Drought Research Priorities for the Dryland Tropics

International Crops Research Institute for the Semi-Arid Tropics

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Cover: Screening of groundnut genotypes for drought tolerance, using a line-source sprinkler technique.

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Foreword

This book is the product of a consultants' meeting held at the International Crops Researech Institute for the Semi-Arid Tropics in Patancheru, India, on 17-20 Nov 1986. The meeting brought together specialists from a number of disciplines to discuss priorities for applied research on improving crop production in the arid and semi-arid tropics. The invitees were asked to focus on research topics with a high degree of promise for the short to medium term, with a particular emphasis on the application of existing knowledge or technology to the problems of the dry tropics.

The meeting was organized into four separate sessions, which have been retained as the four parts of this book. Parts 1 and 2 deal with more effective means of analyzing the climate of dry environments and of selecting technologies to fit the expected moisture patterns. Part 1 considers methodologies for using climate data in conjunction with soil, atmospheric, and crop data to provide a quantitative picture of crop-available moisture in dry environments. Part 2 looks at the basis of, and at methods for, fitting crops, crop and soil management systems, and crop varieties to the specific environments in which they are the most productive and/or provide the greatest stability of production.

Parts 3 and 4 consider the possibilities for modifying existing technology (management methods and crop varieties) to improve their productivity under different moisture conditions. Part 3 considers the analysis and design of crop and soil management systems, to make maximum productive use of available moisture and to reduce variability of crop production due to the variation in inter- and intra-annual rainfall. Part 4 considers the bases of plant adaptation to insufficient-moisture environments and examines specific possibilities for improving this adaptation in crop plants.

The meeting was organized to provide maximum discussion of the ideas presented by the invited consultants, and of their specific applicability to arid and semi-arid tropical environments. Each part of this book includes an interpretive summary of this discussion, prepared by an invited chairman for each session. These summaries present both a framework and a philosophy of research for the general topic of each part, as well as specific areas of promise for research. They thus form the essential part of what this book attempts to accomplish.

While changes in agricultural production in the dry tropics will not be as rapid or as dramatic as those that have occurred in irrigated or in high-rainfall areas, there is still considerable promise in the application of new and better production technology to the resources of these areas. It is our hope that the ideas which this volume presents will help to stimulate more effective research on such technology.

We would like to express our appreciation to the other members of the meeting's organizing committee: A.K.S. Huda, C.K. Ong, J.M. Peacock, and J.H. Williams. They spent many hours in the planning and organizing of the meeting, and served as scientific reviewers for the papers. We thank the ICRISAT staff and others who contributed to the discussion periods. We would also like to thank S.R. Beckerman for his contribution as publication editor. And finally we wish to express our appreciation to the management of ICRISAT for making available the funds to hold the meeting and to publish this book, and to the consultants for the excellent papers that this book contains.

F.R. Bidinger
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ICRISAT Drought Research
Seminar Forum

Part 1.

Defining the problem: translating climatic data into moisture availability patterns usable in drought research

Possibilities and Limitations of Rainfall Analysis for Predicting Crop-available Water (Uncertainties in the Length of the Rainy Season)

G. W. Robertson[1]

Abstract

Monthly climatological data were used to determine general rainfall characteristics and to perform a simple water budget calculation. Weaknesses in the analysis are considered and a simple falling-rate soil water budget, using daily rainfall data, was used to improve the calculation of daily soil water from long -term records. These daily data were then used to calculate the probability of days with wet and dry soil, and runs of consecutive days with wet soil from which the beginning, duration, and ending of the rainy season could be calculated at various probability levels. This simple budget involves a number of assumptions and estimated parameters. Variations in these were used to evaluate uncertainties in the final agroclimatic product, such as length of the rainy season. It is proposed that complex models depending upon many assumptions and estimated parameters may be subject to too many uncertainties to be widely applicable in estimating agroclimatic factors. Further sensitivity research and testing of such models is required.

Résumé

Possibilités et limitations des analyses de la pluviométrie pour la prévision de l'humidité disponible pour une culture. (Incertitudes dans la durée de la saison humide) : Des données climatologiques mensuelles ont été utilisées pour la détermination des caractéristiques générales de la pluviométrie. Ces données ont également été utilisées pour un calcul simple du bilan hydrique. Des faiblesses de ces analyses sont examinées. Un bilan hydrique simple avec les données quotidiennes de la pluviométrie a été utilisé pour un meilleur calcul de l'eau quotidienne du sol à partir des données à long terme. Ces données quotidiennes ont ensuite été utilisées pour le calcul de la probabilité des jours avec des sols humides et secs à partir duquel le début, la durée et la fin de la saison humide pourraient être calculés à des niveaux différents de probabilité. Ce bilan hydrique simple dépend de plusieurs suppositions et paramètres estimés. Des variations des paramètres ont été utilisées pour l'évaluation de l'incertitude dans le produit agroclimatique final, tel que la longueur de la saison humide. Des modèles complexes avec beaucoup de suppositions et paramètres estimés ne pourraient être en mesure de donner des estimations des facteurs agroclimatiques susceptibles d'être largement applicables. Donc une recherche complémentaire et des essais approfondis sont requis.

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Introduction

Climatic information is a necessity for successful agricultural planning and development. Simple climatic analyses such as long-term averages of temperature and rainfall (Table 1) have been in common use for decades, but are of limited use since they mask the effect of weather variability and often do not relate directly to agricultural problems.

Weather variability, particularly the variability of rainfall from year to year, has been the subject of a great deal of study. These data have been presented in various ways, including on a monthly, decadal, and even a weekly basis (Fig. 1).

Various indices (water efficiency indices, thermal indices, heat units, etc.) were developed in early attempts to relate climatic data more closely to agricultural problems such as crop growth, yield, and production as required for land use planning and crop zonation. These usually involved accumulated temperature, some comparison of rainfall with crop water requirements, and the length of the season with favorable indices.

Mathematical models have been used more recently to calculate crop-related factors such as evapotranspiration, soil water, the development rate of crops, and crop growth, yield, and production. Such models vary in their degree of sophistication, and are based on physical characteristics of the soil and microclimate within the crop and the physiological processes taking place within the plant (Robertson 1983a and 1983b).

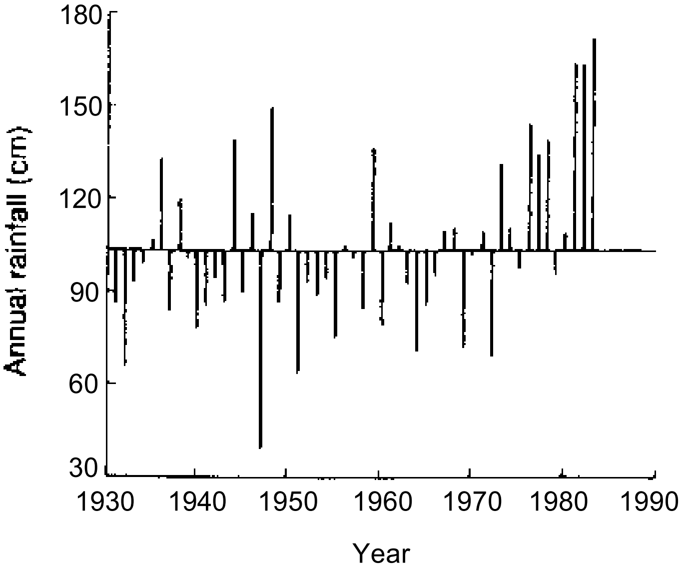

Figure 1. Annual rainfall as a deviation from the 53-year normal of 1035 mm for Chaklala, Pakistan, for the period 1931-1983.

Many of these modeling techniques, although applicable to such weather-sensitive problem areas as monitoring real-time crop conditions and studying the effect of the physical environment on the physiological response of crops, are complex and may require parameters which are not available for general agroclimatic analysis.

For agroclimatic purposes, a need has been recognized for models and techniques that fall somewhere between simple indices and the more complex mathematical models. A technique to express daily rainfall data in terms of soil water, and ultimately in terms of probability of a number of successive days with moist soil, was conceived by the author while conducting a roving seminar for WMO in 1981. This idea was later applied while working with the Pakistan-Canada Cooperative Project for Barani (rainfed) Agricultural Research and Development in Pakistan (Robertson 1984), and while preparing an agroclimatic atlas for Burma (Robertson 1985a).

This technique will be considered here, and along with daily rainfall data from Chaklala, Pakistan, will be used to examine some possibilities and limitations of rainfall analysis to predict crop-available water, including uncertainties in the derived length of the wet (growing) season with ample soil water to support crop growth.

Here we are concerned exclusively with the analysis of historical data to characterize past events in order to foretell future probabilities. This approach assumes that what has happened over some long period in the past will be repeated with similar averages and probabilities over some long period in the future. Any possibility of forecasting trends or cycles is beyond the scope of this study.

Preliminary Analysis of Climatic Information

Long-term averages of various climatic factors are generally useful in many preliminary planning exercises (Table 1). Basic information (monthly mean data) was provided by FAO from their international agroclimatic data bank. Rainfall was updated from information obtained in Pakistan, and the monthly values for PE and global energy were recalculated using modified techniques (Robertson 1985a).

This type of information indicates some of the general features of the climate but gives little or no

Table 1. Monthly mean agroclimatic factors based on historical records, and simple monthly soil water balance (soil water capacity = 100 mm) at Chaklala, Pakistan (latitude 33° 37'N longitude 73° 06% elevation 508 m).

Month	Rain (mm)	Temperature Min. (°C)	Temperature Max. (°C)	V.P. (mb)	Wind (km day^{-1})	PE[1]	Soil water balance (mm month^{-1}) AET[2]	Storage	Deficit	Surplus
Jan	66	2.7	16.3	7.9	55	31	31	35	0	0
Feb	68	4.8	20.1	8.3	77	59	59	44	0	0
Mar	85	10.3	23.6	11.7	89	93	93	36	0	0
Apr	66	14.6	29.7	12.2	98	156	102	0	54	0
May	42	20.2	35.5	13.6	103	223	42	0	181	0
Jun	57	24.4	39.7	16.3	94	243	57	0	186	0
Jul	250	24.9	35.5	25.6	89	167	167	83	0	0
Aug	309	23.8	33.2	28.0	77	140	140	100	0	152
Sep	103	21.8	33.5	23.0	62	123	123	80	0	0
Oct	27	14.4	29.8	13.8	53	99	99	8	0	0
Nov	20	7.2	24.2	9.0	53	60	28	0	32	0
Dec	23	3.4	19.1	8.0	48	34	23	0	11	0
Total	1116					1428	964		464	152
Avg.		14.4	28.4	14.8	75					

1. Potential evapotranspiration (Robertson 1985a).
2. Actual evapotranspiration (Thomthwaite 1948).

indication of the agroclimate, such as: the intensity of wet periods, the severity of dry periods, when dry and wet spells begin or end, the length of the growing season, and their probabilities.

A simple soil-water balance using long-term values of monthly rainfall and potential evapotranspiration (Table 1) gives some indication of the availability of soil water and of surplus water (Thomthwaite 1948). The simplicity of the model (equally available soil water at all soil-water potentials) renders the results questionable.

Complex Soil Water Models

To improve this simple monthly budget, Baier and Robertson (1965) developed the versatile soil water budget which involved several soil layers, a knowledge of the rooting depth and habit of the specific crop in question, a knowledge of the water-holding capacity and water-release characteristics of each soil layer, and which made use of daily data. This model has been used extensively for specific crops and studies of cropping problems (e.g., Baier 1970) and has been upgraded periodically (Dyer and Mack 1984).

Recently the model has been adapted to the specific problem of estimating soil water and actual transpiration from two interplanted crops (Robertson 1985b). This requires additional knowledge concerning row spacing, ground shading by each crop, the effect of heat advection on the potential evapotranspiration rate, and estimates of growth rates for both roots and above-ground vegetation for each crop.

Considering the large uncertainty in even the best measurement of soil water over a large area (Robertson 1973), it appears obvious that its estimation by detailed models involving many parameters of unknown certainty may be over-extending the models' complexity and ability to provide a reasonable estimate. Given this uncertainty, the results of an analysis using a relatively simple soil-water budget were used for this study (Robertson 1984,1985a, and 1985b).

Table 2. Decadal averages of rainfall, PE, soil water, surplus, and soil water extremes. Soil water values are for the fifth day of each decade (decades are the first and second 10-day periods of the month, and the last 8, 9, 10, or 11 days of the month). Soil water storage capacity is 100 mm. Data from Chaklala, Pakistan, 1960-1983.

Month		Decadal averages				Soil water extremes	
No.	Decade	Rain (mm d^{-1})	PE (mm d^{-1})	Soil water (mm)	Surplus (mm d^{-1})	High (mm)	Low (mm)
1	1	1.0	1.0	44	0.2	97	10
	2	1.7	1.0	49	0.1	100	10
	3	3.5	1.4	62	1.2	100	18
2	1	1.2	1.7	69	0.3	100	16
	2	3.3	2.1	69	0.9	100	19
	3	2.8	2.4	74	0.8	100	27
3	1	2.9	2.7	73	1.1	100	41
	2	2.8	3.0	68	0.6	100	36
	3	2.5	3.7	69	0.7	100	25
4	1	2.0	4.4	56	0.3	86	21
	2	2.9	5.2	45	0.9	96	13
	3	1.8	5.9	38	0.1	100	11
5	1	1.5	6.5	28	0.1	100	9
	2	1.3	7.2	22	0.0	69	4
	3	1.2	7.5	18	0.0	81	5
6	1	0.9	7.8	10	0.0	33	2
	2	1.6	8.1	13	0.0	52	2
	3	3.3	7.2	18	0.2	93	0
7	1	6.0	6.3	40	1.3	100	0
	2	7.4	5.4	49	2.3	100	2
	3	10.6	5.1	70	4.7	100	5
8	1	12.0	4.8	82	7.4	100	13
	2	10.5	4.5	85	6.5	100	34
	3	7.6	4.3	86	4.1	100	31
9	1	5.3	4.2	81	2.5	100	31
	2	3.4	4.1	69	0.6	96	37
	3	1.6	3.8	66	0.2	96	36
10	1	1.0	3.5	52	0.2	93	25
	2	0.9	3.2	44	0.0	76	23
	3	0.7	2.8	39	0.0	85	17
11	1	0.8	2.4	37	0.0	77	13
	2	0.8	2.0	34	0.0	94	10
	3	0.3	1.7	35	0.0	88	9
12	1	0.4	1.4	33	0.0	81	13
	2	0.8	1.1	32	0.0	86	12
	3	1.1	1.0	37	0.2	78	11

Simple Analytical System

The falling-rate soil-water budget was used to calculate daily soil water (Thornthwaite and Mather 1955). Here the rate of actual evapotranspiration is dependent on PE weighted according to the percentage of crop-available water remaining in the soil at the time the calculation is made. Daily rainfall is used and calculations are made on a daily basis. PE is assumed to vary little from year to year; most of its variation being from month to month. For this reason, long-term monthly averages of PE (Table 1) were used to calculate decadal averages (Table 2), which were used in the calculations on a daily basis. Rainfall is assumed to evaporate at the PE rate following a day of rain, regardless of the amount of water stored in the soil. A single soil layer is used, and for the purpose of this study, it is assumed to hold 100 mm of crop-available water (Robertson 1984, 1985a, and 1985b). Daily rainfall data for Chaklala, Pakistan, during 1960-1983 are used in the examples.

Long-term averages and daily extremes of calculated soil water and water surplus are summarized by decades in Table 2. Rainfall and potential evapotranspiration units are in mm d^{-1} for ease of comparison and to avoid the problem of the variable length of the last decade in the month.

The calculation of daily soil-water surplus, available for runoff or deep percolation to below the root zone, is a by-product of the daily soil-water budget. The total for the year, as calculated by this daily budget, is 380 mm, in sharp contrast to the 152 mm calculated by the monthly budget (Table 1).

Seasonal characteristics of the average soil water are clearly shown in Figure 2. Calculated daily soil water is not the desired final information. Some method must be used to summarize the vast amount of daily data generated during the calculations.

Markov Chain analysis is used for this purpose. This involves estimating probabilities of the occurrence of runs of consecutive days with wet-soil conditions, by counting the number of days with wet soil and the number of days with wet soil given that the previous day had wet soil. These frequencies are then converted to probabilities, P(W) and P(W/W) respectively. Similarly, other probabilites can be calculated such as P(D), P(D/D), P(W/D), and P(D/W) (where D is a day with dry soil) (Table 3).

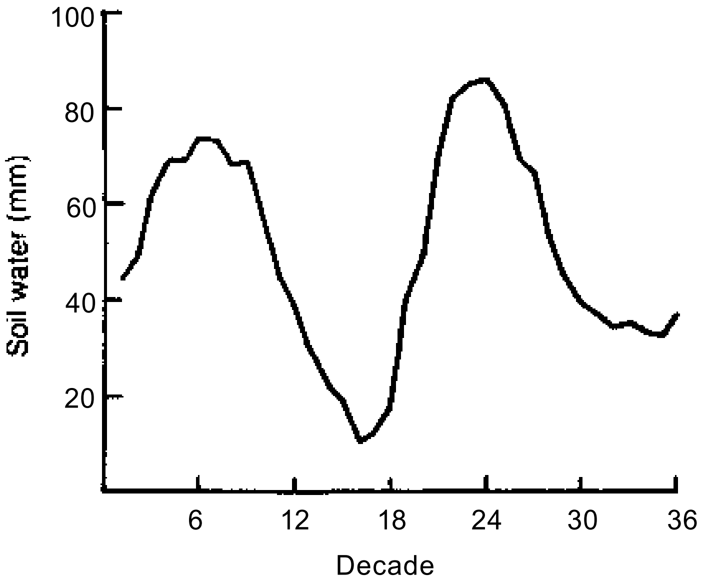

Figure 2. Average estimated daily soil water for each decade assuming a storage capacity of 100 mm. Chaklala, Pakistan, 1960-1983.

