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Climatic Risk in Crop Production: Models and Management for the Semiarid Tropics and Subtropics

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Climatic Risk in Crop Production: Models and Management for the Semiarid Tropics and Subtropics

Risk related to variable and unpredictable climate is a serious constraint to profitable and stable agriculture in the semiarid tropics and subtropics. Problems are compounded because strategies used by farmers to cope with the risk of crop failure in poor seasons also result in failure to take full advantage of good seasons.

This volume contains 24 invited papers from an international symposium held in Brisbane, Australia, in July 1990. The book reviews progress in methods for quantifying climatic risk, for reducing risk and uncertainty by improved long-term weather forecasting, and in optimising management strategies for coping with climatic risk. It is divided into seven parts: • the importance of climatic variability in crop production • estimating climatic risk to crop production – methods • estimating risk – applications • optimising agronomic practice in response to climatic risk • decision-making to reduce risk of crop failure • prospects for and implications of improved weather prediction • setting priorities for research. Given the recent developments in simulation modelling of crops and cropping systems and in computerised design-support systems, this book is a timely publication for agronomists, climatologists and economists.

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QUANTIFYING CLIMATIC RISK IN THE SEMIARID TROPICS: ICRISAT EXPERIENCE

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ABSTRACT

Troll defined semiarid environments in terms of the average period each year when rainfall (R) exceeded potential evaporation (PE). In the semiarid tropics (SAT), rainfall changes rapidly at the beginning and end of the monsoon so that the period when R > PE is insensitive to the arbitrary way PE is defined or measured.

Hargreaves and Robertson used somewhat more sophisticated methods to specify the length of the growing season in terms of the period when "dependable" precipitation (i.e. the amount exceeded in at least 75% of years) was more than PE/3. This criterion was used in early work at ICRISAT. Later, a water balance model (WATBAL) was introduced to estimate the risk of crop failure following dry spells at any time during the monsoon.

SORGF was the first simulation model tested at ICRISAT, calibrated with a set of regional data, and then used for risk analysis. Recently, a simpler simulation model (RESCAP) was developed to predict crop responses to weather and soil water. In this presentation, an even simpler version is described and used to estimate yield probabilities at two sites with contrasting rainfall regimes as a function of maximum available water or of light interception. The analysis demonstrates the interaction of weather, soil and plant factors in determining production risks.

Many environmental constraints endured by crops and by farmers in the SAT are not yet amenable to modelling so that attempts to model risk, even with the most complex simulation models, are somewhat unrealistic. Major problems not yet adequately addressed by modellers include germination, seedling establishment and root penetration in difficult soils, pests and diseases, and damage caused by wind or very heavy rain.

Achieving the right balance between productivity and risk lies at the base of all agricultural development. The SAT is an ecologically fragile region where the production of food is particularly hazardous because rainfall is erratic, soils are impoverished, and few farmers are able to control pests and diseases effectively or to apply optimal amounts of fertiliser. Because population is growing faster than food supplies in many parts of the SAT, subsistence agriculture has extended into marginal land, damaging the environment and threatening the long-term viability of economic and social development.

In this review, we identify salient environmental features of the SAT and consider briefly some of the ways in which ICRISAT scientists have been able to reduce production risks. We then assess progress in climatic analysis and indicate the directions in which we believe the modelling of crop production should be encouraged to develop.

THE SEMIARID TROPICS

Extent

Fig. 1 shows the global distribution of the SAT according to Troll (1965). His classification for tropical ecosystems was based on the number of humid months in which rainfall (R) exceeded potential evaporation (PE) as estimated from monthly mean temperature. A region was arbitrarily described as "semiarid" for tropical dry climates with 2 to 4.5 humid months and wet-dry tropical climates

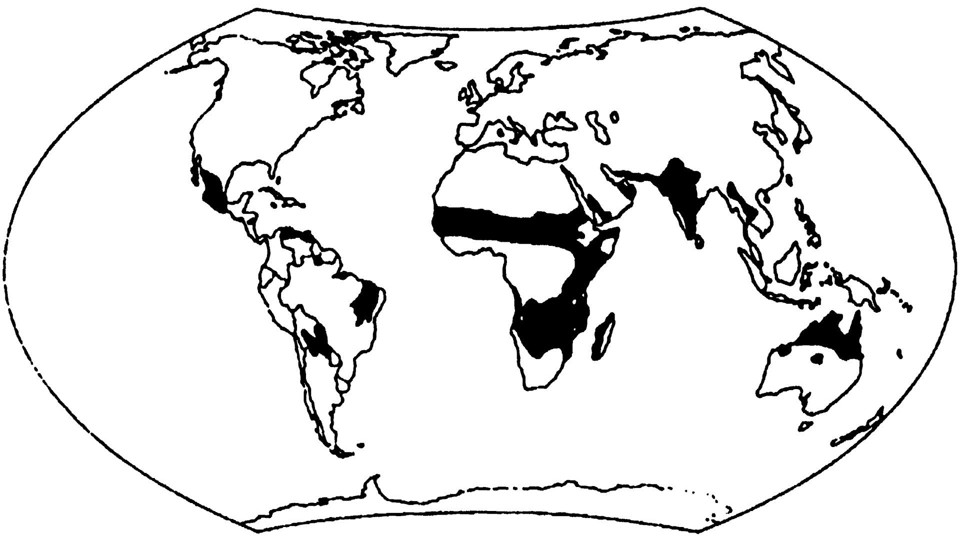

Fig. 1. Global distribution of the semiarid tropics according to Troll (1965).

with 4.5 to 7 humid months. In Africa, the SAT stretches in a wide band from west to east across the Sahara and includes much of eastern and southern Africa. In Asia, it includes most of India, East Java, north-eastern Myanmar (Burma) and Thailand. These are the main areas where ICRISAT scientists presently work in collaboration with national agricultural research services. Elsewhere, parts of northern Australia, Central and South America are semiarid.

More than 600 million people belonging to 50 nations live in the SAT, about 60% of them in India alone. As defined by Troll (1965), the growing season ranges between 60 and 135 days in drier parts of the SAT, and between 135 and 210 days in wetter parts.

Rainfall

The distribution of the SAT according to Troll (1965) bears a close resemblance to the major monsoon regions of the world (Webster 1987), most of which have three distinct seasons:

(i) Dry season of 100 to 200 days, during which temperature and saturation deficit increase and crop production is impossible without irrigation;

(ii) Rainy season of 60 to about 210 days, at the beginning of which temperature and saturation deficit decrease and throughout which dryland crops can usually be grown without recourse to irrigation; and

(iii) Post-rainy season, when temperature decreases and limited crop production is possible on water stored in soil profiles with a capacity of at least 200 mm.

In some regions near the equator, e.g. in Kenya, a long dry spell regularly splits the rainy season into two components (Stewart 1991).

This type of climate contains many potential sources of climatic risk, mainly associated with rainfall. Before the onset of the monsoon, the soil surface is very dry. When first showers are light or widely spaced, seed sown prematurely may not germinate properly; but if sowing is delayed, the land may be too wet to till. Over the decade 1980-1989, for example, the monthly rainfall in June (when rainy season crops are sown) ranged from 87 to 203 mm with a coefficient of variation (CV) of 33% in Hyderbad, India. In October, when post-rainy season crops are sown mainly on deep black soils, the range is even more extreme: from 0 to 155 cm with a CV of 86% (Appendix 1).

Problems of temporal variation in rainfall are compounded by spatial variability. These effects are felt most keenly by individual farmers at the beginning of the growing season. For example, rain recorded at ICRISAT's Sahelian Center on 26 July 1986 ranged from less than 10 mm at the SE corner of the site to 34 mm at the NW corner about 3 km away (ICRISAT 1988). Similar observations have been recorded at ICRISAT Center, Patancheru, India.

