overcome such problems and to increase food crop production in the SAT, ICRISAT has suggested new farming practices based on experimental findings both by ICRISAT and ICAR scientists. Some such recommendations are; Krantz 1979, Indian Council Agricultural Research 1982):

a. improved field drainage (ridge and furrow system)
b. dry sowing ahead of the monsoon (some farmers do follow this practice traditionally)
c. post-harvest cultivation
d. pre-harvest cultivation
e. use of hybrid seeds, fertilizers
f. using improved seed and fertilizer drills to ensure proper placement and stand
g. appropriate plant protection
h. timely harvesting
i. storing runoff for supplemental irrigation.

The idea of runoff colletion and use for supplemental irrigation presupposes that the potentials for using the available root profile storage more efficiently to buffer discontinuities in rainfall have been fully utilized. It is more efficient and cheaper to store water in the soil than in a tank. It must also be realized that runoff will frequently be least available in those years of erratic and low rainfall when the payoffs from supplemental water would presumably be largest. On any given soil type, the potential for supplementary irrigation from stored runoff is influenced strongly by the rainfall patterns, terrain and by subsoil conditions. The actual feasibility of this technique will therefore always be highly location-specific.

Benefits from supplemental irrigation from stored water are more likely on the Alfisols than on deep to medium Vertisols because Alfisols have higher runoff potential and they have a lower water-storage capacity. For more details on the above observations reference can be made to Krantz & Russell (1971), Kampen et al. (1975), Kampen (1976).

DISCUSSION

Therefore, although high temperature and high radiation encourage rapid crop growth, production is limited by insufficient water, for everywhere in the SAT the annual potential evapotranspiration (PE) exceeds rainfall. Many soils are sandy and low in crop nutrients. Because of their sandy texture many top soils have poor moisture holding capacity. The effect of this on crop growth may be aggravated by restricted rooting depth, due to shallowness of profile or compact clay horizon. Soil structure is generally weak. Any structure that exists in the top soil under natural vegetation rapidly deteriorate under cultivation. During humid periods subsoil horizons of low permeability may cause surface waterlogging. In many areas runoff and soil erosion are almost inevitable during the heaviest storms. Runoff and erosion involve the loss of soil and soil nutrients. The farmer suffers from many problems which his counterpart in a temperate climate does not; rain varies unpredictably both between and within years, the soil quickly loses its productivity in tropical storms, while the insects, disease and weeds which thrive in the high temperatures cause heavy loss of crops. Nearly 95% of farmers manage less than 2 hectares of land and farming is primitive with human and bullock power and only simple tools. In many respects the agricultural environment in the SAT is a harsh one. Traditional cropping systems thus reflect climatic variability and traditional practices as well as economic trends and availability of markets. Disease resistance varieties are largely unavailable to small-scale farmers, and fertilizers and pesticides are expensive. The most common system is inter-cropping: by mixing crops the farmer can have a longer cropping season, longer protection for the soil from sun, he can also grow a great variety of crops and can achieve greater yields.

SUMMARY

There is a great diversity in the usage and its practical application of the term "semi-arid". There are two basic reasons for this: firstly, some have defined this relative to "natural vegetation" boundaries and others have defined it in relation to cultural or land use boundaries. Secondly, climatic indices differ both in terms of their choice of attributes and/or choice of class interval. Most approaches use two basic climatic elements: (1) rainfall that supplies water for plant growth and (2) evaporative demand, that expresses moisture need for optimum plant growth. But the parameters used to represent these two climatic elements are significantly different. Older methods used temperature as a surrogate for evaporative demand and defined the SAT relative to natural vegetation boundaries while others used estimated PE or class A pan and defined SAT relative to vegetation types or food crops. Two broad modes of defining the semi-arid zones in terms of moisture and evaporative demand are identified. These are annual indices and the duration of moist and/or dry period. Three methods were compared and analysed in order to understand their potential applicability for demarcation of the SAT with reference to India, Africa, Brazil, Australia and Trailand. These were Troll's (1965) as modified by Gray (1970) and Reddy (1977) humid period; Hargreaves' (1971) dependable moist period; and modified Thornthwaite's (Reddy & Reddy 1973) annual moisture index. The term semi-arid is here defined as the zone of dryland or rainfed agriculture bounded on one side by areas (where rainfed crop production is uneconomical (arid) and on the other by the sub-humid or wet-dry (where rainfed dryland crop production is risky). The modified Thornthwaite approach provided the most relevant agriculturally oriented demarcation of the SAT. The model is not only simple but uses input data that are available for a global network of stations. The other two methods present anomalies with respect to distribution of food crops.

In the case of Troll (1965) as adopted by Gray (1970), the very broadly defined SAT comprises grassland regions with less than 200 mm of mean annual rainfall at the arid margin and rainforests

with mean annual rainfall exceeding 2,000 mm at the humid margin. The revised Troll's map of Reddy (1977) includes more of the wet-dry regions which have more than 1,600 mm within the SAT but dependable dryland areas with about 750 mm were excluded from the SAT and are included within the arid zone.

Hargreaves' approach (1971) is simple but the computation of dependable precipitation requires long term monthly rainfall records. Also, a computer facility may be needed to fit the data to the incomplete gamma distribution where large data sets are involved. Certain anomalies arise with areas with stable agricultural production are included within drier zones (arid) and areas with unstable crop production are included under wetter (wet-dry) zones irrespective of soil type although mean annual rainfall may be comparable.

At least for India the modified Thornthwaite approach best fits existing patterns. The semi-arid tropics (SAT) are thus defined as regions with mean annual temperature > 18°C and the mean annual rainfall meets 25 to 75% of mean annual potential evapotranspiration (PE). The SAT includes major dryland or rainfed agricultural zones with mean annual rainfall varying between about 500 and 1,250 mm. The upper and lower limits of rainfall show slight variation over different countries following PE level. For example, in the Chad where PE level is low the upper limit of rainfall is about 1,100 mm; while in the case of Brazil it is about 1,300 mm as PE level is very high. Major dryland crops are pearl millet, sorghum, pigeonpea, and groundnut.

Water is the major limiting factor in the SAT. Soils do limit the crop production and also they show wide variations on macro and micro-scale. However, they present the stationary feature which can be manipulated by man while climate, particulary rainfall, is not under man's control and presents high variation both spatially and temporally. Therefore, at any place in the SAT the production is highly related to the rainfall patterns. The traditional cropping systems do not make efficient use of natural resources. This involves the characterization of environment, in terms of rainfall, by identifying limitations and then identifying homo-climes using long period climatic data. To achieve this goal the first objective is to identify the climatic limitations as related to crop production. Then using these characteristics the climate can be grouped into agronomically relevant homogeneous zones.

Note:

The semi-arid tropics map of Brazil is based on 200 data points only. When compared to its geographical extent this data set represents the sparse network only. Therefore, it is proposed to redraw the boundaries of the SAT using more representative network of points. The two inputs for this study are the mean annual rainfall and the potential evapotranspiration. The computation of potential evapotranspiration is initiated.

ACKNOWLEDGEMENTS

This work was carried out during the stay of the author at the Australian National University, Canberra.

The author expresses his gratefulness to the Australian National University for financial support and to Drs. H.A. Nix and N.S. McDonald for their valuable discussion and comments on the draft. The author is also thankful to Mr. Kevin A. Cowen for the cartographic assistance.

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