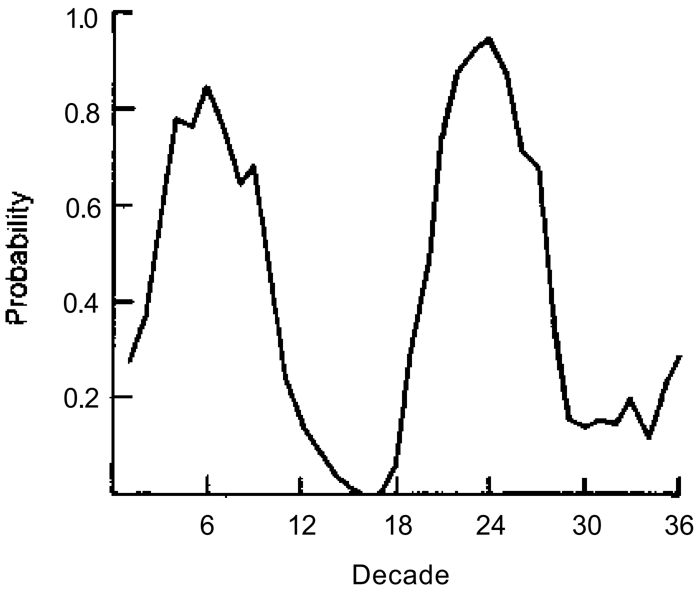

Figure 3. Probability of at least 5-consecutive days per decade with wet soil. Based on estimated soil water with storage capacity (SC) = 100 mm and threshold for wet soil = 50% of SC. Chaklala, Pakistan, for period 1960-1983.

The problem is to define the threshold soil water content dividing dry soil from wet soil. The threshold value of 50 mm used here is 50% of the crop-available water, a value frequently used in irrigation practices as the point at which irrigation should be applied.

The length of the wet (or growing) season was finally calculated using the probability values in Table 3. This is expressed in terms of the probabilities of at least one period with 5 consecutive days of wet soil during each decade. The following formula was used:

$$P(5, W) = P(W) \times [P(W/W)]^4.$$

It is assumed that a 5-day wet spell so defined during each decade will be sufficient to support productive crop growth. These decadal probabilities are shown in Figure 3. Assuming that successful farming is based on good crops being produced at least 7 out of 10 years (probability = 0.7), the length of the wet season for successful farming can be readily deter-

Table 3. Markov probabilities of daily soil water in each decade (decades are the first and second 10-day periods of the month, and the last 8, 9, 10, or 11 days of the month). Soil water storage capacity is 100 mm. Threshold soil water is 50 mm. Data from Chaklala, Pakistan, 1960-1983.

Month		Initial probabilities		Conditional probabilities			
No.	Decade	P(D)	P(W)	P(D/D)	P(W/D)	P(W/W)	P(D/W)
1	1	0.675	0.325	0.988	0.012	0.962	0.038
	2	0.638	0.363	0.975	0.025	1.000	0.000
	3	0.398	0.602	0.910	0.090	0.974	0.026
2	1	0.204	0.796	0.941	0.059	0.995	0.005
	2	0.163	0.838	0.875	0.125	0.980	0.020
	3	0.116	0.884	0.840	0.160	0.988	0.012
3	1	0.158	0.842	0.971	0.029	0.976	0.024
	2	0.292	0.708	0.957	0.043	0.977	0.023
	3	0.246	0.754	0.954	0.046	0.985	0.015
4	1	0.392	0.608	0.966	0.034	0.947	0.053
	2	0.629	0.371	0.972	0.028	0.895	0.105
	3	0.771	0.229	0.978	0.022	0.895	0.105
5	1	0.867	0.133	0.995	0.005	0.939	0.061
	2	0.913	0.088	0.995	0.005	0.833	0.167
	3	0.970	0.030	0.996	0.004	0.875	0.125
6	1	0.996	0.004	0.996	0.004	0.000	1.000
	2	0.988	0.013	0.992	0.008	0.333	0.667
	3	0.925	0.075	0.978	0.022	0.929	0.071
7	1	0.683	0.317	0.959	0.041	0.972	0.028
	2	0.483	0.517	0.886	0.114	0.940	0.060
	3	0.205	0.795	0.881	0.119	0.990	0.010
8	1	0.104	0.896	0.923	0.077	0.995	0.005
	2	0.083	0.917	1.000	0.000	1.000	0.000
	3	0.053	0.947	0.933	0.067	1.000	0.000
9	1	0.054	0.946	0.818	0.182	0.983	0.017
	2	0.175	0.825	0.875	0.125	0.965	0.035
	3	0.229	0.771	0.907	0.093	0.968	0.032
10	1	0.475	0.525	0.972	0.028	0.918	0.082
	2	0.733	0.267	0.982	0.018	0.884	0.116
	3	0.777	0.223	0.971	0.029	0.898	0.102
11	1	0.783	0.217	0.979	0.021	0.923	0.077
	2	0.804	0.196	0.990	0.010	0.938	0.063
	3	0.800	0.200	0.995	0.005	1.000	0.000
12	1	0.858	0.142	1.000	0.000	0.944	0.056
	2	0.783	0.217	0.984	0.016	1.000	0.000
	3	0.712	0.288	0.989	0.011	1.000	0.000

mined from the graph. The length of the wet seasons for both rabi and kharif crops are shown in Table 4.

Uncertainties

Even with this simplified soil water probability system there are a number of uncertainties limiting the usefulness of the results. In this study consideration will be given to the effect of varying some assumed parameters in the system and noting the effect on the probability of wet-soil days and on the resulting calculated length of the wet season.

Uncertainties in the basic data will be considered first. There are four possible sources:

1. Site representativeness involving site exposure.
2. Data management, including taking and recording observations, quality control, and archiving.
3. Length of record, if improperly selected, could result in agroclimatic uncertainties due to epochs of low, high, or variable rainfall (Fig. 1).

   In the case of Chaklala, even though data were available during 1931-1983, only those from 1960-1983 were used since this was the only period with a complete record for all sites to be analyzed in the region. This choice includes a fair sample of both dry and wet years.
4. Data reduction. If available, it is often convenient to use data that have been averaged over various time intervals such as months, decades, weeks, or pentades. The averaging process has the effect of masking dry spells and reducing or obscuring the daily peak rainfall.

   To evaluate the uncertainty arising from the use of reduced data, soil water was calculated using rainfall data that had been averaged over 7-day periods throughout the year. In order to calculate the initial and conditional probabilites of wet-soil days required for estimating spells of wet soil, it was necessary to calculate daily soil water based on a daily rainfall value that had been obtained from a running 7-day average.

Uncertainties in the soil water probability system arise because assumptions and parameter estimates are required for the model. Sources of uncertainty include:

1. Crop-available water-holding capacity of the soil (SC) depends on its depth and texture, and the rooting depth of the specific crop in question. Calculations of soil water and the resulting length of the wet season were made for two variations of SC (80 mm and 120 mm). For defining wet soil the threshold was taken as 50% of SC (40 and 60 mm respectively) (Fig. 4 and Table 4).
2. Uncertainty in the threshold defining wet soil is evaluated by considering two thresholds of + 20% of the assumed value (40 and 60 mm). SC is held constant at 100 mm. The resulting changes in the lengths of the wet periods are shown in Table 4.
3. Potential evapotranspiration may have an uncertainty in the range of ±20%. Decadal soil water values calculated by using 80 and 120% of PE, respectively, throughout the year are shown in Figure 5. The resulting lengths of the wet periods are in Table 4.
4. Representative climatological period. The study period 1960-1983 consisted of two epochs: one dry from 1960 to 1972 with an average annual rainfall of 934 mm, and a wet epoch from 1973 to 1983 with an average annual rainfall of 1326 mm (Fig. 1). This is a range of 84-119% of the average (1114 mm) for the whole 24-year period. Each epoch was analyzed separately to determine the

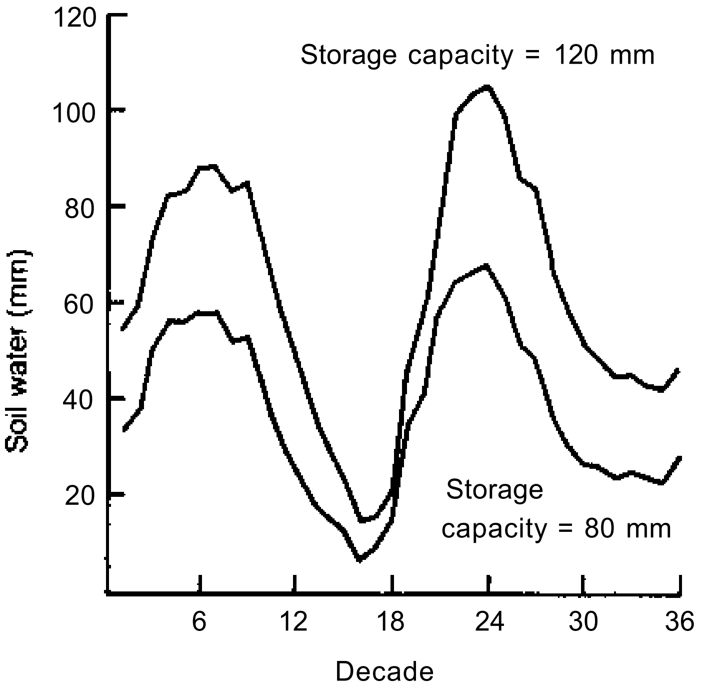

Figure 4. The effect of uncertainty in soil-water storage capacity on uncertainty in the estimated average soil-water content. As in Fig. 2 but for storage capacities of 80 and 120 mm.

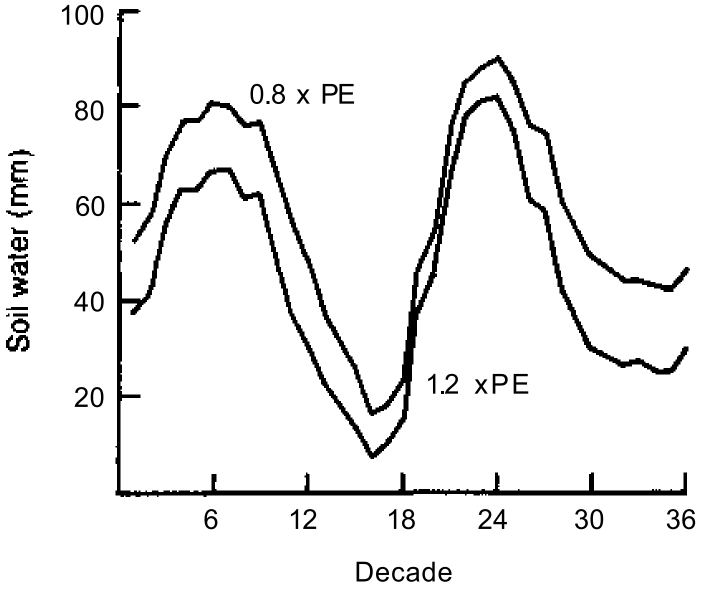

Figure 5. The effect of uncertainty in PE on uncertainty in the estimated average soil-water content. As in Fig. 2 but for alternative values of PE of 0.8 x PE and 1.2 x PE.

Table 4. Comparison of the uncertainties in the calculated minimum lengths of wet seasons at a probability level of 0.7 (based on ± 20% uncertainties in various assumed annd estimated parameters required in the analytical system). Based on daily rainfall data for Chakiala, Pakistan, 1960-1983[1].

Parameter ncertainties	Rabi (winter) season				Kharif (monsoon) season			
	Beginning	-	end	Length (days)	Beginning	-	end	Length (days)
Reference	1 Feb	-	10 Mar	37	24 Jul	-	18 Sep	56
Storage capacity								
120 mm	1 Feb	-	12 Mar	39	23 Jul	-	27 Sep	66
80 mm	1 Feb	-	7 Mar	33	28 Jul		14 Sep	48
Threshold								
60 mm				0	30 Jul	-	6 Sep	38
40 mm	26 Jan	-	4 Apr	68	21 Jul		30 Sep	71
Potential evapo-transpiration								
x 1.2				0	31 Jul	-	7 Sep	38
x 0.8	27 Jan	-	6 Apr	75	19 Jul		2 Oct	75
Epoch								
Dry (1960-1972)	12 Feb	-	3 Mar	19	31 Jul	-	17 Sep	48
Wet (1973-1983)	25 Jan	-	24 Mar	58	19 Jul		26 Sep	69
Data reduction								
Daily	1 Feb	-	10 Mar	37	24 Jul	-	18 Sep	56
Weekly				0	21 Jul		15 Sep	56

1. Unless otherwise specified, the water-holding capacity of the soil is assumed to be 100 mm and the threshold between wet and dry soil is 50% of the water-holding capacity.

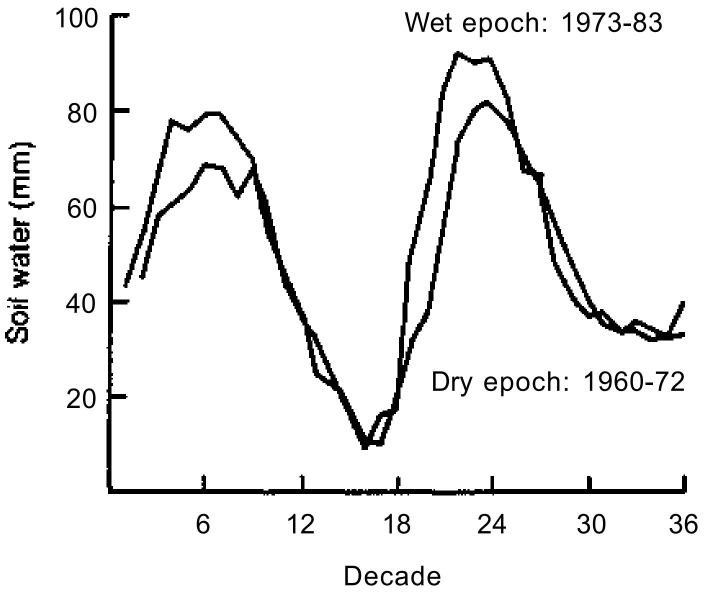

Figure 6. The effect of uncertainty in choice of epoch on uncertainty in the estimated average soil-water content As in Fig. 2 but for a dry epoch (1960-1972) and a wet epoch (1973-1983).

effect of the extreme conditions on the final estimate of soil water (Fig. 6). The resulting lengths of the wet periods are in Table 4.

Discussion

Original weather data are usually taken daily and form the basis for the calculations of all climatic and agroclimatic factors. Where yearly summaries of monthly data are available, these can be used for calculating simple long-term averages and totals and for simple monthly water-budget calculations. Such information is useful for general climatic purposes but much of the detail about wet and dry spells and extremes of rainfall are lost in the averaging process (Table 1, Fig. 1).

Land use planning, crop zonation, and other agriculture activities require specific agroclimatic information related to agricultural activities. This information includes such factors as the beginning, ending, and duration of the wet or growing season, and, among other things, the probability of spells of dry weather during the growing season. Such operationally-specific factors can be calculated by means of mathematical models which make use of simple daily rainfall observations and an estimate of monthly PE values (Tables 2, 3, and 4). The necessary daily data and models can easily be handled by microcomputers.

Although the analyses of rainfall in terms of annual patterns and seasonal probabilities may be of academic interest, it appears redundant to pursue such analysis when it is a relatively simple matter to transform rainfall into soil water (Fig. 2) from which operationally-oriented information can be derived (Table 3, Fig. 3).

Similarly, instead of attempting to characterize the dependability of rainfall, why not the dependability of soil water (Table 3) or, to use a more practical agroclimatic factor, the estimated length of the growing season (Fig. 3)?

Soil water models involve a number of assumptions and estimated parameters. Uncertainties in four of these were considered and each produced uncertainties in the final answer, i.e. , the length of the wet season expressed in days (Table 4).

Differences in the treatment of wind and global energy in Penman's formula create the largest uncertainty, PE. When estimated from observations of free water evaporation, PE is subject to large uncertainties resulting from poor design and management of the equipment, difficulties in obtaining reliable observations during very wet and very dry weather, and uncertainty in the coefficient used to reduce pan evaporation to PE. There is also some degree of uncertainty in the definition of PE and its practical application to a site-specific soil/crop evapotranspiration.

The next largest uncertainty is in the choice of the threshold soil water content at which crops suffer drought stress sufficiently to appreciably and irreversibly reduce growth. This threshold is not easily defined. In fact crops appear to suffer, to some extent, any reduction in soil water below maximum water-holding capacity, but may survive increasing stresses right down to zero water content.