To meet the constraints imposed by such variability, many farmers in the SAT cultivate small, dispersed fields rather than contiguous areas. This strategy makes field operations difficult to complete in a timely way, but helps to stabilise yields by spreading risk.

The seasonal movement of the monsoonal front is governed by annual changes in solar declination and is therefore inherently systematic. However, monsoons interact with depressions generated within the general circulation of the atmosphere. Randomness in the appearance and strength of these systems is responsible for the characteristically erratic and unpredictable distribution of monsoon rain (Shukla 1987). Fig. 2 shows the annual distribution of rainfall at Hyderabad over 89 years. No statistically significant trend or cycle exists (ICRISAT 1988) although several sequences of dry or wet years are evident. In the Sahel, annual totals followed a clear downward trend over the period 1970 to 1987. Although there is evidence that this has now been reversed, rainfall in August, a month critical for pearl millet production, continues to fall below the long-term average (M.V.K. Sivakumar pers. comm.).

In the Indian SAT, the amount of water received during the monsoon is weakly correlated (r^2 = 0.58) with the length of the growing season so it is not possible, even in principle, to reduce production risks by changing cropping strategies (e.g. Stewart 1991). In contrast, the length of the growing season at ICRISAT's Sahelian Center in Niger is very strongly correlated (r^2 = 0.94) with the date when the rainy season begins (Fig. 3). Scientists at ICRISAT are exploring cropping systems based on millet and cowpea which can be adapted to match the season length (Sivakumar 1990). In 1986, for example, it was possible to follow pearl millet by a crop of cowpea that produced 0.42 t ha^{-1} of hay under rainfed and 0.68 t ha^{-1} under irrigated treatments. Legume hay is a valuable commodity in this dry region.

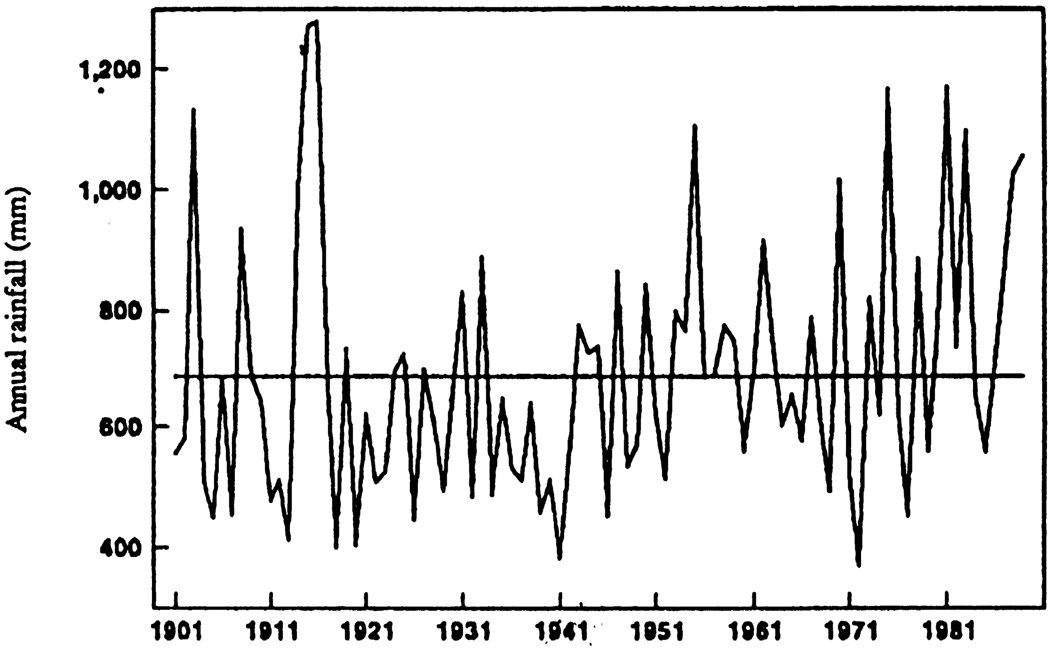

Fig. 2. Annual rainfall at Hyderabad (17° 27'N, 78° 28'E) from 1901 to 1989. Average annual rainfall is 690 mm.

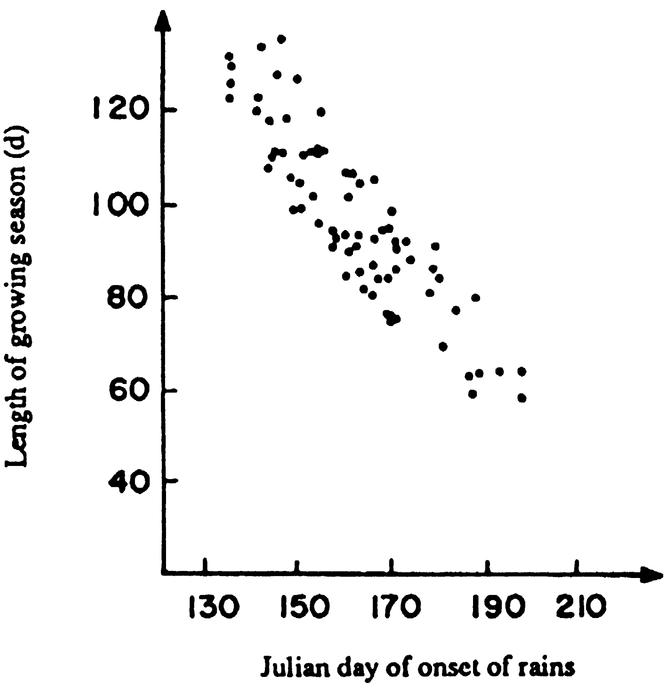

Fig. 3. Correlation between seasonal rainfall and date of onset of rains at ICRISAT Sahelian Center, Niamey, Niger. Source: Sivakumar (1988).

Climate and Soil

Throughout the SAT, substantial amounts of rain are received in intense storms of high intensity associated with vigorous cumulonimbus activity, which can occur at any time of year. Intensities between 20 and 60 mm h^{-1} are common (Table 1). Storms can destroy crops and are responsible for rapid runoff and erosion, particularly on land that has not been graded to control runoff. For example, Miranda *et al.* (1982) showed that over the 5 years 1977-1981 at ICRISAT Center, the average annual loss of soil from a vertisol, fallowed in the rainy season and cropped after the rains, was 7 t ha^{-1}. This figure was reduced to 1.2 t ha^{-1} by using broadbeds and furrows with improved cropping systems in both seasons (Table 2).

In addition to the risk of erosion, many soils in the SAT contain little organic matter. Structure is therefore poor and soils such as alfisols tend to set hard after the onset of the rains. Infiltration rate decreases rapidly after cultivation, particularly on alfisols. Infiltration is also restricted during the early part of the rainy season when the impact of raindrops may seal the surface.

The interaction of climate and soil in the SAT is therefore responsible for a complex set of risks to which all crops are exposed. After sowing, seeds may be surrounded by soil that dries very rapidly or remains waterlogged. Subsequent root growth is extremely sensitive to soil bulk density and yield is depressed on hard-setting soils because water and/or nutrient uptake are restricted. Major losses of yield occur when crops are lodged by intense rainstorms, and sandstorms bury seedlings and damage leaves. Epidemics of pests and diseases are also strongly dependent on weather patterns, introducing yet another dimension of risk.

Many of the models for crop production that work well in more favourable environments are of limited relevance in the extremely risky SAT environment.

Table 1. Rainfall intensities at two sites in the SAT. Source: Hoogmoed (1981).

Location (year)	Size of storm	Percentage of rainfall events with intensities (mm h^{-1}) higher than		
	(mm)	20	50	100
Niamey, Niger (1963)	All	72	52	17
	> 20 mm	78	61	21
	10-20 mm	69	42	16
	< 10 mm	-	-	-
Hyderabad, India (1975)	All	43	18	11
	> 20 mm	48	25	14
	10-20 mm	27	0	0
	< 10 mm	25	0	0

Table 2. Runoff and soil loss from two vertisol watersheds at ICRISAT Center subjected to different treatments. Source: Miranda *et al.* (1982).

Year	Seasonal rainfall (mm)	Broadbed and furrow layout with improved crop management system		Traditional flat with bunds, rainy season fallow system	
		Runoff (mm)	Soil loss ($t\ ha^{-1}$)	Runoff (mm)	Soil loss ($t\ ha^{-1}$)
1976/77	688	73	0.80	238	9.20
1977/78	586	2	0.04	53	1.68
1978/79	1125	273	3.40	410	9.70
1979/80	690	73	0.70	202	9.47
1980/81	730	116	0.90	166	4.58
Mean	764	107	1.17	214	6.93

Over generations, farmers in the SAT have learnt how to weigh up risks to production, and how to make good use of their very limited resources, without the help of personal computers and simulation models!

Having entered that substantial caveat, we now describe a series of models of increasing sophistication that have been used at ICRISAT to identify risks associated with the uncertainty of rainfall distribution.

CLIMATE MODELS

Troll (1965)

The first and simplest model has already been referred to. Troll's criterion R > PE coarsely defines months when there is relatively little risk of drought. Of the two variables needed for this simple assessment, rainfall is commonly measured even at very isolated stations. Potential evaporation on the other hand, cannot be measured and has therefore been defined in many different ways: (i) as a fraction of evaporation from a pan; (ii) as a simple empirical function of a single element of climate (e.g. Thornthwaite, Koppen); or (iii) as a physically-based function of several elements (Penman).

Gross errors could occur in estimating the length of a growing season from the R/PE ratio were it not for the fortunate fact that R increases very rapidly with the arrival of the monsoon, whereas PE decreases slowly as radiation and saturation vapour pressure deficit decrease. It can be shown that if the error in PE is d at the point where R = PE, the error in determining the date of that point will be: $d / (\delta R/\delta t - \delta(PE)/\delta t)$ where the differentials with respect to time t are evaluated at the point.

At Hyderabad, for example, the mean value of $\delta R/\delta t$, when rainfall starts to exceed pan evaporation, is about 3 mm d^{-2}, and the corresponding value of $\delta(PE)/\delta t$ it is less than -0.2 mm d^{-2}. It follows that, even if the difference between pan evaporation and "true" potential evaporation was, say, 4 mm d^{-1}, the error in defining the date when R = PE would be approximately one day. The same argument can be applied to the error in defining the end of the growing season.

Troll adopted the criterion of R>PE to identify months when crop production is possible, and Table 3 contains this simple type of analysis for four SAT sites at which PE was calculated from Penman's equation. At Maradi in Niger, Troll's criterion suggests that a 60 to 70 day crop could be grown with little risk and the area is, in fact, suitable for short duration varieties of pearl millet. Hyderabad (India) and Kaolack (Senegal) are suited to the cultivation of crops over 90 to 120 days; and in Addis Ababa (Ethiopia), crops of 120 to 150 days duration can be grown.

Table 3. Average rainfall, potential evaporation (PE = .8 x pan evaporation), dependable precipitation (PD) and moisture availability index (MAI) at four SAT sites. Source: Hargreaves and Samani (1986).

		Month												
Location		**Jan.**	**Feb.**	**Mar.**	**Apr.**	**May**	**Jun.**	**Jul.**	**Aug.**	**Sep.**	**Oct.**	**Nov.**	**Dec.**	**Annual**
Maradi, Niger	Rainfall	0	0	0	7	25	70	156	204	88	9	0	0	559
	PE	114	124	147	153	158	154	142	138	138	145	120	113	1644
	PD	0	0	0	0	2	41	114	153	51	0	0	0	475
	MAI	-	-	-	-	-	0.27	0.80	1.11	0.37	-	-	-	-
Hyderabad, India	Rainfall	6	10	14	23	30	101	168	149	173	83	28	5	790
	PE	112	123	160	173	188	135	105	106	113	127	115	102	1560
	PD	0	0	0	2	6	58	111	91	98	27	1	0	644
	MAI	-	-	-	-	-	0.43	1.06	0.86	0.87	0.21	-	-	-
Kaolack, Senegal	Rainfall	1	0	0	0	3	48	133	235	173	56	7	1	656
	PE	98	121	146	158	158	146	134	108	128	121	102	98	1518
	PD	0	0	0	0	0	9	74	149	119	23	0	0	521
	MAI	-	-	-	-	-	-	0.55	1.29	0.93	0.19	-	-	-
Addis Ababa, Ethiopia	Rainfall	19	39	66	85	87	136	272	287	190	30	11	11	1233
	PE	86	90	100	97	90	73	58	65	78	99	96	88	1020
	PD	0	5	17	44	41	95	232	230	139	3	0	0	1085
	MAI	-	-	0.17	0.45	0.46	1.30	4.00	3.54	1.78	-	-	-	-

Hargreaves (1971)

Because of the variability in rainfall received during a given month in the SAT (e.g. Hyderabad, Appendix 1), Hargreaves pointed out that mean values are inappropriate as climatic indices. He argued that for economically stable farming, crops should reach maturity without significant loss of yield because of drought in at least 3 out of 4 years. His "moisture availability index" is the rainfall exceeded in 75% of years (i.e. dependable precipitation) divided by the mean value of PE. On this basis, the length of the growing season in Maradi, Hyderabad, and Kaolack is again about 90-120 days, but it is about 180 days in Addis Ababa (Table 3).

Hargreaves' method of defining the length of growing seasons is more logical than Troll's but needs longer records to define probabilities - at least 30 years of rainfall and preferably 50.

Robertson (1976)

Attempting to define growing season length more precisely, Robertson interpreted rainfall totals for 5, 7 or 10 days in terms of Markov chain, first-order probabilities in order to characterise the risk of drought over short periods. Virmani *et al.* (1982) used weekly values of rainfall and the criterion $R/PE > 0.33$, suggested by Hargreaves, as a threshold value for establishing and maintaining crops.

Fig. 4 compares analyses for Hyderabad and Sholapur, both in the Deccan plateau, India, with long-term mean rainfall of 764 mm and 742 mm respectively. Initial probabilities are shown along with conditional probabilities of a wet week being followed by another wet week (W/W) or by a dry week (W/D). Within the growing season, it appears that conditional probabilities add little to the information already contained in initial probabilities. The rainfall distribution at Sholapur is less dependable than in Hyderabad and few weeks exceed 70% initial probability. In contrast, Hyderabad rainfall is dependable at the 70% level for two spells: between mid-June and the end of July, and again from about mid-August to mid-September (i.e. a bimodal distribution). Even though the two stations have almost the same annual mean rainfall, rainfed crops grown near Hyderabad are less at risk, as shown below, and this difference is reflected in traditional practices. On deep black soils (vertisols), farmers near Hyderabad raise crops during the rainy season. In Sholapur, because the risk of dry spells is greater, most land is left fallow during the monsoon, and crops are grown during the post-rainy season on 200 to 250 mm of water stored in the soil profile.