Uncertainty in the representativeness of the long-term climatic data is also important. It is well recognized that annual rainfall may be subject to large variations from year to year or may be persistent from year to year (Fig. 1). The duration of epochs with variable or persistent rainfall appears to occur quite at random, and are unpredictable except in a statistical sense. Thus the recommendation that agroclimatic analysis should make use of as long a record as possible (20 or more years), remembering that for interstation comparisons, the choice of epochs with similar rainfall patterns is desirable.

Uncertainty in maximum soil water-storage capacity appears to be of lesser importance, particularly if it is assumed that the threshold soil water is a constant percentage of the maximum capacity. This is fortunate since the water-holding capacity of the soil within the crop root zone may vary greatly, even within small fields, and is extremely difficult to determine (Robertson 1973).

The average decadal soil water based on average weekly rainfall data is, in general, less than that based on calculations using daily rainfall data. The exception is during the rainy season.

The probability of at least 5 consecutive days per decade with wet soil (threshold 50%) is markedly different during the rabi (winter) season for the two data bases. There is no growing season based on calculations using weekly average rainfall data and a probability level of 0.7. Based on daily rainfall data, the length of the season is 37 days. The estimated length of the kharif (summer) growing season is the same, 56 days, for both data bases.

Total annual surplus water calculated from weekly rainfall data (312 mm) is 18% less than for calculations based of daily rainfall data (380 mm).

The use of reduced rainfall data such as weekly averages for calculating soil water can lead to uncertainties in the estimated length of the growing season and in the estimated amount of surplus water available for runoff or deep percolation. These uncertainties can be avoided by using daily rainfall data.

The number and size of the uncertainties in estimating soil water, and interpretation in terms useful for agriculture planning, renders the absolute magnitude of the final results of limited value. Nevertheless, the final results should be of greater value than attempting to interpret rainfall data per se in terms of agricultural problems. Such interpretations also involve many assumptions, most of which have larger uncertainties than those in a soil water model.

One might be tempted to suggest that results might be improved by a more complete model (Robertson, 1985b). However, models of increasing complexity will use more assumptions. This is not to say that more complex models should not be developed, but rather, such models should be subjected to sensitivity tests to evaluate all uncertainties arising from assumptions, and to show that more complex models do increase the certainty of an improved soil water estimation when compared with a simpler model.

Regional maps of the various agroclimatic factors could be prepared, but there would be many maps since only one factor can be shown on each map. Furthermore, the map preparation may produce further uncertainties from interpolation between climatological sites. It is considered more judicious to prepare detailed publications of climatic and agroclimatic factors for each site. These could be used in the field by experts to correlate and extrapolate the data by making an on-the-spot study of soils, topography, and native vegetation.

Recommendations

In spite of the uncertainties arising from several assumptions and estimated parameters in a soil water budget and in the calculation of the probabilities, the system has many advantages over the analysis of rainfall per se for agroclimatic purposes:

- It provides a systematic and objective method to express rainfall and potentional evapotranspiration data in terms directly useful to the agriculturalist. These include:
  - soil water storage;
  - an estimate of surplus water for runoff and deep percolation;
  - an estimate of actual daily crop evapotranspiration;
  - probability estimates of the beginning, duration, and end of the growing period based on wet soil;
  - probability estimates of runs of dry periods of various lengths during the growing season; and
  - probability estimates of the times and amounts of soil water deficits and crop water requirements for irrigation planning purposes.
- The analysis can be made specific for various soils, crops, and management practices by the proper choice of parameters. A canopy cover index could be introduced to provide a means for partitioning PET into ETC and ETS.
- The calculations, using daily data, can be undertaken on a microcomputer.
- Parameters and assumptions can be kept to a minimum by careful measurement and/or estimation, thus minimizing uncertain results.

Uncertainties in end results can be kept to a minimum by:

- Careful choice of basic data giving particular care to length of record and climatic trend.
- The use of daily data and daily calculations.
- Improving knowledge concerning soil profile, soil physical characteristics, and rooting habits of crops, including changes with time.
- Giving careful consideration to crop age and management practices when selecting crop parameters.

This study should be considered only a preliminary demonstration of the uncertainties of soil water budgets. It does indicate the magnitude and complexity of the problem and suggests that more detailed studies of this nature are required, using data from other sites with different rainfall amounts, variability and seasonal patterns, and using different models.

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Simplified Soil-Water Balance Models to Predict Crop Transpiration

G. S. Campbell and R. Diaz[1]

Abstract

Crop dry matter production is closely linked to the quantity of water transpired by the crop. Transpiration is one component of the water budget of the soil-plant system. The other components—precipitation, irrigation, deep percolation, evaporation from the soil surface and the canopy, and runoff—vary widely. The water available for transpiration, and therefore the dry matter production of the crop, is determined primarily by the amount of water left after other demands in the water budget have been satisfied. It is therefore necessary to consider all of the components in the water budget in order to determine the amount of water available for transpiration.

Estimates of the various components of the water budget must be based on models of soil water since direct measurement is, in most cases, not possible. We present a simple model in BASIC which uses empirical or mechanistic submodels of the components of the soil water budget. Locally derived equations or constants are easily substituted for the ones in the model, and the model is simple enough so that most users can alter it to meet individual needs. Requirements for input data and model parameters are discussed, and a sensitivity analysis of some inputs and model parameters is given.

Résumé

Modèles simplifiés du bilan de l'eau du sol pour la prévision de la transpiration des cultures : La production de la matière sèche est étroitement reliée à la quantité d'eau transpirée par la culture. La transpiration est un constituant du bilan hydrique du système sol/plante. D'autres constituants qui varient largement sont la précipitation, l'irrigation, l'infiltration profonde, le ruissellement et l'évaporation à partir de la surface du sol et du couvert végétal. L'eau disponible pour la transpiration et la production de la matière sèche est déterminée par l'eau résiduelle après la satisfaction d'autres exigences dans le bilan hydrique. Donc tous les constituants du bilan hydrique doivent être pris en compte pour la détermination de la quantité d'eau disponible pour la transpiration.

L'estimation des divers constituants du bilan hydrique doit être basée sur les modèles de l'eau du sol, la mesure directe n'étant pas possible dans de nombreux cas. Un modèle simple dans le langage BASIC qui utilise des sous-modèles empiriques ou mécanistiques des constituants du bilan hydrique du sol est présenté. Des équations ou des constantes dérivées localment sont facilement substituées pour celles données dans le modèle. Les utilisateurs peuvent adapter ce modèle simple pour des besoins individuels. Les besoins pour les données d'entrée et les paramètres du modèle sont examinés. L'analyse de sensibilité de quelques entrées et paramètres du modèle est également donnée.

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Introduction

The annual rainfall at a site is often used as an indicator of the water available for crop growth. While correlations certainly exist between the amount of rain received and the amount of water available to plants, other factors are also important. The differences in vegetation which exist between north- and south-facing slopes in mountainous terrain indicate how important factors other than rainfall are. Both slopes receive identical amounts of rain, yet the north slope (in the northern hemisphere) provides a much more mesic environment than does the south slope. The differences in plant-water relations of the two sites are the result of differences in evaporative loss, rather than differences in water supply.

The water supplied to the soil surface by precipitation or irrigation can be lost in several ways. Some of the water is intercepted by the crop canopy and the soil surface, and is evaporated without passing through the plant. If the water is supplied to the soil surface faster than it can infiltrate, the excess water may be lost as runoff. That fraction of water input that does enter the soil is either held for plant use, or drains beyond the root zone and is lost by deep percolation. Only that water which is stored in the soil, and taken up by the plant roots, is useful for producing crop dry matter. This component of the water budget is called transpiration.

The close relationship between dry matter increase in plants and the quantity of water transpired by those plants has been well documented (Lawes 1850, Briggs and Shantz 1913, and many others). Tanner and Sinclair (1983) and Monteith (1986) present the physical and physiological principles that underlie this phenomenon. Because of this close relationship, that fraction of the precipitation which is available for transpiration must be determined.

The transpirational water loss has little effect on other terms in the water budget, except, perhaps deep percolation, but transpiration is strongly affected by the other terms because it is the water left after the other components are satisfied. It is therefore necessary to determine the water loss to evaporation, interception, and runoff before reliable estimates of transpiration can be made.

Precipitation is relatively easy to measure, and is widely reported. The other terms in the water budget are much more difficult to measure, and estimates of their magnitude generally require the use of a model. It is the models for these water budget components that will be the focus of the remainder of this paper.

Modeling the Components of the Soil Water Budget

Models of the soil water budget range in complexity from simple bookkeeping methods such as that of Thornthwaite and Mather (1955), to complex computer models such as that described by Norman and Campbell (1983). Models that are intermediate in complexity, are those of Retta and Hanks (1981), Ritchie (1972), Saxton et al. (1974), Reddy (1983), Stockle and Campbell (1985), and Stockle (1985). While these models differ in detail, they all use soil and environmental data as input, and various empirical or physical relationships to estimate the loss terms in the soil water budget. The inputs, rain and irrigation, are assumed to be known in all cases. The water budget components that are modeled include runoff, evaporation from the soil, transpiration, interception, deep percolation, and moisture storage in the soil.

In order to structure this discussion, we have produced the simple, BASIC model (Fig. 1). This model incorporates what we consider to be the best features of the water budget models previously mentioned. Where possible, mechanistic, rather than empirical approaches have been used, but high priority has been given to keeping the model simple. One-day time steps are used, and minimal soil, plant, and atmospheric data are required for input.

We will first consider each of the model components, then examine model response to changes in some input variables. Finally, we will consider alternatives that could give improved performance and discuss the additional information that would be required to use such models.

Interception

Of the rain that falls on the crop, part is intercepted by the canopy foliage, and is evaporated without entering the soil or the plant. The actual amount that is intercepted depends on the fractional ground cover and the storage capacity of the canopy for water. We will assume that the fractional

Figure 1. Example of a BASIC program for computing a soil water budget.

```
10NL=11 'NUMBER OF SOIL LAYERS
20 DIM DZ(NL), WC(NL), SPSI(NL), F(NL), TMAX(365), TMIN(365), PRECIP(365)
30 FC=.25: PWP=9.00000IE-02: ADWC=.02  'FIELD CAPACITY PWP AND AIR DRY WC
40 RMIN=100000!:PSIPWP=-1500:PSIFC=-30  'ROOT RES, WP AT PWP, WP AT FC
50 AX=.7:BX=.0026:CX=2.4  'CONSTANTS FOR SOLAR RAD. CALC.
60 PLDA=119:EMDA=130:MTDA=180  'PLANTING, EMERGENCE AND MATURITY DATES
70 RDMAX=2 'MAXIMUM ROOTING DEPTH - METERS
80 KC=.4  'AVE DAILY CANOPY TRANSM. COEFF. FROM RITCHIE (1972)
90 DWR=50 'DRY MATTER WATER RATIO - KG DM-G/M3/M H20, TANNER & SINCLAIR (1983)
100 S=. 1: 'SURFACE STORAGE CONDITION - METERS OF WATER
110 PI=3.14159: LA=.84  'LATITUDE IN RADIANS
120SUMTRANS=0:SUMEVAP=0:SUMRUNOFF=0:SUMINT=0:SUMPRECIP=0
      :SUMDRAIN=0:AT=0
130 TDM=.003:CDM=TDM  'TOP AND CANOPY DRY MATTER AT EMERGENCE
140  DZ(1)=.1:  WC(1)=FC:    DZ=RDMAX/(NL-1)
150 FOR 1=2 TO NL
160    DZ(I)=DZ:  WC(I)=FC     'START AT HELD CAPACITY
170 NEXT
180 OPEN "WHEAT2.DAT" FOR INPUT AS #1:  M=1
190 WHILE NOT EOF(1)
200    INPUT  #1,  TMAX(M),TMIN(M),PRECIP(M)
210    PRECIP(M)=PRECIP(M)/1000: M=M+1:
220 WEND
230 CLOSE:   M=M-2
240 FOR I=1 TO M: DA=I+PLDA
250   'SOLAR RADIATION AND POTENTIAL EVAPOTRANSPIRATION CALCULATION
260    DEC=.39785*SIN(4.869+.0172*DA+.03345*SIN(6.224+.0172*DA))
270    X=-SIN(LA)*SIN(DEC)/(COS(LA)*COS(DEC))
280    HA=PI/2-ATN(X/SQR( 1-X*X))
290    PSR=117.5*(HA*SIN(LA)*SIN(DEC)+COS(LA)*COS(DEC)*SIN(HA))/PI
300    DT=TMAX(I)TMIN(I)+TMIN(I+1))/2:TAVE=(TMAX(I)+TMIN(D)/2
310    TR=AX*(1-EXP(-BX*DT^CX))
320    SOLAR=TR*PSR:PRECIP=PRECIP(I):SUMPRECIP=SUMPRECIP+PRECIP
330    ETP=.000014*(TAVE+3)*SOLAR
340   'CALCULATION OF MAXIMUM ROOTING DEPTH
350    RD=RDMAX*(1/(1+44.2*EXP(-8.5*(DA-PLDA)/(MTDA-PLDA))))
360   'CALCULATION OF DRY MATTER, LAI AND FRACTIONAL INTERCEPTION
370    VDD=(TMAX(I)-TMIN(I))*((.00109*TAVE+.011)*TAVE+.35)
380    IF DA<=EMDA THEN GOTO 420
390    TDM=TDM+AT*DWR/VDD  'PRODUCE DRY MATTER FROM ACTUAL TRANSP.
400    IF AT/PT>.95 THEN CDM=CDM+AT*DWR/DD  'GROW CANOPY
410    CDM=CDM*(.8+.2*AT/PT)        'SENESCE        CANOPY
420    LAI=4/(1+.24/CDM)
430    FI=1-EXP(-KC*LAI)
440   'PARTITION ETP INTO PE AND PT
450    PE=(1-FI)*ETP: PT=FI*ETP
460   'RAIN INTERCEPTION CALCULATION
```

Continued...

Figure 1. *Continued.*

```
470   IF PRECIP=0 THEN GOTO 630
480   INTLOSS=.001*FI  '1 MM INTERCEPTION PER RAIN EVENT
490   PRECIP=PRECIP - INTLOSS:  IF PRECIP<0 THEN PRECIP=0
500   SUMINT=SUMINT+INTLOSS
510  'RUNOFF  CALCULATION
520   IF PRECIP<=.2*S THEN RUNOFF=0
        ELSE  RUNOFF=(PRECIP-.2*S)^2/(PRECIP+.8*S)
530   PRECIP=PRECIP -  RUNOFF:SUMRUNOFF=SUMRUNOFF+RUNOFF
540  'INFILTRATION CALCULATION
550   J=1
560   WHILE (PRECIP>0) AND (J<=NL)
570     IF PRECIP<=(FC-WC(J))*DZ(J) GOTO 590
580     PRECIP=PRECIP-(FC-WC(J))*DZ(J): WC(J)=FC: GOTO 600
590     WC(J)=WC(J)+PRECIP/DZ(J): PRECIP=0:
600     J=J+1
610   WEND
620   IF PRECIP>0 THEN SUMDRAIN=SUMDRAIN+PRECIP
630  'EVAPORATION  CALCULATION
640   IF WC(1)<PWP THEN PE=PE*((WC(1)-ADWC)/(PWP-ADWC))^2
650   NWC=WC(1)-PE/DZ(1)
660   IF NWC<ADWC THEN NWC=ADWC
670   SUMEVAP=SUMEVAP+(WC(1)-NWC)*DZ(1):WC(1)=NWC:
680  TRANSPIRATION  CALCULATION
690   RBAR=RMIN/FI
700   B=LOG(PSIPWP/PSIFC)/LOG(FC/PWP):A=EXP(LOG(-PSIFC)+B*LOG(FC))
710   AVEPSI=0:   Z=0
720   FOR J=2 TO NL   'NO TRANSPIRATION FROM LAYER  1
730     Z=Z+DZ(J):    SPSI(J)=-A*EXP(-B*LOG(WC(J)))
740     IF Z<=RD THEN  F(J)=DZ(J)*(2*(RD-Z)+DZ(J))/(RD*RD):GOTO 770
750     IF (Z>RD) AND (Z-DZ(J)<RD) THEN F(J)=((RD-Z+DZ(J))/RD)^2:GOTO 770
760     F(J)=0
770     AVEPSI=AVEPSI+F(J)*SPSI(J):
780   NEXT
790   PSIX=AVEPSI-RBAR*PT
800   IF PSIX<PSIPWP THEN PSIX=PSIPWP
810   AT=0
820   FOR J=2 TO NL
830     LOSS=F(J)*(SPSI(J)-PSIX)/(RBAR*DZ(J))
840     IF WC(J)-LOSS<PWP THEN LOSS=WC(J)-PWP
850     AT=AT+LOSS*DZ(J):  WC(J)=WC(J)-LOSS
860   NEXT
870   SUMTRANS=SUMTRANS+AT
880   PRINT  I,TDM,SUMTRANS,SUMEVAP,SUMINT
890 NEXT
```

Figure 1. Example of a BASIC program for computing a soil water budget.

interception of precipitation by the canopy is the same as the fractional interception of radiation (FI), which will be discussed later. Storage capacities of canopies vary depending on the leaf angle distribution of the canopy and surface properties of leaves and shoots. Rutter (1975) gives some typical values of surface storage.

Interception is calculated in lines 460-500 of Figure 1. A typical value for interception of 1 mm has been assumed. This, multiplied by the fractional interception, FI, is subtracted directly from rainfall, and the remainder is passed on to the runoff calculation.