This type of risk analysis can also be used to estimate the probability of obtaining adequate rain for planting on a series of dates, the probability of dry weather for harvest, and the risk associated with fertiliser application and weeding at different times.

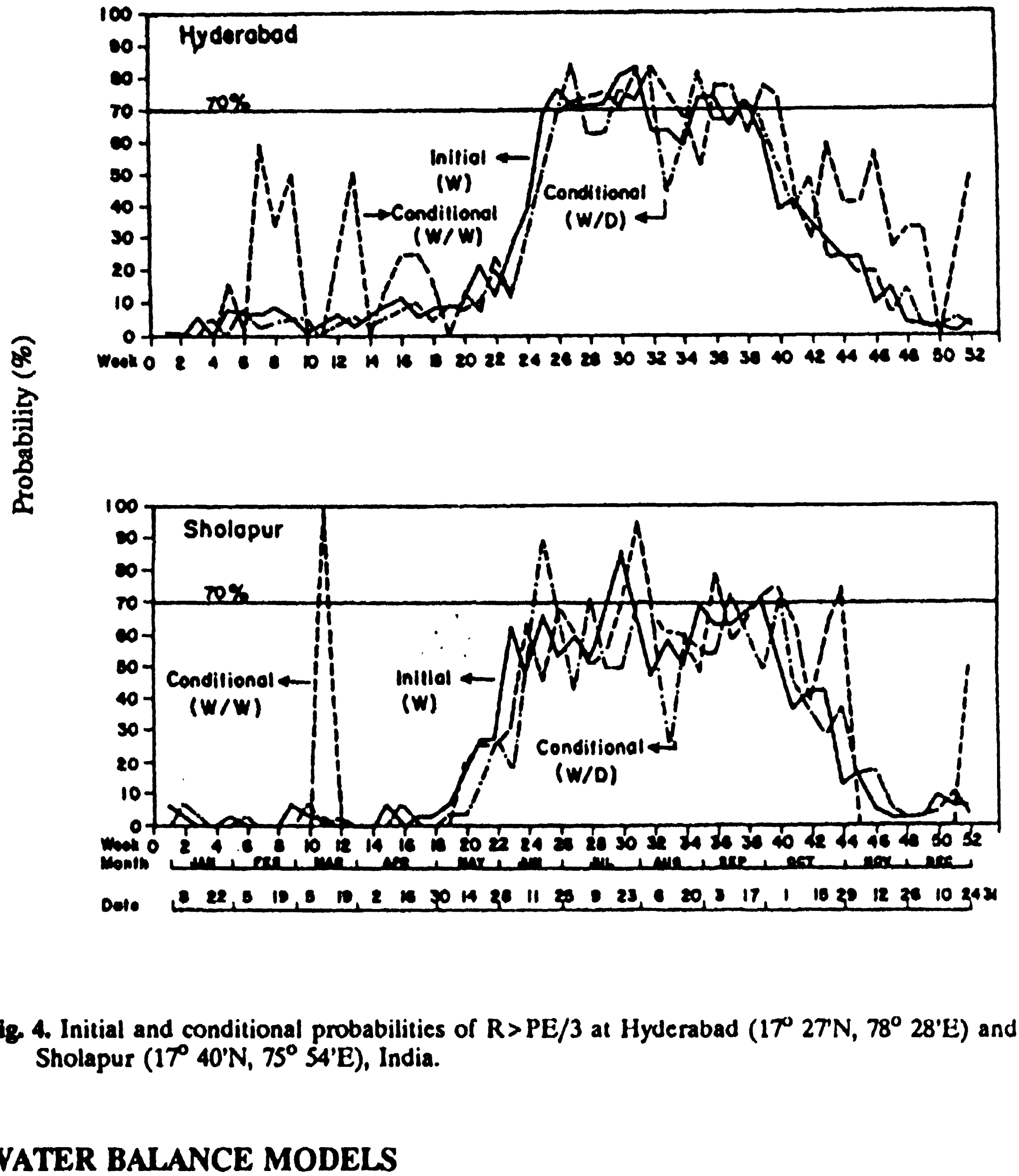

Fig. 4. Initial and conditional probabilities of R>PE/3 at Hyderabad (17° 27'N, 78° 28'E) and Sholapur (17° 40'N, 75° 54'E), India.

WATER BALANCE MODELS

Following the pioneering work of Thornthwaite (1948), many attempts have been made to establish the water balance of plant communities. Fitzpatrick (1965) and Fitzpatrick and Nix (1969, 1970) showed how the concept of water balance could be used to estimate the reliability of the water supply for a crop during its growth. Using WATBAL, a model developed by CSIRO, Australia, Virmani *et al.* (1979) found that the length of the growing season at ICRISAT Center ranged between 12 and 21 weeks for shallow alfisols holding 50 mm of water; and between 20 to 30 weeks for deep vertisols holding 300 mm. Corresponding levels of probability are shown in Table 4.

Based on this analysis, ICRISAT intensified its work on intercropping systems and selected crops with growing seasons that matched the 25 and 75%

probabilities. For the vertisols, for example, the intercrops chosen were medium-duration pigeonpea maturing in 150 to 180 days and short-duration sorghum or maize maturing in 90 to 105 days. It was found that intercropping gives higher returns, spreads labour needs over the season, and generally reduces risk. Rao and Willey (1980) examined the stability of 94 experiments involving sole sorghum and sorghum/pigeonpea intercrops. They found that whereas the sole sorghum failed one year in eight, the intercrop failed only one year in 36.

Table 4. Length of growing season (weeks) for different soils and water storage capacities at ICRISAT Center, Patancheru, India. Source: Virmani *et al.* (1979).

Probability	Soil type (Available water storage capacity)		
(%)	alfisol (50 mm)	alfisol (150 mm)	vertisol (300 mm)
25	20	24	30
Mean	18	21	26
75	15	19	23

In general, ICRISAT's breeding programme has concentrated on developing genotypes that mature within the growing season, as determined by rainfall distribution and soil type, rather than those that can survive through drought at the expense of yield. The germplasm (at ICRISAT Center) now contains: sorghum maturing in 85 to 120 days; pearl millet from 65 to 85 days (complementing sorghum); groundnut from 90 to 150 days (or longer for indeterminate lines); and chickpea from 75 to 115 days.

Binswanger *et al.* (1980) extended the application of water balance models by estimating the "reliability" of crop production in terms of the probability of water in the soil profile being enough to maintain transpiration at a potential rate. This rate was calculated from potential evaporation values as proposed by Rao *et al.* (1971). Table 5 shows specimen calculations for three stations:

(i) Sholapur where rainfall is erratic (see Fig. 4) and where the water-holding capacity of a deep vertisol was taken as 230 mm;

(ii) Hyderabad with more dependable rainfall than Sholapur but with the same soil water-holding capacity of 230 mm; and

(iii) Akola for a medium vertisol holding 120 mm of water.

At Sholapur, where rainfall is less dependable (Table 5), good growing conditions (as defined in terms of rainfall and evaporation) occur in only one year in three compared with two in three for Hyderabad and Sholapur. According to the criteria adopted, the most significant risk at Sholapur is lack of rain for germination before mid-July.

Therefore, we examined the criterion for germination defined in terms of an assumed need for rain on two consecutive days to exceed a certain value.

Table 5. Reliability of a 90-day rainy or postrainy season crop on vertisols at three locations. Source: Binswanger *et al.* (1980).

Location and soil type	Probability (percent of years)*					
	1 Emergence before 15 July	2 Seedling survival	3 Adequate soil moisture	4 Good growth	5 Adequate soil moisture for postrainy sorghum following sorghum	6 Adequate soil moisture for postrainy sorghum following fallow
Sholapur, deep vertisol	65	76	84	33	60	80
Hyderabad, deep vertisol	85	90	90	62	50	83
Akola, medium vertisol	92	87	92	66	n.a.	n.a.

*The sequential probabilities are for:

1. Emergence before 15 July, assuming 25 mm of rain is needed (after mid-July the risk of damage by shoot fly increases rapidly);
2. No water stress for 2 weeks after emergence;
3. Soil water reserves exceeding 50 mm during vegetative growth and 100 mm during grain-filling;
4. Fulfilment of all previous conditions;
5. More than 150 mm left in the profile from mid-September to mid-October for a post-rainy season crop; and
6. As (5) but with rainy season fallow.

The choice of this value is based on the fact that seed of a crop such as sorghum is usually sown to a depth of about 10 cm. The amount of water needed to wet a vertisol to that depth is about 20 mm plus losses by evaporation from the soil surface. Fig. 5 shows that, provided the criterion adopted for minimum rainfall lies between 20 and 40 mm, the probability of the sorghum crop failing to achieve germination remains 2 to 3 times larger in Sholapur than in Hyderabad.

CROP MODELS

SORGF Model

One of the main shortcomings of the water balance model used to derive Table 4 is that the transpiration rate is estimated from: (i) a "potential" or maximum value depending only on climatic factors; and (ii) from a ratio of actual to potential evaporation which is an arbitrary function of soil water content. In the late 1970s, ICRISAT climatologists began to explore the possibility of using

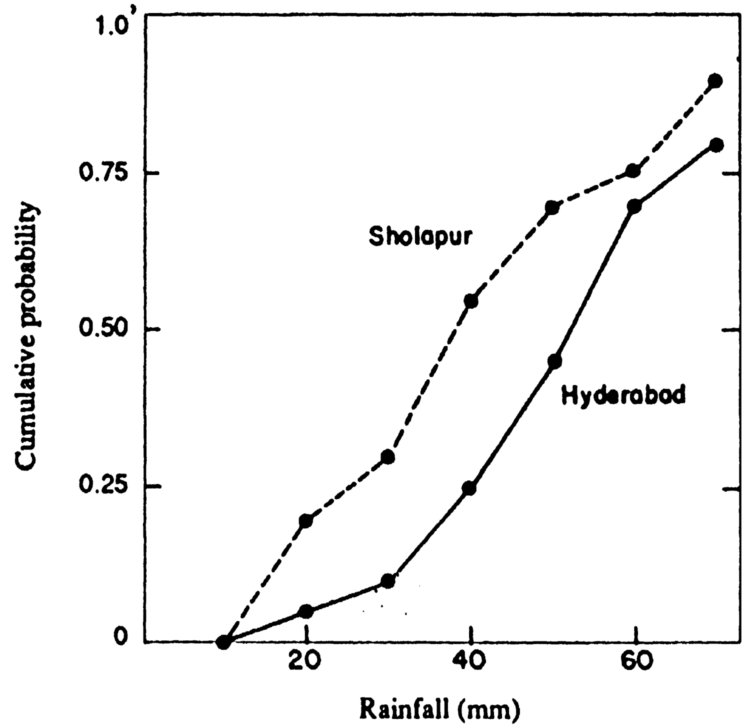

Fig. 5. Cumulative distribution functions for total rainfall on two consecutive days at Hyderabad and Sholapur, India.

simulation models to estimate crop growth and water use as functions of prevailing weather and soil properties. An early version of SORGF was tested using measurements from a multi-location trial in India within which five sorghum cultivars were grown at nine stations from latitude 11 to 31° N with annual rainfall ranging from 450 to 900 mm. The following modifications were subsequently made to the SORGF model (Huda 1987):

(i) New algorithms were developed to estimate the thermal time for each stage of development, and to include the dependence of growth stages 1 and 2 on daylength as well as on temperature;

(ii) To correct for a systematic overestimation of the amount of light transmitted by a canopy, row spacing was introduced as a parameter;

(iii) The calculation of water balance was improved by introducing subroutines for root growth and for drainage;

(iv) Photosynthesis functions were replaced by a simple relation between dry matter production and intercepted radiation; and

(v) Cultivar-specific coefficients were used to distribute dry matter between organs.

These changes improved the correlation between observed and simulated grain yield from r = 0.52 to r = 0.86, but at the cost of increasing the number of subroutines, and parameters in the model. In an attempt to reverse this trend and to avoid some of the empiricism and illogical features of some current models, ICRISAT has now developed a substantially simpler generic model (RESCAP), which is described below.

Use of the revised SORGF to estimate yield probabilities for sorghum at four Indian sites with contrasting rainfall regimes is shown in Fig. 6. The corresponding need for nitrogen (N) fertiliser was estimated on the simple assumption that 20 kg ha^{-1} of N was required to produce 1 t ha^{-1} of grain, and that the base N level for an unfertilised field could be set at 30 kg ha^{-1}.

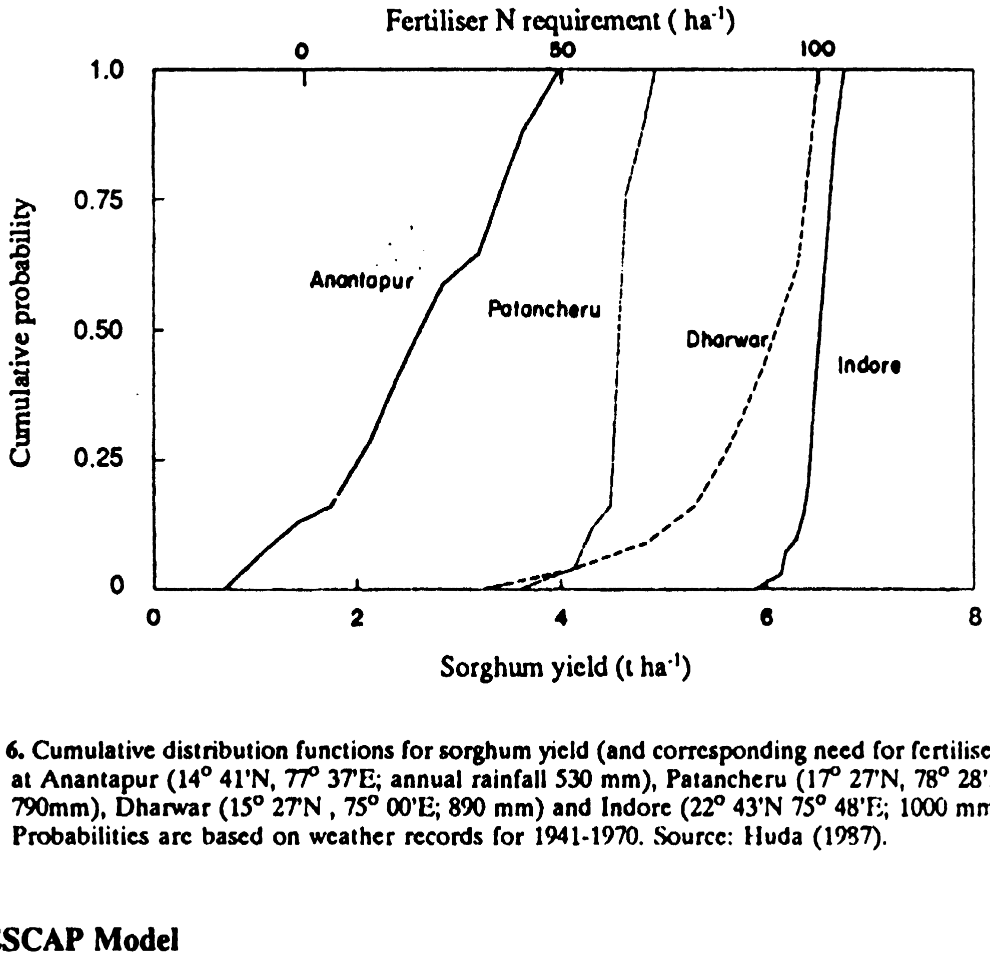

Fig. 6. Cumulative distribution functions for sorghum yield (and corresponding need for fertiliser) at Anantapur (14° 41'N, 77° 37'E; annual rainfall 530 mm), Patancheru (17° 27'N, 78° 28'E; 790mm), Dharwar (15° 27'N , 75° 00'E; 890 mm) and Indore (22° 43'N 75° 48'E; 1000 mm). Probabilities are based on weather records for 1941-1970. Source: Huda (1987).