Runoff

The runoff model we used is based on the work of Stewart et al. (1976), and is similar to the model used by Saxton et al. (1974). It is semi-empirical, and is based on the assumption that runoff increases as daily precipitation increases, once the precipitation is greater than some value representing initial infiltration and surface storage.

The algorithm is in lines 510-530 of Figure 1. The parameter S is the surface storage condition, and is set in line 100. Some values for S, from Stewart et al. (1976), are given in Table 1. The relationship between rainfall and runoff, which is used in line 520, is plotted in Figure 2. Any runoff is also subtracted from precipitation, and the remainder is available for infiltration.

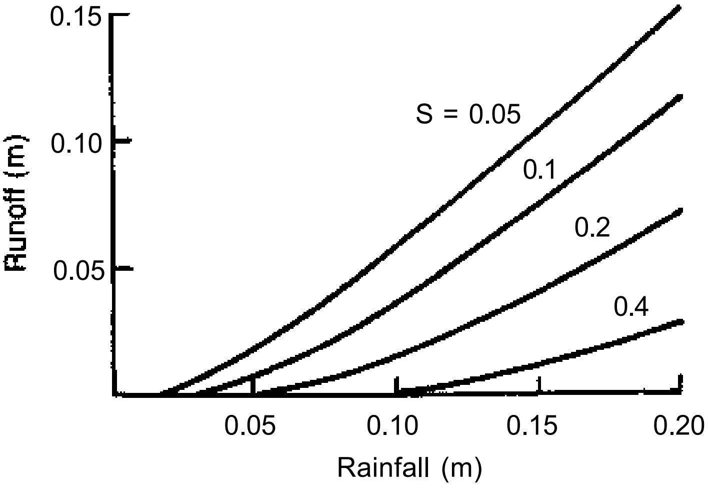

Figure 2. Runoff as a function of rainfall for several S values (Stewart et al. 1976).

Infiltration and Deep Percolation

We use an infiltration algorithm similar to that of Retta and Hanks (1981). The soil is divided into layers, and each layer is assumed to fill to field capacity and then pass on any remaining water to the layer below. Any water which passes beyond the bottom layer is assumed lost to deep percolation. No upward movement of water in the soil profile is allowed.

The calculation takes place in lines 540-620 of Figure 1. The water content (m^3 m^{-3}) of each layer is WC(J), and FC is the field capacity water content of the soil profile, set in line 30. This is to be determined from field measurements, and is the water content of the wetted layers several days after a heavy rain or irrigation, when evaporation from soil and water uptake by plant roots has been prevented. The layer thicknesses are DZ(J). Starting from the soil surface, each layer is checked. If there is enough storage capacity to hold the amount of water in PRECIP, then the water content of that layer is increased by that amount and PRECIP is set to zero (line 590). If there is not enough storage in a layer to hold PRECIP, the layer water content is increased to FC, and the water stored in that layer is subtracted from PRECIP (line 580). Line 620 designates any extra water which could not be stored in the soil as deep percolation or drainage.

Potential Evapotranspiration and Partitioning of Potential ET

One of the most important calculations in a soil water budget is that of potential evapotranspiration (ETP). It is also important to know how this is partitioned between potential transpiration (PT) and potential evaporation (PE) at the soil surface.

Several methods have been used in water budget models to estimate ETP. Saxton et al. (1974) and Retta and Hanks (1981) use daily pan evaporation. Van Keulen (1975) uses the Penman evapotranspiration equation. Stockle and Campbell (1985) and Stockle (1985) use the equation of Priestley and Taylor (1972). Thornthwaite and Mather (1955) use the temperature-based Thornthwaite calculation.

We chose to use a simple, solar radiation- and temperature-based equation from Campbell (1977). The equation is on line 330 of Figure 1. The equa-

Table 1. Runoff parameter, S, calculated from Stewart et al. (1976) assuming antecedent moisture condition I.

Land use	Treatment[1]	Hydrologic condition	Runoff parameter (m) for hydrologic soil groups[2] A	B	C	D
Fallow	SR	—	0.17	0.10	0.06	0.04
Row crops	SR	poor	0.22	0.14	0.08	0.06
	SR	good	0.28	0.16	0.10	0.07
	C	poor	0.24	0.15	0.11	0.08
	C	good	0.30	0.19	0.13	0.10
	C&T	poor	0.29	0.20	0.14	0.13
	C&T	good	0.34	0.23	0.16	0.14
Small grain	SR	poor	0.30	0.18	0.11	0.08
	SR	good	0.33	0.19	0.12	0.09
	C	poor	0.33	0.20	0.13	0.10
	C	good	0.36	0.21	0.14	0.11
	C&T	poor	0.36	0.22	0.15	0 13
	C&T	good	0.39	0.24	0.16	0.14
Close-seeded legumes or rotation meadow	SR	poor	0.29	0.17	0.10	0 07
	SR	good	0.41	0.22	0.14	0.10
	C	poor	0.32	0.19	0.12	0.10
	c	good	0.47	0.25	0.16	0 12
	C&T	poor	0.33	0.21	0.14	0.12
	C&T	good	0.56	0.28	0.18	0.14

1. Treatments: SR, straight row; C, contoured, and C&T, contoured and terraced.

2 Hydrological groups:

A. Soils having high infiltration rates even when thoroughly wetted and consisting chiefly of deep, well- to excessively drained sands or gravels. These soils have a high rate of water transmission

B. Soils having moderate infiltration rates when thoroughly wetted and consisting chiefly of moderately deep to deep. moderately well to well-drained soils with moderately fine to moderately coarse textures These soils have a moderate rate of water transmission.

C. Soils having slow infiltration rates when thoroughly wetted and consisting chiefly of soils with a layer that impedes downward movement of water, or soils with moderately fine to fine texture These soils have a slow rate of water transmission.

D. Soils having very slow infiltration rates when thoroughly wetted and consisting chiefly of clay soils with a high swelling potential, soils with a permanent high water table, soils with a claypan or clay layer at or near the surface, and shallow soils over nearly impervious material. These soils have a very slow rate of water transmission.

tion can be derived from the familiar Penman equation by assuming that vapor deficit is highly correlated with net radiation, so the vapor deficit term might reasonably be combined with the net radiation term, giving the Priestley-Taylor formula. The net radiation is strongly correlated with incoming short-wave radiation, so ETP can be written as the product of a temperature-dependent term and the solar radiation. The constant, 0.000014, in line 330, gives ETP in meters of water when solar radiation is in MJ m^{-2}. The value given is for moderate advection, and could decrease substantially in humid regions. The calculation from line 260 to 320 computes the solar radiation from latitude, time of year, and maximum and minimum temperature data. The algorithm of Bristow and Campbell (1984) is used for this calculation.

It is a simple matter to substitute pan evaporation or some other algorithm for ETP in place of the one used here. Where a locally calibrated ETP equation exists, such an equation would likely be preferable to the one given in lines 250-330 of Figure 1.

Potential ET is partitioned into PE and PT using a method similar to that of Ritchie (1972). The potential transpiration is assumed to be the fractional interception, FI, times ETP. Potential soil evaporation is assumed to be the remainder of ETP. This calculation is on line 450 of Figure 1. The fractional interception is calculated from canopy dry matter in line 430. The relationship shown between canopy dry matter and leaf area index in line 420, is that used by Stockle (1985) for spring wheat, and may need to be altered for other species and planting densities.

Models such as those of Saxton et al. (1974) and Retta and Hanks (1981) require that estimates of the crop cover be provided as input to the model. Production of canopy dry matter is, however, strongly influenced by the availability of soil water. We therefore felt that it was important to have the model grow the crop as well as use the water. The statements at lines 360-410 calculate dry matter production from transpiration and vapor density deficit using the equation of Tanner and Sinclair (1983). Vapor density deficit is calculated as the product of the slope of the saturation vapor density function and the difference between maximum and minimum temperature. Actual vapor deficit data should be used in place of this calculation, if available.

Total dry matter increases in direct proportion to water loss, but we assume that canopy growth occurs only when actual transpiration is greater than 95% of potential (line 400). Line 410 is an empirical function which gradually senesces the canopy when drought stress occurs. This function was chosen to simulate the data reported by Stockle (1985) for wheat. Some modification may be needed for other crops.

Evaporation from the Soil Surface

Water evaporation from the soil surface is one of the most important components in the water budget in arid and semi-arid climates. This is probably best simulated using models like those used by Norman and Campbell (1983) and Stockle (1985), which solve the finite difference equations for water flow in the soil to determine evaporation. These, however, run too slowly and are too complicated for our purposes here. The approach shown in lines 630-670 of Figure 1 behaves similarly to finite difference models, in that it simulates both first- and second-stage drying, but runs faster and is simpler to implement. It is similar to the approach used by Reddy (1983) for bare soil evaporation. Reddy assumed that evaporation proceeds at the potential rate until the water content in the surface 10 cm of soil reaches the permanent wilt percentage. He then uses an empirically determined equation to calculate the actual evaporation rate from the potential rate, the time since wetting, and soil characteristics. We used Reddy's assumption for first stage evaporation, but chose a simpler approach for the second stage. We assumed that the fraction of potential evaporation is equal to the square of the remaining evaporable water. This limits evaporation in about the way that it is limited by second-stage drying in soil.

The main uncertainty in this approach results from the depth of the soil layer chosen for evaporation. In sandy soils, this should probably be less than 10 cm, and in clay soils it should be more. Some adjustment may therefore be necessary to fit particular soils.

Transpiration, Root Growth, and Root Water Uptake

Perhaps the most important component of the water budget, from the standpoint of crop production, is transpiration. It is therefore important that this component be simulated as realistically as possible. When soil water is freely available, transpiration is at the potential rate. The factors determining this rate were previously discussed. Water becomes available to the plant through water movement to the roots and root growth to intercept water. Correct simulation of both of these processes is necessary for correct prediction of water uptake when soil water becomes limiting.

Root growth is simulated as suggested by Borg and Grimes (1986) using a sigmoidal function. We refit their data using a logistic equation which, we feel, is the correct functional form for a growth process (they used a sine function). The approach, however, is similar, in that we represent the fraction of maximum root depth in terms of the fraction of time from planting to maturity. The equation is on line 340 in Figure 1. Planting date, maturity date, and maximum root depth are parameters supplied by the user for a particular crop in lines 60 and 70.

The root water uptake equations are based on the algorithm of Campbell (1985). The soil is divided into several layers (line 10 in Fig. 1), and the uptake from each layer is assumed directly proportional to the difference in water potential between the soil in that layer and the xylem, and inversely proportional to the root resistance in that layer.

The root resistance is proportional to the fraction of roots in a given layer. We assumed that rooting density decreases linearly with depth, so that the fraction of roots in a layer depends only on the root depth. These calculations are in lines 740-750 of Figure 1, where F(I) is the fraction of the root system in each layer. Soil resistance to water flow is assumed negligible.

The soil water potential is computed from the water content using a power equation fitted to the field capacity and permanent wilt water contents. Field capacity water potential is assumed to be -30 J kg^{-1}, and permanent wilt -1500 J kg^{-1}. These are set in line 40. The water contents at field capacity, permanent wilt, and air dryness must be entered for the soil being modeled (line 30). The coefficients for the power equation are calculated in line 700, and then the water potential of each layer is determined in line 730. The water potentials, weighted by the rooting fractions for each layer, are summed in line 770. This weighted average water potential is the potential of a uniform soil profile which would supply water at the same rate as the actual soil-root system. Using this potential, the potential transpiration rate, and the total root resistance, RBAR, an estimate of the xylem water potential, is calculated in line 790. The total root resistance is assumed to decrease as the plant grows so that water supply and demand are balanced. This is achieved in line 690 by dividing the minimum resistance (set in line 40) by the fractional interception.

The limitation to water uptake is accomplished in line 800 by preventing the xylem water potential from going below the permanent wilt water potential. Once a value for the xylem water potential has been found, water uptake from each layer and new water content of the layer are calculated in lines 820-860. Roots are assumed absent from the top 10 cm of soil.

Input Data Requirements

The data that need to be supplied by the user are shown at the beginning of Figure 1. Required weather data includes daily maximum and minimum temperature (°C) and precipitation (mm). The data are read from a file in lines 180-220. The precipitation is converted to meters of water in line 210.

Soils data are shown in line 30. These are the water contents at field capacity, permanent wilt, and air dryness. These are best obtained from field observations. Cassel and Nielsen (1986) describe several methods for determining these values.

The minimum root resistance is chosen such that the xylem water potential is around 2/3 of the permanent wilt water potential when the soil water potential is near zero and potential transpiration is near maximum. The value 2/3 is chosen so that the plant will start to limit water uptake when the leaf water potential is close to the permanent wilt potential. The root resistance is usually around 2/3 of the total resistance to water flow through the plant, so when the xylem potential is 2/3 of permanent wilt, the leaf water potential will be at permanent wilt. In Figure 1, line 40, RMIN is 1000 J kg^{-1} divided by 0.01 m.

Other information required for the simulation is planting date, emergence date, and maturity date (line 60), and maximum rooting depth (line 70). These are supplied from field data.

Examples and Model Sensitivity

It is difficult to discuss model performance and its sensitivity to assumptions in general terms because the sizes of the water budget components depend so heavily on the input data. Here we will present the model response to one set of input data, for which

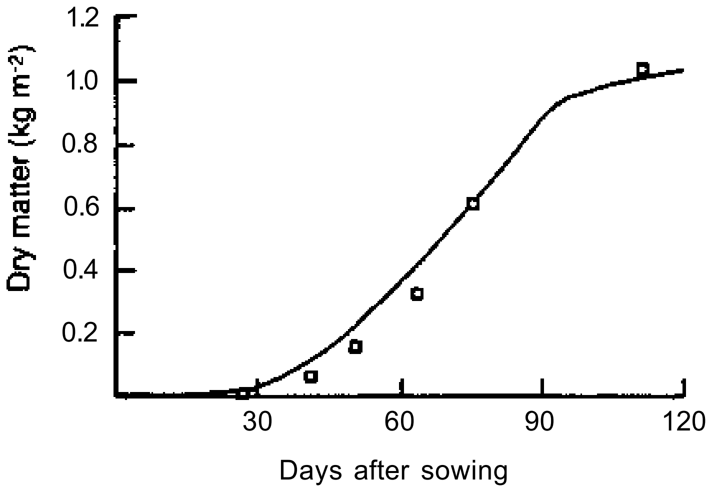

Figure 3. Modeled (line) and measured (points) top dry matter production for wheat at Davenport, Washington, USA, 1983.

field verification is available. Since the model is simple, and runs on a microcomputer, readers are encouraged to try to program their own data. The program in Figure 1 was written in BASICA on an IBM PC. It is, however, easily adapted for other computers.

Table 2 shows the input data used for the simulation. This was taken from the study by Stockle (1985), and represents temperatures and precipitation at Davenport, Washington, USA during the summer of 1983. Figure 3 compares above-ground dry matter production predicted by the model with measured values. Cumulative evaporation and transpiration are also shown along with cumulative rainfall (Fig. 4). Figure 5 compares modeled with measured soil water profiles. These results indicate that the model is performing satisfactorily. The soil water profiles predicted by this model do not agree as well with measured values as do those simulated using Stockle's more detailed model. We feel, however, that the agreement is good enough for most water budget calculations.

It is not feasible to test the model sensitivity to all parameters and assumptions, and such a test, even if it were possible, would apply only to the particular input data set used for the test. It is useful, however, to determine the sensitivity to some key parameters. Some key model parameters are the advection correction in the potential evapotranspiration calculation (ETP), maximum rooting depth (RDMAX), depth of the soil layer from which evaporation occurs (DZ(1)), the canopy extinction coefficient (KC), the dry matter to water ratio (DWR), maturity date (MTDA), and available water capacity of the soil (FC-PWP).

When model values are decreased by 10%, the percentage change in simulated total dry matter, transpiration, and soil evaporation is about as one would expect (Table 3). Dry matter production is very sensitive to DWR and moderately sensitive to RDMAX and available water, both of which determine the amount of water used by the plant. Transpiration is sensitive mainly to root depth and available water, the factors which determine the total water available for growing the crop when summer rainfall is limited. Evaporation is most sensitive to

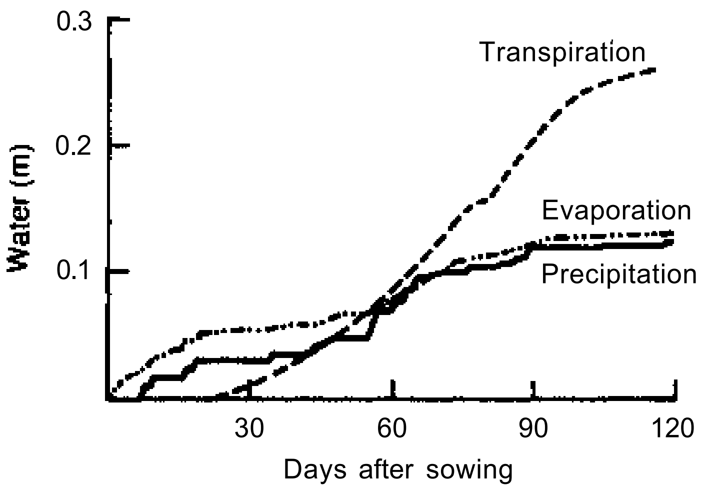

Figure 4. Precipitation, and modeled transpiration and soil evaporation at Davenport, Washington, USA, 1983.

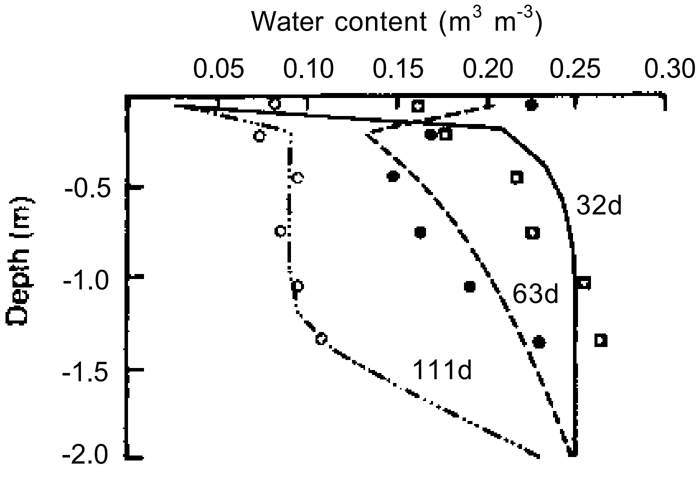

Figure 5. Modeled (lines) and measured (points) soil water distribution on days 32,63, and 111after sowing at Davenport, Washington, USA, 1983.

Table 2. Weather data used as input for simulation trials, summer 1983 at Davenport, Washington, USA.

Day	Temp (max) (°C)	Temp (min) (°C)	Prcp (mm)	Day	Temp (max) (°C)	Temp (min) (°C)	Prcp (mm)	Day	Temp (max) (°C)	Temp (min) (°C)	Prcp (mm)
119	17.2	1.1	0.0	161	22.8	10.0	1.3	203	26.7	11.1	0.0
120	18.9	1.1	0.0	162	11.7	3.3	4.8	204	30.0	15.6	5.1
121	20.0	3.3	0.0	163	17.8	6.7	0.0	205	28.3	15.0	1.5
122	19.4	1.7	0.0	164	20.0	5.6	1.5	206	26.1	12.8	0.0
123	15.0	0.6	0.0	165	23.9	9.4	0.0	207	20.6	6.7	7.0
124	15.6	1.7	0.0	166	27.2	8.9	3.3	208	21.7	7.8	0.0
125	16.1	4.4	0.0	167	20.0	4.4	0.0	209	20.0	10.6	0.0
126	18.3	5.0	9.7	168	21.7	9.4	0.0	210	23.9	8.3	0.0
127	13.3	5.0	0.0	169	23.9	3.3	0.0	211	28.9	10.6	0.0
128	13.9	0.0	8.4	170	18.9	1.1	0.0	212	32.2	14.4	0.0
129	11.7	-2.2	0.0	171	18.3	3.3	0.0	213	31.1	15.6	0.0
130	11.1	0.6	0.0	172	18.9	6.1	0.0	214	31.7	12.2	0.0
131	14.4	1.1	0.0	173	20.0	6.7	0.0	215	29.4	10.6	0.0
132	18.3	1.7	0.0	174	24.4	10.6	13.0	216	30.6	11.7	0.0
133	18.3	1.1	0.0	175	15.0	5.0	8.9	217	32.2	10.6	0.0
134	20.6	1.1	0.0	176	18.9	3.9	0.0	218	35.0	11.7	0.0
135	18.9	5.0	6.1	177	23.3	11.7	0.0	219	36.1	14.4	0.0
136	14.4	2.8	0.0	178	24.4	12.8	0.0	220	34.4	18.3	0.0
137	13.9	1.7	6.1	179	23.9	6.1	6.1	221	32.2	17.8	0.0
138	18.9	3.3	0.0	180	26.7	11.1	2.5	222	33.9	20.0	0.0
139	17.8	1.1	0.0	181	17.8	6.7	6.9	223	32.8	11.1	1.8
140	19.4	5.0	0.0	182	20.6	8.9	0.5	224	22.2	6.7	0.0
141	26.1	7.2	0.0	183	17.8	7.2	8.6	225	25.6	10.0	0.0
142	23.9	5.6	0.0	184	21.7	3.9	1.5	226	30.0	11.7	0.0
143	28.3	8.3	0.0	185	25.6	7.8	0.0	227	31.1	10.6	0.0
144	26.7	6.1	0.0	186	26.1	12.8	0.0	228	31.1	8.9	0.0
145	28.9	7.8	0.0	187	27.2	13.9	0.0	229	29.4	10.6	0.0
146	30.0	7.2	0.0	188	23.3	12.2	0.0	230	30.0	8.3	0.0
147	28.9	10.0	0.0	189	23.9	9.4	2.8	231	29.4	10.0	0.0
148	32.8	12.8	0.0	190	17.2	6.1	0.0	232	30.6	7.2	0.0
149	28.3	15.6	0.0	191	21.1	7.8	0.0	233	27.8	5.0	0.0
150	30.6	18.9	0.0	192	23.3	10.6	0.0	234	29.4	10.0	0.0
151	30.6	11.1	0.0	193	29.4	12.8	0.0	235	26.1	15.6	0.0
152	25.6	6.7	0.0	194	22.8	13.3	0.0	236	20.6	10.6	1.3
153	23.9	9.4	4.8	195	18.3	5.6	4.8	237	21.7	11.1	0.0
154	20.0	5.6	0.0	196	18.9	6.7	0.0	238	26.7	12.8	1.5
155	23.9	5.0	0.0	197	17.2	10.0	0.0	239	31.1	12.2	0.0
156	24.4	5.6	0.0	198	20.0	8.3	0.0	240	26.7	13.9	0.0
157	25.6	7.2	0.0	199	25.6	10.0	0.5	241	28.3	13.9	0.0
158	25.6	8.9	0.0	200	30.0	11.1	0.0	242	27.8	14.4	0.0
159	28.3	10.6	0.0	201	28.9	11.7	0.8	243	29.4	15.0	0.0
160	29.4	9.4	0.0	202	23.3	6.7	0.0				

Table 3. Percentage change in top dry matter (TDM), transpiration (TRANS), or soil evaporation (EVAP) due to a 10% change in the indicated component.

Component	Total dry matter	Transpiration	Evaporation
ETP	5.5	0.8	0.0
RDMAX	6.0	8.5	0.0
DZ[1]	-0.4	-0.8	3.2
KC	5.4	2.7	-2.4
DWR	12.6	1.5	-1.6
MTDA	-0.2	-0.4	0.0
FC-PWP	5.9	8.5	1.6

the depth of the surface layer, which determines how much of the water from rain is stored for evaporation.

Alternatives

Many alternative water budget models are available. Several have been mentioned already. Models that are simpler than the one presented here treat the entire root zone as a reservoir for water, and include various assumptions about water availability. Data requirements are similar to those used here. Those that are more complex generally use finite difference solutions to the soil water flow equations, and operate in hour time steps, rather than daily steps. The most complex models, such as that of Norman and Campbell (1983), include details of heat and moisture transport within the canopy. These models require information about thermal and hydraulic properties of the soil, and, of course, require hourly meteorological data (although this is often estimated from daily values). In addition to temperature and rainfall data, wind and solar radiation must also be input. A severe limitation to the use of these complex models is the availability of the input data that are required.

There appears to be little advantage in simpler models over the one presented here, since input data requirements are similar for both, and models that simulate root growth and canopy development are substantially better than those that ignore these. By the same token, this model makes a number of simplifying assumptions that could limit its accuracy. Time has not permitted comparisons of this model with the more complex models, but such comparisons need to be made.

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Interpreting the Results from Simulated Drought Experiments

R.D. Stern[1]

Abstract

In many countries interannual rainfall differences are a major cause of yield variation. An experiment conducted at ICRISAT investigated the effect of water shortage on groundnut yields. This is used as a case study to outline methods by which results from such experiments may be related to sites and seasons other than where the experiment was conducted. For any given site the methods range from a simple summary of the climatic records to the incorporation of the experimental results in a detailed crop-growth model.

Résumé

Interprétation des résultats des essais sur la sécheresse simulée : Des fluctuations interannuelles dans la pluviométrie sont une cause majeure de la variation des rendements dans beaucoup de pays. L'expérience décrite a été effectuée par l'ICRISAT pour étudier l'effet du déficit hydrique sur le rendement des arachides. L'expérience utilisée en tant qu'une étude de cas est une aide à l'esquisse de certaines méthodes qui donneraient des applications des résultats à partir de telles expériences à d'autres sites et à d'autres saisons. Les méthodes pour un site donné varient d'un résumé simple des données climatiques à l'incorporation des résultats expérimentaux dans un modèle de croissance détaillé de la culture.

Introduction

Climatic variability is accepted to be a major cause of the interannual variability of crop yields in all environments. In the tropics, rainfall is the major climatic factor whose variability affects farming practices and crop yields. It is therefore important for experimenters to try to include 'rainfall amount' as a factor in experiments. Field experiments that manipulate the water balance for different treatments are difficult to organize. Pallas et al. (1979) describe a rooflike structure on a fixed track which moves to protect plots when there is rain, coupled with a 3-m barrier of sheet metal and gravel to prevent groundwater movement. An alternative strategy is illustrated by Williams et al. (1986). They applied irrigation treatments in an experiment planted in the dry season where almost all the water was provided by irrigation. This latter experiment is described briefly in the next section. The main objective of this paper is to discuss methods by which climatic records can be used when examining the results from such an experiment.

Experimental Details

This groundnut experiment is fully described in Williams et al. (1986), and Nageswara Rao and Williams, personal communication), which is denoted W/NR in the remainder of this paper. The experiment was actually 12 separate experiments, each of which had a different drought pattern (P1

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ICRISAT (International Crops Research Institute for the Semi-Arid Tropics). 1988. Drought research priorities for the dryland tropics (Bidinger, F.R., and Johansen, C., eds.). Patancheru, A.P. 502 324, India: ICRISAT.

to P12). There were two factors within each experiment, genotype and drought intensity, and each experiment was replicated three times. Within each replicate there were 22 genotypes and 8 irrigation levels. The irrigation was provided by a combination of uniform and line source sprinkler irrigation. The line source sprinkler irrigation provided the different irrigation amounts, which was a factor that varied systematically across eight levels.

Figure 1 (from Williams et al. 1986) gives the 12 drought problems and indicates further points that will be relevant to the methods considered here. The crop was irrigated uniformly for the first 30 days after sowing to ensure crop establishment and a fully charged soil profile, which had a water-holding capacity of approximately 100 mm. For example, treatment P2 consisted of uniform irrigation for all but the period from 58 to 83 days after sowing. During the 'drought period' irrigation was from the line source sprinkler, so that the plots nearest the sprinkler continued to receive adequate irrigation, while the furthest plots received practically no water.

It is important to distinguish between two levels of analysis for this experiment. They correspond roughly to a within and between site analysis. The first level is a separate analysis of the yields for the

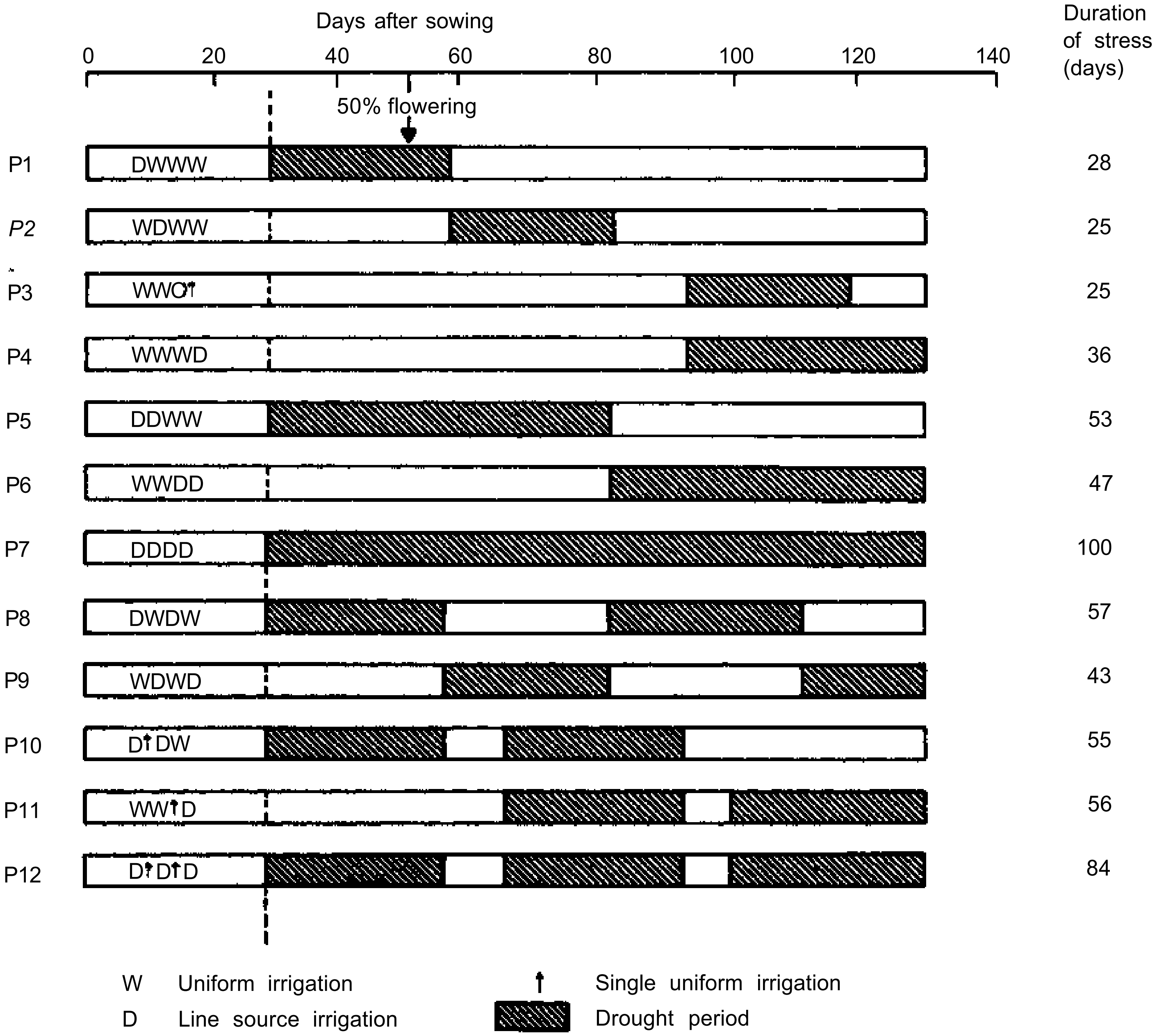

Figure 1. Timing and duration of drought treatments applied in W/NR experiments (Williams et al. 1987).

different genotypes under different drought intensities for each drought pattern (Williams et al. 1986). Their results indicate differences in the sensitivity of different genotypes to drought stress and a statistically significant genotype by drought pattern interaction, although this F value is low compared with that for the main effect of the different genotypes (Nageswara Rao and Williams, personal communication).

The second level is an overall comparison of the different drought patterns (Nageswara Rao and Williams, personal communication). They analyze the mean yield for the 22 genotypes and consider primarily regression equations for this mean yield against a drought index based on the irrigation deficit given. These equations are compared informally for the different drought patterns, but this comparison is not particularly hampered by the lack of replication of the drought patterns for two reasons. The first is that sites close to the sprinkler received adequate water throughout the season in all patterns. Differences between those results were not significant, giving some confidence that the different areas in the overall experiment are similar for the crop. The second reason is that some of the differences described in W/NR are very large and hence are clearly all that were required for the researchers to be confident they represent a true difference.

Both levels of analysis considered the same drought index, which was defined as

$$X = 100(1 - I/E) \qquad (1)$$

where

X = percentage water deficit,

E = cumulative pan evaporation for the period of drought, and

I = cumulative irrigation applied for the period of drought.

This drought index varied from 30% to almost 100% deficit for each of the patterns because it was calculated only over the relevant drought period. The actual amount of water deficit (entire crop season) varied considerably between patterns because the drought period for these patterns ranged from 25 to 100 days.

Using the Climatic Data

There are various methods by which climatic data can be used to put the results from experiments such as the one described into a larger climatic perspective. W/NR emphasize that the detailed results from their experiment should not be extrapolated to different seasons or sites without due caution; however they also claim that the relative effects of the different irrigation deficits within a drought pattern should be repeatable across environments, and that this allows constructive use of their information. As an example, data from Hyderabad are considered. Daily rainfall data from Hyderabad are available for 70 years (1901-70) and daily class A pan evaporation data for the ICRISAT site are available for 1974-83. The methods suggested below could, however, also be used with data from any other site.

This extrapolation of results from designed experiments to 'real life' is a common problem. For example, many fertilizer experiments are conducted at research institutes. A survey of farming practices might initially establish what fertilizer levels are actually used by farmers, then a study of their yields could be used to assess the extent to which the experimental results are consistent with those observed in the field. What is attempted here corresponds to the initial exercise: an assessment of the frequency with which different drought patterns occur in practice.