RESCAP Model

Unlike most other models, RESCAP is based on the premise that daily dry matter production depends either on the capture of light by leaves or on the capture of water by roots, but not on both simultaneously. A major simplifying assumption based on field evidence is that, when water is not limiting, the rate of dry matter production and of water use are both proportional to intercepted radiation. When these potential rates cannot be sustained because the soil is too dry or because the root system is too small, the maximum uptake rate is estimated from the vertical distribution of soil water content and root length density. The rate of dry matter production is then assumed proportional to the (actual) rate of transpiration and inversely proportional to the saturation deficit.

At the end of each day, new biomass is allocated to leaves and roots thus increasing the size of RESource CAPturing systems. A brief description of the RESCAP model, as originally developed for sorghum, is given in Monteith *et al.* (1989). When used with a climatic data set (daily values of rainfall, solar radiation, wet and dry bulb temperature and pan evaporation), RESCAP can provide estimates of production risks in dryland farming, and can be used to explore the merits of different systems of management. To avoid becoming entangled in unnecessary detail, a simplified version of RESCAP (Monteith 1989) was used for the following analysis. Details are given in Appendix 2

The model was used to estimate cumulative yield probabilities at Hyderabad and Sholapur from daily records of weather for the past 20 years. In this example, water was assumed to be the only constraint to production. Fig. 7 displays probabilities as a function of the maximum amount of water (MAW) available to the root system, set at values of 50 mm (representative of a vertic inceptisol), 100 mm (shallow vertisol or medium alfisol), and 200 mm (deep vertisol).

At Hyderabad (Fig. 7a), dependence on MAW is most pronounced in the intermediate range of probabilities corresponding to near-average rainfall. MAW has little effect on yield either in the "best" years (yields above the middle of the range) or in the "worst" 20%, including those in which the criterion for sowing was not satisfied. Sensitivity to MAW appears only in about one-third of seasons. In contrast, at Sholapur, sensitivity to MAW is evident from 30 to 90% probability, i.e. in two-thirds of seasons (Fig. 7b). For 10 of the 20 years in the analysis, yield was less than 1.8 to 2.0 t ha^{-1} in Hyderabad.

These figures are appropriate for high-input agriculture, represented in the model by a crop canopy intercepting 90% of incident radiation throughout most of the growing season. In the real world, lack of fertiliser, damage by pests and diseases, and poor establishment combine to keep interception to a much lower level. These constraints can be a much larger source of yield loss than depressed rates of photosynthesis associated with poor fertility and disease (e.g. Green 1987). The impact of low inputs can therefore be simulated by running the model with smaller values of fractional interception of radiation (f_i), as in Fig. 8 where the range is from 0.3 to 0.9. At both sites and with f_i = 0.3 (low inputs), yields in most years fall in a narrow range (1.4 to 1.8 t ha^{-1} in Hyderabad and 1.4 to 1.6 t ha^{-1} in Sholapur). Here, the interception of radiant energy is the dominant limiting factor. (Note that the response of the root system to shortage of inputs is not allowed for in the model. We have evidence that this is a realistic assumption both for nitrogen and for water.). At f_i = 0.6, the spread in yield is still small at Hyderabad, but is much larger at Sholapur in the 20 to 50% probability range where water as well as light is a limiting factor.

At Hyderabad, the mean rainfall during the growing season was 498 mm compared with 393 mm at Sholapur. Corresponding figures for rain falling after the crop matured were 221 mm and 291 mm, so that the annual rainfall totals at the two sites differed by less than 5%. The CVs for rainfall were an order of magnitude larger than those for radiation and for effective temperature (assessed as the number of days to reach maturity based on thermal time). The

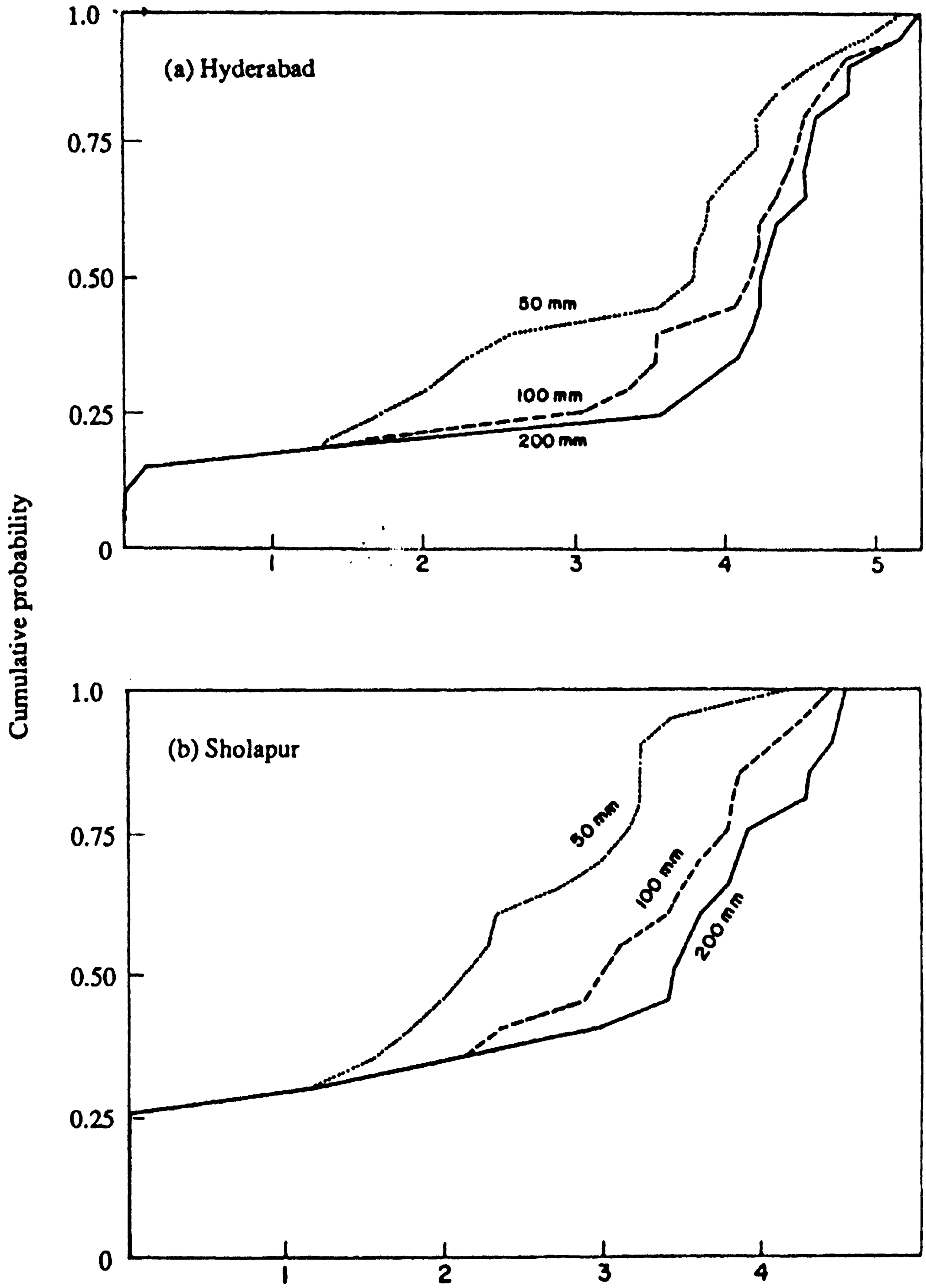

Fig. 7. Cumulative distribution functions for sorghum yield at (a) Hyderabad and (b) Sholapur, India, for three values of maximum available water, using the simplified RESCAP model.