The method of analysis of the rainfall data is considered first. The choice is between a simple summary of the actual data and fitting a model to the daily records from which data can be simulated. The modeling approach would have to be used where there are only short records or where climate change is suspected and hence records from many years ago may not demonstrate current drought patterns. There are also some questions considered below which would benefit from the modeling approach, even when a long record is available. There are many papers on methods of fitting models to daily rainfall records, for example Stern and Coe (1984). However, with 70 years of rainfall data available, we chose simplicity and consider only direct summaries of the actual records.

Initial Analysis of the Climatic Data

It is assumed that a summary of the rainfall data has been made, perhaps on a 10-day basis, and that there is some information on when the crop is sown in the rainy season. Data from Doorenbos and Pruitt (1984) are used here to define growth stages in a 130-day groundnut crop. Four growth stages are assumed to be 30, 30, 40, and 30 days, respectively. When a fixed sowing date is considered, it is for illustration taken to be 20 June, but in a full study a variety of dates would be considered. It is useful initially to examine a few years of data; Figure 2a shows the water balance for 1967-70 using a very simple daily water balance equation:

$$W_{in}=W_{1(n-1)} + R_{in} - 0 \le W \le 100 \qquad (2)$$

where

W_{in} and R_{in} are the available soil water and rainfall, respectively, on day n in year i; and

E_{in} is the evaporation on day n.

W_{in} is set equal to 0 or 100 mm if it goes outside this range. The maximum value for W of 100 mm is for consistency with W/NR.

The results from Figure 2a permit an informal assessment of how a 130-day groundnut crop might fare. There are sufficient rains (30 mm) for planting in June in 3 of the 4 years (not 1969), although in each year the crop might experience some stress before the soil profile fills in July. The crop might experience some midseason stress in 1968 and possibly 1967, while there is little rain at the end of the season for the crop sown in 1969.

The experiment described in W/NR was not concerned with stress in the first stage of growth. If their experiment had been conducted in the rainy season all treatments would have had a full soil water profile on 19 Jul (if sowing was assumed to be on 20 Jun). This is illustrated for the same 4 years in Figure 2b. This has relatively little effect on possible problems later in the season, because the soil profile often fills up at about this time anyway. An exception is 1968; the midseason problems may be less in such a year assuming a full profile on 19 Jul, than they would be without this assumption (Figs. 2a and 2b).

Table 1 gives a general indication of the proportion of years when the total rainfall may be inadequate. For consistency with W/NR, the percentage water deficit, X, is calculated using the equation (1) but with the cumulative irrigation replaced by the total rainfall. There is a 40% or greater water deficit in about 1 year in 5 (80% of the cumulative distribution) in the middle of the season (Periods 2 and 3). The worst deficit is about 70%. The end of the season (Period 4) often experiences a considerable deficit. Half the years have a deficit of 49% or more and a few years have no rainfall at all. This type of result indicates that relatively few years at Hyderabad experience the most extreme droughts conducted in the experiment of W/NR until the end of the season. This might not be the case at other sites where the rainfall pattern is more bimodel. It should be noted that the problem may be underestimated in Table 1 because equation (1) makes no allowance for runoff.

W/NR found there was an increase in drought sensitivity following a single irrigation in the middle of a drought period. A more detailed analysis of the rainfall data would indicate the percentage of years in which such events occur, and when during the year they are likely. This type of detailed query is one that would benefit from the long records that could be simulated after fitting a model to the daily rainfall data.

Using a Crop Water Model

A more detailed assessment of the problems of growing a groundnut crop is possible using a crop water model. Crop models vary tremendously in

Table 1. Maximum percentage rainfall deficit accruing at 50,80, or 100 percentage points of the cumulative distribution of years for Hyderabad, 1901-70. Data are presented separately for each of the four growth periods.

Cumulative distribution percentage points	Maximum rainfall deficit (%) by growth period			
	Period 1 20 Jun-19 Jul	Period 2 20 Jul-18 Aug	Period 3 19 Aug-28 Sep	Period 4 29 Sep-28 Oct
50%	35	0	0	49
80%	61	39	36	86
100%	77	70	76	100

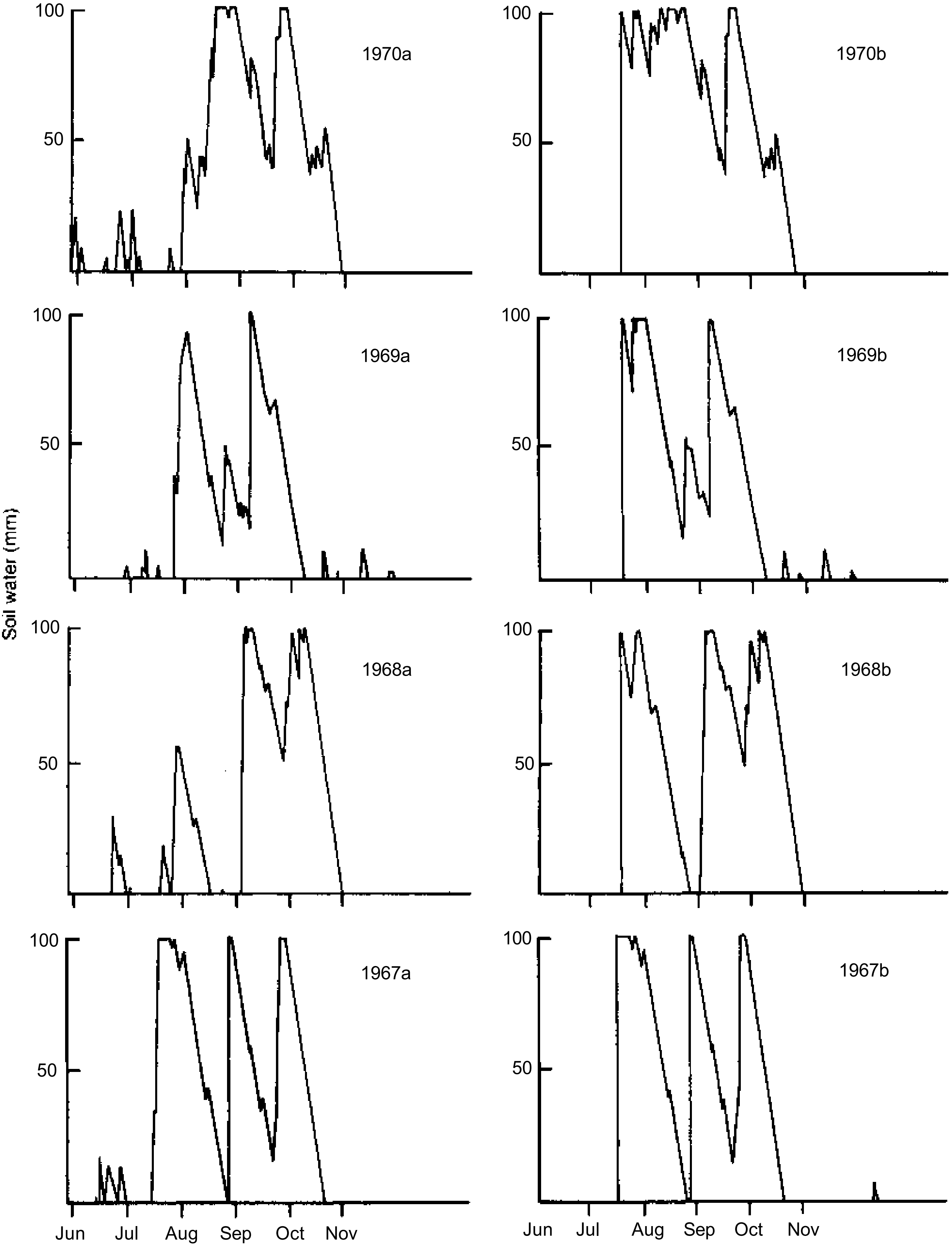

Figure 2. Water balance at Hyderabad for 1967-70 using equation (2). (a) Unconditional (b) conditional on a full profile on 19 Jul (30 days after assumed sowing on 20 Jun).

their complexity. Here we consider only the simplest possible model. It is effectively a water budgeting scheme, from Frere and Popov (1979).

Table 2 illustrates the use of this model for the data in 1969. For simplicity the budget is taken on a 10-day basis. Sowing is assumed to be in the first decade in June with more than 30 mm rainfall and the total available soil water is assumed to be 100 mm. The yield index is initially 100 and remains at this value until there is a water deficit, when it is decreased by the percentage deficit as a fraction of the total (seasonal) water required. For example in the third decade in October the crop has 16 mm less water than it requires. With a total water requirement of 422 mm, the decrease in the index is 16/422 x 100 ≃ 4. The index is therefore reduced by 4 units from 95 to 91.

Table 2 confirms the simple water balance plot given in Figure 2, which indicates that this is the most difficult of the 4 years plotted. In fact the other 3 years all finish with an index of 100. All the years in the 70-year data set in which the index dropped below its initial value of 100 are given in Figure 3. This figure indicates both the sowing decades in each year and the decades in which the model predicts some crop stress.

The combination of this type of result with the experimental data of W/NR can indicate what a decrease in the index might correspond to in terms of reduced yield. An overall summary of the results (Table 3) shows that, with the 30 mm criterion, sowing was possible in June in 59 of the 70 years and took place by the second decade in July in all years. The index dropped to below its initial value

Table 2. Water budget (Frere and Popov 1979) for groundnut at Hyderabad, 1969. Total water requirement is 421 mm.

	Jun			Jul			Aug			Sep			Oct			Nov
Decade	1-10	11-20	21-30	1-10	11-20	21-30	31-9	10-19	20-29	30-8	9-18	19-28	29-8	9-18	19-28	29-7
Rainfall (mm)	6	13	23	33	23	119	16	8	57	137	12	12	0	21	12	0
PET (mm)	118	87	80	68	66	50	44	48	45	45	47	41	46	54	46	47
Crop coeff.	—	—	—	0.3	0.3	0.4	0.5	0.7	0.9	1.0	1.0	1.0	1.0	0.6	0.6	0.6
Water requirement (mm)	—	—	—	20	20	20	22	33	40	45	47	41	46	32	27	28
Soil water (mm)	—	—	—	13	16	100	94	69	86	100	65	36	0	0	0	0
Surplus/ deficit (mm)	—	—	—	0	0	15	0	0	0	77	0	0	-10	-12	-16	-28
Index				100	100	100	100	100	100	100	100	100	98	95	91	84

Table 3. Summary values for the Frere and Popov Index for Hyderabad, 1901-70.

		Soil capacity 100 mm		Soil capacity 60 mm	
Sowing decade	Frequency	Proportion of years with index <100	Mean index	Proportion of years with index <100	Mean index
June I	19	0.63	95	0.68	93
June II	21	0.33	97	0.76	94
June III	19	0.58	95	0.89	89
July I	8	0.88	91	1.00	82
July II	3	-	100	1.00	97
Overall	70	0.53	95	0.81	91

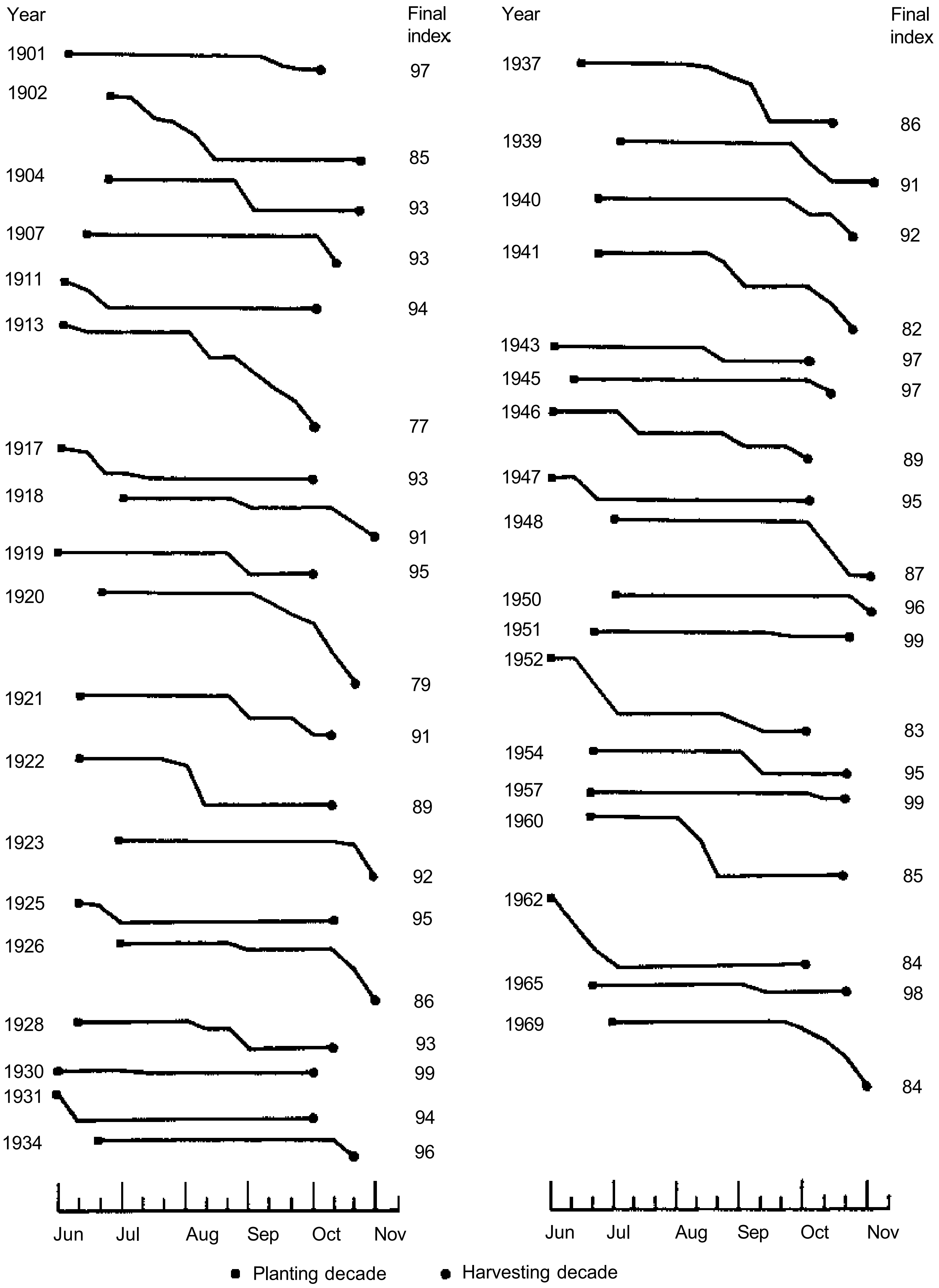

Figure 3. Index for a 130-day groundnut crop at Hyderabad in years for which the index dropped from an initial value of 100 (after Frere and Popov 1979).

of 100 in half the years with an overall mean of 95. The extent to which the value of the final index is related to the planting decade is not clear from the data, and the facilities to simulate a longer record would be welcome to examine this aspect in more detail.

Even with such a simple index it is useful to examine the sensitivity of the results to some of the values of the index parameters. As an example, Table 3 also gives the corresponding results for the 70 years if the assumed water-holding capacity is only 60 mm. The index is sensitive to this value; in this case, 80% of the years finish with an index of less than 100. The differences in the two sets of results are on average greater in those years in which planting was relatively late.

A third run of the index was made with an assumed fixed planting date of 20 Jun and a full water profile (of 100 mm) for the first 3 decades (corresponding to W/NR's experimental conditions). In this case the overall mean index was as high as 97 and it dropped below 100 only in 16 of the 70 years.

Conclusions

There is currently a role for both simple and sophisticated models of crop growth and yield to put results from experiments such as W/NR into perspective. In addition, the direct summary of climatic records (Table 1) can provide useful information. The mapping of an area for drought risks at different stages in the growing season will become easier to interpret if results from experiments such as W/NR can be used to indicate some of the consequences of timing and duration of droughts. In constructing meaningful maps it is important to use the same years of record for all sites wherever possible. This is another area where the initial modeling of the daily records is valuable because it permits useful analysis using shorter records, particularly if the objective is to compare risks at different sites.

Crop indices such as Frere and Popov (1979) are currently being used for modeling purposes in a number of countries. It would be of interest to compare the values for this index on W/NR's climaticArrigation data with their observed yields. This would give users more information on the types of drought conditions which can be modeled sensibly by such a simple index. This index includes crop information only indirectly via the crop coefficients in each period; hence detailed comparisons of different genotypes could not realistically be helped much by this type of model.

Alternatively, the results from W/NR could be used to refine a physiologically based model of groundnut growth. Such models should eventually provide an effective method of synthesizing research results in a way that is transportable to different sites, particularly those for which sufficient climatic and soil data are available.

The final element required is crop data from the growing season. The study by Bunting et al. (1982) of groundnut yields at Kano shows the value of long series of yield data even if such series are only available for a few sites.

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Interpretive Summary of Part 1:

Calculated Soil-Water Balances as Tools to Evaluate Crop Performance in Drought-prone Regions

J.J. Landsberg[1]

Introduction

This report is a synthesis based on the three review papers (Robertson 1988, Stern 1988, and Campbell and Diaz 1988) and the discussions that followed their presentation. The objectives are to organize and summarize this information in order to provide recommendations for drought research in the arid and semi-arid tropics.

To evaluate probable crop performance in relation to available soil water in the semi-arid tropics, we need to determine how crop productivity is related to water use, and how crops are affected by water shortage. The first section of this paper deals with crop growth in relation to water use and availability, and the second with the detailed water-balance models needed to calculate crop water use and responses to drought periods. To evaluate the likely success of crops in drought-prone environments, we need quantitative descriptions of the patterns and probability of water availability in those environments, as well as the crop water use and growth models that can be used in conjunction with those descriptions.

No attempt has been made to define all the terms and explain all the concepts used in this paper; it is assumed that the reader will be familar with these, and most are explained in more detail elsewhere in this publication.

Crop Growth in Relation to Water Use

In selecting crop species and cultivars for drought-prone areas, decisions have to be made about whether to emphasize yield stability so that the farmers are guaranteed some acceptable—but probably modest—yield in all but the very worst years, or maximum yields in good years. As background to the discussion on these choices and the options that can be offered to plant breeders, it is necessary to examine some aspects of crop growth in relation to water availability.

It is now well established (see, for example, Sinclair et al. 1984) that dry matter production per unit water transpired by plants (WUE) is approximately constant in a given atmospheric environment. Futhermore, WUE multiplied by the vapor pressure deficit of the air (D) is also approximately constant for particular crops (see Squire et al. 1986). These relationships provide a convenient means to model potential crop productivity, but good quality data are required to quantify them for many of the crops grown in arid and semi-arid regions. They also explain why higher-yielding varieties are likely to be more vulnerable to severe drought.

The amount of the water supplied by rainfall

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that is transpired by a crop will depend on the distribution of the rainfall over the growing period of the crop, the water holding-characteristics of the soil, and the extent to which the crop roots can exploit the soil. However, the most important factor is likely to be the extent to which the crop-growth cycle matches the growing season, as defined by the period for which the soil is wet enough to sustain physiological activity.

If there is a good match between the growing season requirements of a crop and the available soil water, and WUE and D values are appropriate, potential dry matter production can be immediately estimated. As a first approximation, assuming no drought periods *during* the season, the water used by a crop is season length x average transpiration rate, where season length takes account of water stored in the soil after the rains have stopped. It is an estimate because of uncertainties in the calculation of transpiration (as opposed to evapotranspiration, which includes the water lost by evaporation from the surface of the soil when wet), and of course uncertainties in the value of WUE and the applicability of D for different periods. These relationships explain why the likelihood of failure is greater with higher-yielding crops: high yields are likely to be associated with longer growing seasons, hence greater drought risk before the end of the season. Failure is also more likely from crops that have been bred for maximum yield rather than for tolerance to periods of water shortage during the growing season.

There appears to be little opportunity to manipulate WUE, but the ratio of grain mass to total (above-ground) biomass—the harvest index—may be altered by plant breeding (as with wheat) or affected by growing conditions. In crops where the most important part is the vegetative component (for fodder), a shortened growing season will simply mean less fodder. If the most important yield component is grain, then reduction of the growing season may lead to inadequate grain filling and hence significantly lower yields (reduced harvest index). The magnitude of the lower yield will depend on the ability of the crop to tolerate drought stress.

Crop growth and productivity will be affected by drought during the season as well as at the end of it. Early stage drought—shortly after establishment—may cause high seedling mortality, and hence reduced plant populations. It will also slow development of leaf area, which will reduce yield potential because of reduced energy interception and photosynthesis, even if conditions in the rest of the growing season are optimal. Drought stress at periods such as floral initiation, anthesis, and seed set will also reduce grain yield. The quantitative definition of drought stress at these periods must be in terms of particular combinations of root zone soil water content and potential transpiration rate, and their effects on the physiological processes that govern growth.

The study of physiological processes must be a vital component of any experimental approach to the evaluation of the drought effects at different growth stages on final crop yields. Peacock and Sivakumar (1986) discuss some of the physiological measurements that should be made, including visual assessments of drought effects at various growth stages, quantitative measures—such as relative water content and plant water potential—of the degree/intensity of stress, and measurements of stomatal conductance. An important objective must be to determine the point where soil water becomes limiting to growth—determined by the point where physiological processes are essentially halted. If transpiration can be measured directly, or estimated indirectly through stomatal conductance measurements, the ratio of actual to potential transpiration can be estimated. It is argued that the onset of stress occurs when this ratio falls to about 0.6-0.7, but this needs experimental testing. It is also important to evaluate the capacity of plants to recover from severe drought stress.

From such information, coupled with growth analysis, models can be developed that use weather data and information about soil water-holding characteristics, and allow calculation of the effects of drought periods on crop yields. Crop growth models may be simple or complex. Simple models can use WUE and D, and information on the effects of harvest index from drought stress periods at particular growth stages. They suffer from the disadvantages of a high degree of empiricism, but these must be weighed against ease of use and economy of input data. Complex models are likely to be mechanistic descriptions of growth in terms of carbohydrate production and the physiological processes affected by drought that govern yield. Detailed mechanistic crop-growth models can be used, in conjunction with weather data from many years and detailed crop water-use models, to analyze the likely performance of the crop(s) in a particular region. The probability of acceptable yields can be determined from such analyses.

The principle that must be observed in any such experimental modeling work is the need for rigor and careful experimention in the development and testing of detailed models. Close collaboration between agroclimatologists, crop physiologists, and modelers is essential.

Detailed Water Balance Models

Detailed water balance models provide information about soil water content under a crop at any time, and about rates of crop water use, and hence the amount of water used in a given interval. These models essentially solve the basic hydrological equation for a specified crop x soil situation:

$$P + RO + Dr + \Delta\theta + ET = 0 \quad (1)$$

where

P = precipitation,

RO = runoff,

Dr = drainage out of the root zone,

$\Delta\theta$ = the change in soil moisture content in the crop root zone (the soil water-holding capacity of the root zone is θ_S [max] - θ_S [min]), and

ET = evapotranspiration (water lost by transpiration through the crop and evaporation from the soil surface).

Detailed water balance models are deterministic, involve fewer assumptions than simple water balance models, require more input data, and hence can be expected to produce more accurate results. They have an important role in drought studies, since it is only by developing and carefully testing such models that estimates of crop water use and growing season length can be refined, and the potential for improved water use, and hence dry matter production by crops, accurately evaluated. The water balance model presented by Campbell and Diaz (1988) is well developed and includes sufficient detail to meet most requirements, although it is clear that specific investigations may need to be conducted to determine parameter values for the functional relationships used for crops grown in drought-prone regions.

The calculation of transpiration rates from full canopied (leaf area index > 3) crops is soundly based and has been widely tested, but careful determination of the best form of equation(s), and the simplest weather data that can be used, will remain necessary for many situations. In view of the variability of weather over a region—particularly where there are marked topographical differences—it may not be worth using detailed soil water-balance and crop water-use models where daily weather conditions have to be estimated by interpolation and corrected for topography. Solar radiation can probably be estimated with acceptable accuracy, but temperature, air humidity, and wind speed should be measured where possible.

The question of the lower limit of extractable water is important for the calculation of water uptake by crops, and hence for definitions of growing season length and the prediction of the onset of "significant" stress. It has been proposed that 30% of the total available water in the root zone usually provides a reasonable approximation of this limit—at which point the ratio of actual to potential transpiration would be expected to be 0.6-0.7. However, this value clearly depends on root exploitation of the soil and on the soil water-holding characteristics. It should be investigated in association with physiological studies and measurements of plant growth. Rates of root growth into the soil, and the duration of root growth, play a major role in determining the ability of a crop to tolerate midseason droughts and to use stored water after the end of the rainy season. Root growth and water uptake by roots can be studied indirectly by means of water extraction measurements. These may need to be supplemented by excavation and evaluation of root-growth patterns in various soils, and studies in tubes of the rooting properties of particular species and cultivars, and the extent to which they vary.

Detailed crop water-use models are only useful, through the life cycle of crops, if used in conjunction with good descriptions of crop development, particularly leaf area index. Such descriptions may be empirical or they may be mechanistic, based on carbon uptake and carbohydrate allocation patterns. These proceses may be affected by drought stress, hence information is required about how drought stress affects plant growth patterns.

Detailed crop water-use models provide an analytical tool that can be used in association with plant breeding programs and physiological studies to provide estimates of soil water content at any time. They could also be used as a advisory tool; extension workers and agronomists could use such models, with input data provided from their first-hand knowledge and experience, to evaluate various options and the consequences of alternative courses of action for farmers. There is no reason, in principle, why detailed soil water-balance models should not be used in conjunction with climatological models—the limitation is not the data handling or calculating power of computers, but our inadequate knowledge of soil and weather variability.

Climatological Models

Since drought is a consequence of rainfall shortage in relation to potential water loss by evaporation, analyses of rainfall patterns in drought-prone areas are of obvious interest. However, since the water available for crop growth is determined by soil moisture content rather than rainfall per se, and since it is relatively simple to calculate soil water balances from rainfall and other climatological data, the calculation of such balances seems the most useful way to characterize the climate of a region in terms of cropping potential.

Climatological analyses in terms of equation (1) involve a number of simplifications, assumptions, and estimates. First, precipitation is generally all assumed to be effective. There is no allowance for interception losses and evaporation from crop surfaces, which may be significant, particularly when crops provide nearly complete ground cover and rainfall occurs in intermittent showers. Second, runoff is usually assumed negligible except during periods when rainfall exceeds ET, and the soil profile is full. Excess precipitation is then attributed either to runoff or loss by drainage below the root zone. The values of the parameters defining soil water-holding capacity are also sources of considerable uncertainty when applied to large areas. Finally there is uncertainty in ET, which strictly depends on environmental factors such as radiant energy and the vapor pressure deficit of the air (D) interacting with crop leaf area and leaf stomatal resistance.

Robertson (1988) suggested that for climatological analyses for land-use planning recommendations about crops that may be successful in particular areas, the length of the growing season may be calculated in terms of the probability of at least one 5-consecutive-day period with wet soil (i.e., soil where $\theta_S > \theta_s(\mathrm{min})$ in any 10-day period.) This type of assumption can be tested and refined by studies on crop responses to drought. It may be that there are better criteria to define the length of the growing season. From such calculations the probability of growing crops without suffering significantly lower yields from drought can be calculated. Robertson discussed some of the uncertainties associated with the use of simple water-balance models and argued that agroclimatic analyses should make use of as long a record period as possible (20 or more years) to avoid bias caused by long-term rainfall trends and epochs.

Another problem with the analyses of climatic data is the uncertain applicability of the results to any particular area. Weather measurements are made at points, often widely separated, and maps drawn from these points may be very unreliable guides to the conditions some distance from the measurement point. Variograms of the type used in soil surveys might help resolve this problem.

Computer technology now makes it a simple matter to store all the climatic data available from any region, and transfer these data to mapping or analytical programs. This would permit investigation of some of the uncertainties discussed above and would eliminate others; for example the soil water-holding characteristics for a particular region, together with estimates of the rooting zones of crops, can be provided as input data.

The average length of the (climatic) growing season in any region is essential information for the plant breeder. Breeders can select plants for differences in the length of their phenological growth stages (at standard temperatures) and hence can seek cultivars that fit the climatic patterns of particular regions. The agroclimatologist can calculate the probability of longer or shorter growing seasons and the probability of drought at particular stages of the season, and thus provide a basis for evaluating the likely success in a particular region of a crop with a specified growing season requirement.

Climatological models are likely to be of value to planners and economists concerned with the agricultural production of regions—those who want to make general statements about the potential of regions, the likelihood of crop failure, or the probability that new species or crop cultivars will succeed. For the extension worker, agronomist, and crop physiologist, climatological analyses may be of interest to interpret multilocational genotype x environment or treatment x environment interactions, and for initial analyses of drought occurrence. Over the longer term, however, more detailed soil water-balance and crop-growth models, used as analytical tools to explore the "what if......" type question, and hence as a basis for decision-making, will be much more useful to them.

Conclusions

A number of conclusions emerged from analysis of the papers and subsequent discussions. They were:

- Crop growth, in terms of dry matter production, can be quite accurately estimated from the amount of water transpired and the water-use efficiency of the crop. Detailed crop-growth models, developed and tested from careful experimentation of stress effects on crop growth processes, provide a means to evaluate the significance of experimental results in relation to weather and other conditions. These detailed models can be run with many different (real) weather data sets. The results can be analyzed to determine the probability of crop success in specified conditions: growing season length, planting dates, and soil water-holding characteristics.
- Detailed crop water-use models provide valuable analytical tools that can be used to analyze the performance of different genotypes in relation to the weather patterns in particular seasons or locations, or as an aid to farmers. They require detailed knowledge and accurate physical descriptions of crop water use in relation to weather conditions, considerable 'input data, and relatively precise specification of the conditions to which they are to be applied.
- The calculation of soil water balances from simple models and climatological data provides useful information about season length and its variation in any particular region. This information is of considerable potential value to planners and economists, and is essential to plant breeders, whose main objective in drought-prone areas must be to breed crops that fit the *average* growing season.
- Climatologial models can be used to assess the probability of success for crops requiring a given season length. Variable weather across regions may be a problem with these models (although this may be reduced by using data covering many years), as well as uncertainties in the calculation of transpiration and knowledge about available soil water. They are therefore not suitable for detailed analysis of the consequences of specific actions or decisions in particular situations.

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Part 2.

Making the best use of available technology: fitting cropping systems, crops, and crop varieties to the environment

Principles of Crop Water Use, Dry Matter Production, and Dry Matter Partitioning that Govern Choices of Crops and Systems

A. H. Bunting and A. H. Kassam[1]

Abstract

Many of our basic concepts of crop water use have been developed only during the previous 25 years; these are briefly reviewed. The concepts of water use efficiency, evaporative demand of the air, water supplying power of the soil, potential and actual evapotranspiration, and crop coefficients are explained. For most crops it appears that maximum evapotranspiration occurs when leaf area index is in the range 2-4.

The characteristics of water regimes in the seasonally arid tropics are discussed and the contrast in drought environments between cool-dry areas and warm/hot-dry areas is emphasized. In order to improve crop productivity in drought-prone areas it is suggested that more detailed agroclimatological analyses are required and further understanding of the factors controlling crop phenology is needed. Closer matching of crop phenology to climatic events appears to offer the best scope for improving and stabilizing crop yields. However, the importance of adopting a systems approach in crop adaptation to drought is emphasized. Where water is the major limiting factor for the entire production system of a region, improving the drought resistance of a particular crop should not be considered in isolation.

Résumé

Utilisation de l'eau par les cultures, production de la matière sèche et répartition de la matière sèche ayant une influence sur les choix des cultures et des systèmes : Beaucoup de nos concepts fondamentaux de l'utilisation de l'eau par les cultures ont été développés pendant les 25 dernières années. Cette communication présente brièvement les concepts de l'efficacité de l'unité de l'eau, du besoin évaporatif de l'air, du pouvoir de l'alimentation en eau du sol, des coefficients K et de l'évapotranspiration potentielle et réelle. L'évapotranspiration maximum pour plusieurs cultures survient quand l'indice de surface foliaire varie de 2 à 4.

Les caractéristiques des régimes de l'eau dans les tropiques à longue saison aride sont discutées. Le contraste dans l'environnement aride entre régions sèches fraîches et régions sèches chaudes est souligné. Les analyses agroclimatologiques détaillées sont requises pour l'amélioration de la productivité dans les régions sensibles à la sécheresse. Une bonne compréhension des facteurs déterminant la phénologie de la culture est également requise. Le calage plus étroit de la phénologie de la culture aux facteurs climatiques semble donner des meilleurs résultats pour l'amélioration et la stabilisation des rendements. Cependant, l'importance d'une approche des systèmes pour l'adaptation des cultures à la sécheresse est

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ICRISAT (International Crops Research Institute for the Semi-Arid Tropics). 1988. Drought research priorities for the dryland tropics (Bidinger. F.R., and Johansen, C., eds.). Patancheru, A. P. 502 324, India: ICRISAT.

soulignée. L'amélioration de la résistance à la sécheresse d'une culture ne devrait pas être considérée isolément quand l'eau est le principal facteur limitant pour la totalité du système de production dans une région.

Introduction

This paper was compiled by A.H. Kassam and reviewed in consultation with A.H. Bunting. During the review, it became evident that a more rigorous and systematic treatment could be based on an analysis of the effects of water deficits on yield development in terms of time, and time courses of leaf area duration, the rate of assimilation per unit of leaf area, and the partition of accumulated dry matter among competing sinks. This paper assembles parts of the raw materials that will be needed for that fuller treatment.

All of us are familiar with the standard concepts and terms of water relations, and so this paper omits much of the formal detail. However, it was only in the early 1960s that many of the more important physiological, biophysical, and morphological principles of crop water use were either discovered or transformed into general tools-of-the-trade. During the past 25 years the thermodynamic treatment of water movement in the soil-plant-atmosphere system (Slayter and Taylor 1960) has come to be generally used: transpiration is accepted as an aspect of evaporation, and the evaporative demand of the atmosphere is assessed by combined energy-balance and aerodynamic methods of the type associated with Penman (Doorenbos and Pruitt 1984; Monteith 1973).

The C_4-carbon assimilation pathway and the differences between C_4 and C_3 plants were discovered (Calvin and Bassham 1962; Hatch and Slack 1966). Models representing the relationships between canopy structure, light interception, photosynthesis and transpiration (de Wit 1965; Monteith 1965, 1972, 1973) are widely used, and the critical role of ecophysiological, morphological, and phenological behavior in determining adaptability, adaptation, productivity, and yield (Bunting 1961, 1964, 1971, 1975; Bunting and Elston 1980; Elston and Bunting 1980; Monteith and Elston 1971) are now far more completely understood.