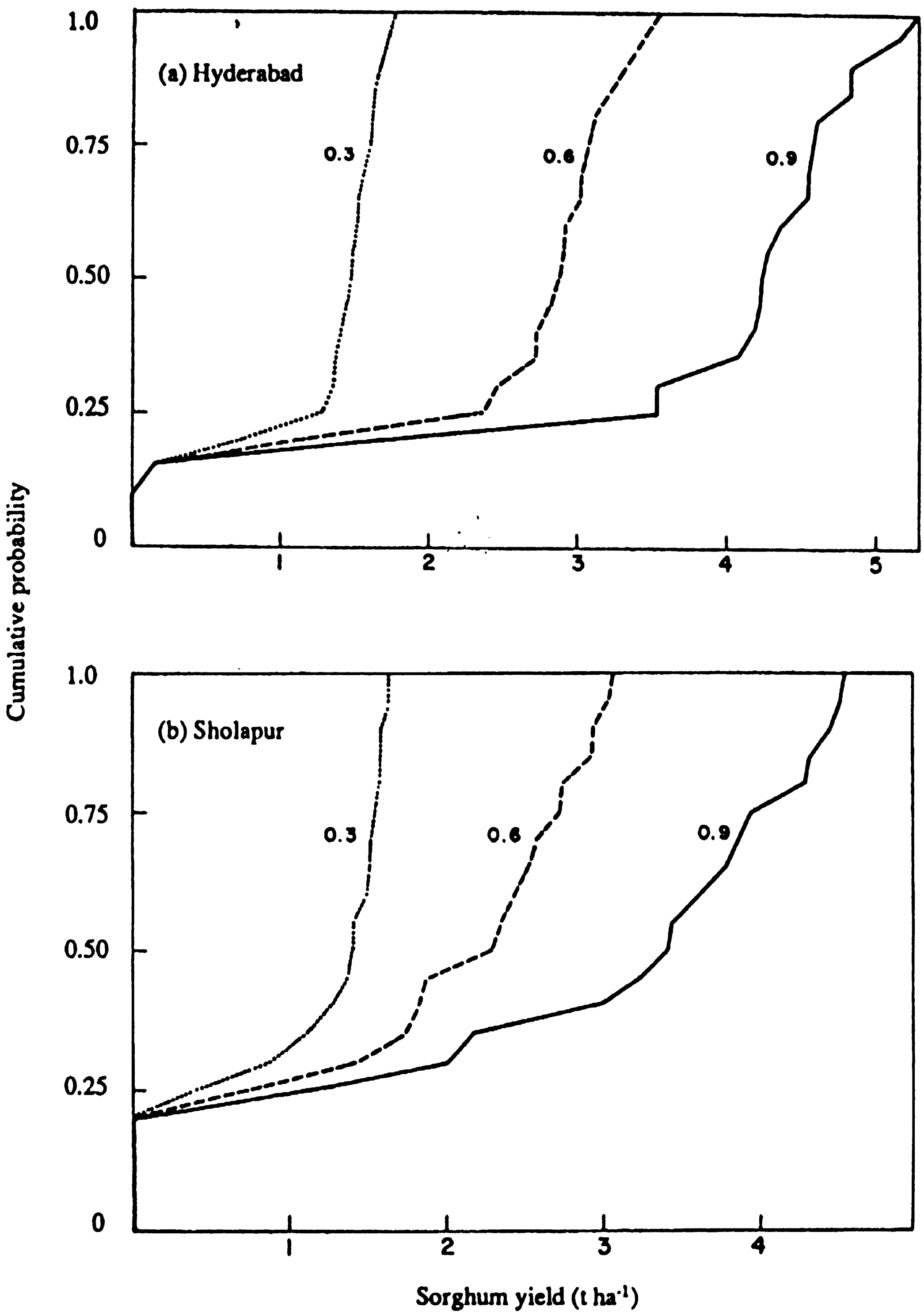

Fig. 8. Cumulative distribution functions for sorghum yield at (a) Hyderabad and (b) Sholapur, India, for three values of f_i, using the simplified RESCAP model.

CV for yield (Table 6) was somewhat larger than for rainfall because of years when conditions for sowing were not satisfied. Yield CVs were larger at Sholapur but changed surprisingly little with the value of maximum available water and intercepted radiation.

Trials at ICRISAT Center over the period 1976-1985 showed that the CV for the combined grain yield of a sorghum/pigeonpea intercrop grown on a deep vertisol was 16% compared with 26% for rainfall. This demonstrates, in regions where rainfall is dependable and soils have a good storage capacity, how risk can be greatly reduced by making use of water in the soil profile during the post-rainy season in addition to rainfall during the monsoon.

Table 6. Estimated mean yield (t ha^{-1}) and variability at Hyderabad and Sholapur as a function of maximum available water (MAW) and fractional interception of radiation (f_i).

	f_i = 0.9			MAW = 200 mm	
	MAW = 200	100	50	f_i = 0.6	0.3
Hyderabad					
Mean yield	3.6	3.5	3.0	2.4	1.3
Standard deviation	1.7	1.7	1.6	1.1	0.6
CV (%)	11.0	11.0	12.0	10.0	10.0
Sholapur					
Mean yield	2.8	2.5	2.0	1.9	1.1
Standard deviation	1.7	1.6	1.4	1.1	0.6
CV (%)	13.0	15.0	16.0	13.0	13.0

CONCLUSIONS

We have reviewed the progress of attempts to quantify the relation between climate and risk in the SAT, culminating in the development of simulation models. Choice of model is dictated by the availability of data and the nature of the application. Climate models (e.g. Hargreaves 1971; Robertson 1976) are appropriate for general surveys and preliminary agroclimatic mapping. Water balance and crop models are needed to define the length of the growing season and the dependence of yield on the interaction of weather and soil conditions.

The review has drawn attention to constraints to crop production that are often acute in the SAT, but which cannot yet be dealt with even in very large models because governing mechanisms are not fully understood. These constraints include the relation between the physical state of the seedbed and seedling establishment; the relation between root penetration and the bulk density and composition of soil, especially the presence of cracks and of stony layers; damage to root systems by nematodes and other soil organisms; the interaction of nutrients and water; fungal diseases depending on microclimatic conditions and on the vigour of the host plant; and virus diseases carried by insect pests whose trajectories and life cycles are strongly related to weather over a wide range of scales.

This is a formidable list. Modelling risks to crop production is a much greater challenge in tropical than in temperate agriculture - and is more urgent in terms of the need to increase and stabilise food supplies in regions where, despite the rigours of the environment, populations are expanding rapidly. We believe this challenge cannot be met until modelling and measuring are more tightly coupled. Experimenters need to be guided by the framework of knowledge already provided by the discipline of modelling. Modellers should constantly try to simplify components of models already shown to be robust in order to make way for components based on new information from the field. More emphasis is also needed on the stochastic use of models, an activity stimulated in a timely and effective way by this symposium and the discussion it has generated.

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APPENDIX 1.

Monthly rainfall (mm) at Hyderabad, India, 1980-1989.

Year	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.	Annual
1980	0	4	17	7	18	141	127	306	153	6	0	2	782
1981	16	0	77	3	2	203	209	218	287	155	2	0	1170
1982	0	0	0	34	38	193	155	69	180	59	12	0	739
1983	0	0	13	0	47	87	211	305	287	132	1	17	1099
1984	5	1	21	31	0	92	172	148	99	80	6	0	655
1985	2	0	20	31	19	89	173	46	76	93	0	8	558
1986	53	44	0	35	0	118	131	231	57	0	37	6	713
1987	4	0	2	6	30	143	144	98	62	149	240	1	879
1988	0	4	0	100	16	122	256	273	247	2	0	7	1026
1989	0	0	76	6	31	99	416	109	286	27	0	6	1055
Mean	8	5	23	25	20	129	199	180	173	70	30	5	868
SE	5	4	9	9	5	13	27	31	31	19	24	2	66
CV	208	256	131	118	82	33	43	55	56	86	251	116	24

APPENDIX 2

Simplified RESCAP Model

This model is based on daily calculations of the soil water deficit and on the gross assumption that dry matter production proceeds at a potential rate determined by radiation except when the deficit is equal to the water available in the root zone. In this case, the rate is zero. Other assumptions used to estimate growth and water use of sorghum are:

(i) Soil water content is zero initially;
(ii) The simulated crop can be sown when the rainfall total for two consecutive days exceeds 25 mm; germination occurs two days later;
(iii) Water lost by evaporation from the soil surface comes from the top 10 cm of soil; the evaporation rate is proportional to saturation deficit, to the fraction of radiation not intercepted by the canopy, and to the amount of water left in the layer. Evaporation rate therefore declines exponentially with time after wetting;
(iv) Between a depth of 10 cm and the bottom of the root zone, water is extracted by roots at a rate proportional to the rate of dry matter production which is proportional to the interception of solar radiation. For maximum production, the fraction of interception is assumed to be 0.9 from 22 days after emergence until harvest (Goudriaan and Monteith 1990); the dry matter equivalent of radiation is 1.5 g MJ^{-1} during vegetative growth and 1.2 g MJ^{-1} thereafter;
(v) The maximum soil water deficit is assumed equal to the water held in the top 10 cm of soil until 22 days after emergence and thereafter increases at a constant rate (to simulate the downward movement of the root front) until, at anthesis, it reaches the value assumed for the total amount of water "available" in the soil profile;
(vi) Percolation occurs on a day when the rainfall exceeds the water deficit in the root zone; runoff is neglected so that seasonal percolation is overestimated;
(vii) The length of each growth stage (GS) is calculated as a function of temperature using coefficients given by Huda (1987); and
(viii) Grain yield is taken as the amount of dry matter accumulated in GS 3.

The functioning of the model for a specific year at Hyderabad is shown in Fig. 9. Despite the fact that the model has few parameters that can be altered for calibration, estimates of biomass production and yield for sorghum cultivar CSH 9 agree well in most years with measurements from a long-term trial on the vertisol watershed at ICRISAT (Fig. 10). Large discrepancies occurred in years when little rain fell during seedling establishment so that the population was probably small; and when grain developed during a particularly wet spell of weather when mould would be expected. Such constraints are not incorporated even in more complex models.

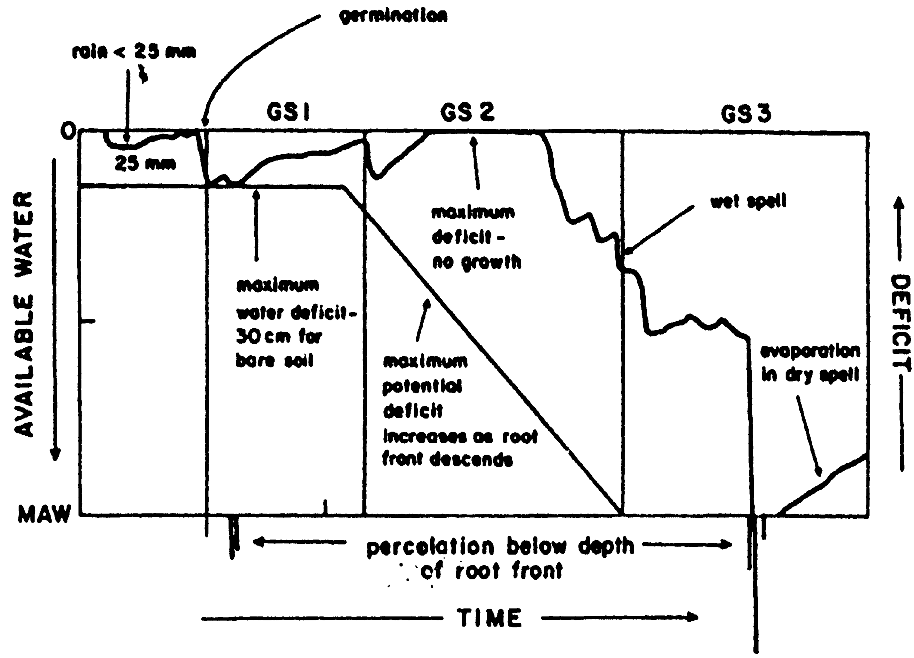

Fig. 9. Seasonal change in soil water deficit estimated for sorghum growing at ICRISAT Center using the simplified RESCAP model and climatic data for 1980.

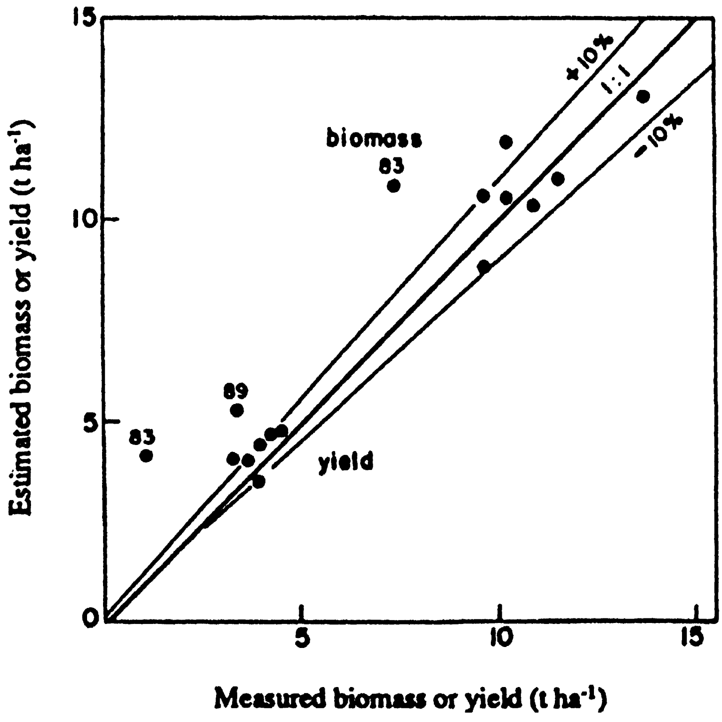

Fig. 10. Estimated and measured sorghum biomass and grain yield for cv. CSH 9 grown at ICRISAT Center from 1982 to 1989.