May and Milthorpe (1962) defined "drought resistance of crop plants" as follows: "The term 'drought resistance' as applied to crop plants is normally used as an all-embracing term to describe those varieties or species which are able to grow and yield satisfactorily in areas liable to periodic drought. It covers an extensive complex of properties which can best be appreciated by considering the ecological situations which lead to, and the consequences of, a shortage of water within the plant."

Today, nearly 25 years later, we can examine these ecological situations more precisely. Moreover, we can consider effects of, and adaptation to, drought at a number of operational levels: cells, tissues, and organs of individual plants; of whole plants; the crop as a whole; and the systems within which crops are produced.

This paper attempts to depict the context in which some of the many expressions and effects of drought in field crops occur, and so provide links between Parts 1 and 2 of this book. The presentation is certainly not a formal review. Many of the ideas and information presented are not new and have been expressed in greater detail elsewhere in published as well as unpublished papers (Bunting 1975, 1985; Bunting et al. 1982; Bunting and Elston 1980; Doorenbos and Kassam 1979; Elston and Bunting 1980; FAO 1978-81; Kassam 1976; Kassam et al. 1976; Kowal and Kassam 1978).

Crop Water Use

A field crop retains or consumes no more than about 1-2% of all the water it takes up during its active life. The rest is transpired, mainly from the leaves, into the surrounding atmosphere. The small amount of water that is retained is, however, of great significance because water is essential to plants in many ways (Sutcliffe 1968):

- water is a constituent of protoplasm, sometimes comprising as much as 95% of the total weight;
- it is an ionising solvent in which many other substances are dissolved, and in which they undergo chemical reactions;

- water participates directly in many chemical reactions in the protoplasm;
- it is the source of hydrogen atoms for the reduction of carbon dioxide in photosynthesis, and it is a product of respiration;
- much of the water in plants occurs in large vacuoles within the protoplasts, where it has the mechanical function of maintaining the rigidity ("turgidity", or positive turgor potential) of cells, tissues, organs, and the whole plant;
- many, if not all, of the physiological and biophysical processes related to photosynthesis and growth of cells, tissues and organs appear to depend on cell turgor potential;
- water acts as a "hydraulic fluid" permiting regulation of internal pressure differences facilitating nontranspirational flow involved in mediating changes in angle, shape, and posture of plant parts;
- water forms a continuous network of films in the microspace within and between the "solid" material in the cell wall (the apparent free space) throughout the plant; these films are important in the entry and movement of dissolved substances;
- water also provides a medium in which dissolved and suspended substances move in the xylem and phloem; and
- water is the medium through which motile gametes or nuclei effect fertilization, it is an essential component of nectar, and it plays an essential role in many of the mechanisms of dissemination of spores, fruits, and seeds.

Transpiration and Water Potential

Crops increase their dry mass and grow only by taking in carbon dioxide from the air, and together with the radiant energy derived from sunlight, fixing it as sugars and other organic compounds. The carbon dioxide diffuses into the plant through the stomata as long as they are open, and at the same time water vapor diffuses out of the plant through the stomata into the atmosphere. The movement of water out of the plant by transpiration is therefore an inevitable consequence of the assimilation of carbon dioxide. The latent heat of evaporation enables mesophytic plants to dissipate excess heat energy and "regulate" tissue temperature. The movement of water into the plant, as a result of transpiration losses, helps bring dissolved substances to the root surface from more distant regions in the moist soil, and carries them into and through the roots to the rest of the plant.

The amount of water transpired per day by a plant or crop (the transpiration *rate)* depends not only on the "evaporative demand" of the atmosphere but also on the proportion of each day during which the stomata are open, and the size of the evaporating surface area (leaf area) that is intercepting radiant energy or receiving reflected or advected heat. If this rate is greater than the rate at which water can be taken up, the plants lose water, leaf water potential decreases, and water potential gradients are set up within the plant. These gradients represent the aggregate potential difference which "draws" the water from the soil. The substomatal water potential is the "sucking" component which leads to the movement of water from soil pores into the plant. When the transpiration rate decreases at night or on humid days, and water in the soil is also available at greater water potentials, rehydration takes place until the water potentials of the soil and leaves are more or less in equilibrium.

The size of the gradients at a particular evaporative demand depend on crop variety and growth stage, and on water supply. When water is freely available the water potentials of all field crops tend toward zero overnight. During the daytime, water deficits develop and water potential gradients are established. Typical leaf water potentials are generally greater than -0.5 MPa when water is freely available and there is no drought stress.

As water shortage develops, the water potential becomes smaller (more negative) due to dehydration, and at some point changes in the turgor potentials of the different leaf cells lead to partial or complete stomata closure. If the water supply shortage and the associated plant water deficits continue to increase, then the proportion of each day that stomata remain open decreases, leaf (and crop) temperature rises, and osmoregulation of solute (osmotic) potential occurs. Initially the decrease in solute potential maintains positive cell turgor potential as water potential continues to decrease, but later serves to avoid irreversible dehydration and to withstand desiccation.

In general, cultivated leguminous crops do not have a large working range of water potential; typical figures at zero turgor potential (wilting) range from -1.0 to -2.5 MPa. In cereals, they range from -2.5 to -7.0 MPa; consequently these crops can withstand greater dehydration levels and can extract more water from the soil.

The *rate* of water use is influenced by three sets of conditions:

- the evaporative demand of the air,
- the size of the canopy cover, and
- the water supply.

The *total* amount of water used by a crop depends on the length of life of the crop and the time course of the rate at which it uses water.

Evaporative Demand of the Air

When water is freely available to the crop and the canopy covers most or all of the ground, the rate at which water is lost depends on the evaporative demand of the air. This is determined by:

- the temperature and the relative humidity of the air, which affects the rate of diffusion of the water molecules;
- the net amount of radiant energy or heat received by the leaves of the crop, which provides the latent heat of evaporation; and
- the movement of the air, which carries water vapor away from the crop and therefore tends to maintain the gradients of water potential from leaves to the adjacent part of the atmosphere, and may in addition import (advect) heat energy and less humid air from warmer or drier locations.

The evaporative demand of the air can be quantified from weather data, using a combined energy balance and aerodynamic procedure of the type initially developed by Penman. The computed evaporative demand of the air for open water surface is designated E_0; for a flat grass crop of short stature, completely covering the ground and freely supplied with water, the evaporative demand is called potential (or reference) evapotranspiration (ET). ET differs from E_0 mainly because of the difference in albedo and surface roughness of the evaporating surface.

Crop Cover

Field crops do not cover the ground completely throughout their lives, and generally develop an aerodynamically rougher surface than flat grass. Actual evapotranspiration (ET) for dryland crops is generally less than ET when crops only partially cover the ground surface. In the early stages of an annual crop before it covers the ground fully, or in a widely-spaced crop, the crop uses water less rapidly than ET, even if water is freely available, because part of the radiant energy falls on the soil surface and is reradiated from the soil surface without impinging on the leaves. As the crop approaches full cover of the surface, the rate of water loss reaches a maximum, equal to or greater than the reference evaporative demand of the air, ET, if water is freely available. ET_a is generally greater than ET because of greater surface roughness. The growth of additional leaves, however, does not always increase the rate except where it increases the aerodynamic roughness of the crop and makes the movement of air in it more turbulent.

It is possible to make practical estimates of ET_a from computed ET using empirically-derived crop coefficients (k_c), such as $ET_a = k_c$ ET. Values of k_c for different crops at different growth stages are given in Doorenbos and Kassam (1979). For many dryland annual crops, k_c at the time of crop emergence and establishment is 0.4-0.6, increasing to a maximum of 1.0-1.3 when the crop canopy covers most or all of the ground and is able to intercept most or all of the incoming radiation. This occurs in many crops and environments when leaf area index (LAI) is 2-4. The relationship between LAI and relative evapotranspiration (ET_a / ET) for several field crops at Samaru, northern Nigeria, is shown in Figure 1 (Kowal and Kassam 1978). At a given LAI, crops of markedly different canopy structure (e.g., sorghum, cotton, groundnut) use water at very similar rates.

Water-use Efficiency

The total amount of water used when water is freely available depends mainly on the changes in crop cover with time and the length of the crop life. Since different crop varieties grow and expand their canopies at different rates, have different economic yields per unit time, and also live in environments with different evaporation conditions, water-use efficiencies for total dry matter and economic yield vary between and within crops, and between environments. Some data from Samaru for

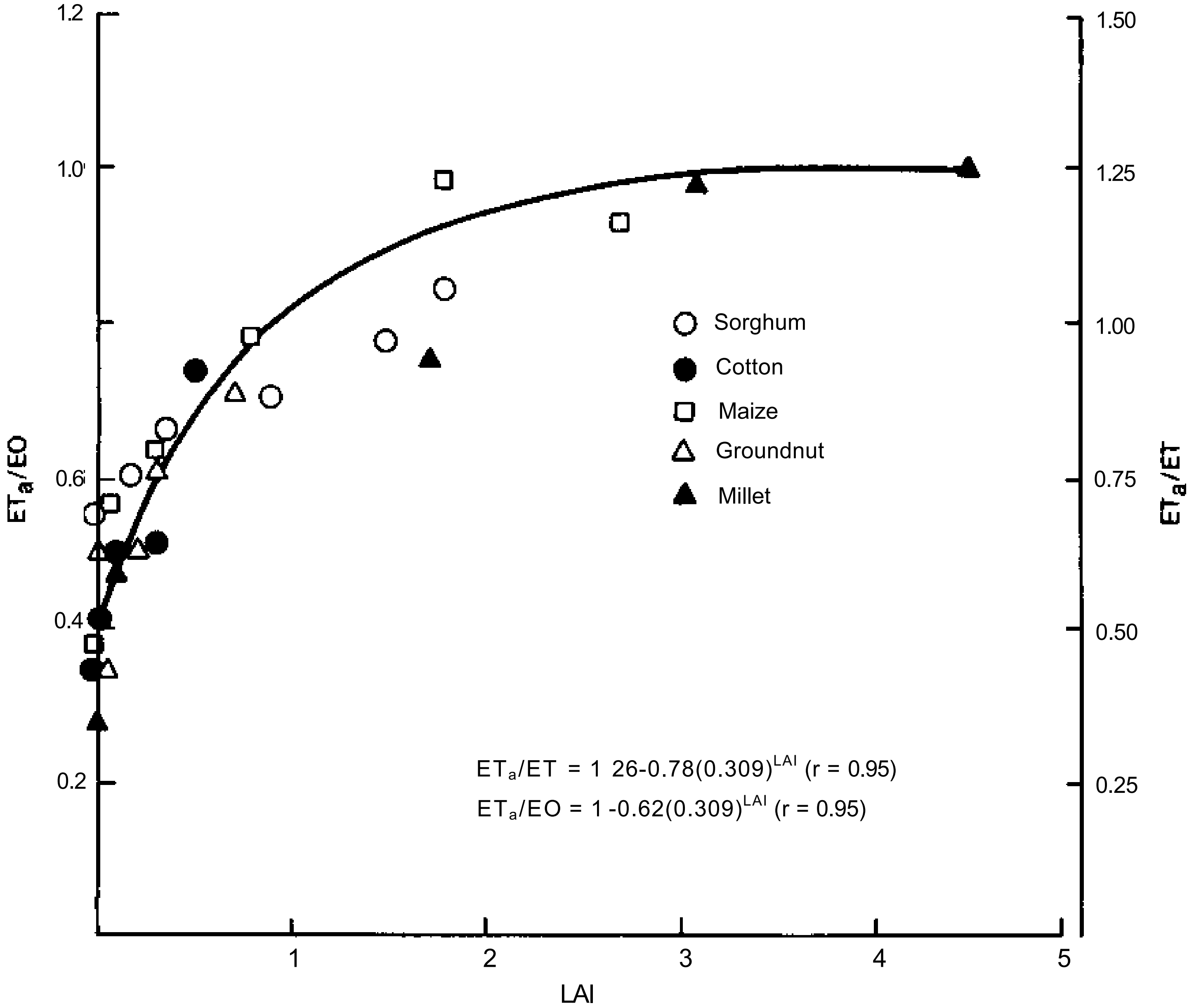

Figure 1. Relationship between leaf area index (LAI) and relative evapotranspiration (ETa/ET), and between LAI and relative evaporation (ET_a/EO) for several field crops at Samaru, northern Nigeria.

pearl millet (Kassam and Kowal 1975), maize (Kowal and Kassam 1973), and groundnut (Kassam et al. 1975) are presented in Table 1. The average amounts of water used per day (3.5-4.2 mm) was similar in all these crops but the amounts of dry matter (DM) produced per day (67-264 kg ha^{-1}), and hence the water-use efficiencies for total dry matter (1.7-6.6 g DM kg^{-1} water), were very different.

Different growth rates between crops are due both to differences in the leaf area or other assimilatory surfaces per unit area of land (which arise largely from differences in the rate of expansion of the canopies), and also to differences, at a given LAI and level of light interception, in the rate of canopy photosynthesis per unit area of assimilatory surface (which arise partly from differences in the optical structure of the canopy and partly from the differences in the pathway of photosynthesis). These growth rate differences affect the time course of water-use efficiency. The groundnut crop grew more slowly because its leaf area expanded more slowly because its more planophile habit limits the leaf area that can use radiation, and because it uses the C_3-pathway of carbon assimilation. Millet and maize, with taller canopies into

Table 1. Water used, dry matter produced, and water-use efficiency of three experimental crops at Samaru, Nigeria (Kassam and Kowal 1975, Kassam et al. 1975, and Kowal and Kassam, 1973).

	Pearl millet	Maize	Ground-nuts
Crop life (days)	85	117	125
Total water used (mm)	330	486	438
Average water used per day (mm)	3.9	4.2	3.5
Dry matter produced ($t\ ha^{-1}$)	22.5	19.1	8.4
Average dry matter per day ($kg\ ha^{-1}$)	264	163	67
Water-use efficiency ($g\ DM\ kg^{-1}$ water)	6.6	3.9	1.7

which light penetrates more deeply, use the C_4-pathway, which for equal LAI values produces dry matter somewhat more efficiently than the C_3-pathway.

Water Supply

The greater part of the water required by crops is met by uptake from the soil through the root system. The actual rate of evapotranspiration (ET_a) in relation to evaporative demand (ET) is determined by the rate at which water can move from soil to and into roots. If this rate falls below ET_a the crop will lose water faster than it can take it up until the stomata begin to close, and thus lessen the rate of transpiration. During this period the crop is often said to be under drought stress.

The reference total available amount of water stored in the soil (S_a) is generally the soil water content at field capacity (soil water potential of -0.01 to -0.03 MPa) minus that at wilting point (soil water potential of -1.5 MPa). S_a varies widely between soils depending on texture and bulk density. Approximate data on S_a for different soil texture types are given Table 2. In general, values of S_a for fine-, medium-, and coarse-textured soils are in the region of 200, 140, and 60 mm m^{-1} soil depth, respectively.

Only a portion of the water from S_a in the root zone is readily available to the crop. The level of maximum depletion of soil water that a crop can tolerate without a decrease in growth rate varies with type of crop as well as with variety. This quantity of readily-available water is defined as $p(S_a)$ where p is the fraction of the total available soil water that can be used by the crop without affecting its actual rate of evapotranspiration, ET_a, and/or growth. The value of the empirical fraction p depends in part on the type of crop, the soil, and the evaporative demand. Some crops such as potato, onion, and strawberry, require the soil to be continuously wet if they are to produce good yields; others such as cotton, wheat, and safflower will tolerate drier conditions. However, the level of depletion that a crop will tolerate varies greatly with the stage of its development; most crops prefer a smaller depletion during changes from vegetative to reproductive growth or during the period from heading and flowering to fruit and seed setting.

Table 2. Relation between soil water potential (MPa) and available soil water (mm m^{-1} soil depth).

	Soil water potential			
Soil type	-0.02	-0.05	-0.25	- 1.50
	Available soil water			
Fine-textured soils	200	150	70	0
Heavy clay	180	150	80	0
Silty clay	190	170	100	0
Loam	200	150	70	0
Silt loam	250	190	50	0
Silty clay loam	160	120	70	0
Medium-textured soils	140	100	50	0
Sandy clay loam	140	110	60	0
Sandy loam	130	80	30	0
Loamy fine sand	140	110	50	0
Coarse-textured soils	60	30	20	0
Medium fine sand	60	30	20	0

The *total* amount of water that is readily available to the crop is equal to $p(S_a)$ over the root zone (D), i.e., $[p(S_a) \times D]$. The depth and density of rooting varies during the life of the crop, and there are inherent differences between crops and varieties in rooting characteristics in space and time. In general, $p(S_a) \times D$ is greater during the ripening stage, when roots have penetrated more deeply or branched more freely, and smaller during earlier stages when the soil volume to which the roots have access is still small.

The fraction p also varies with the level of evaporative demand. When ET is small (< 3 mm day^{-1}), the crop can continue to meet the evaporative demand to a soil water depletion greater than when ET is large (> 8 mm day^{-1}). This difference is somewhat more pronounced in heavy soils than in coarse soils.

Further, crops vary in the extent to which leaf water potential can fall without interrupting transpiration or doing damage to the leaves or other parts of the plant. For a given soil type and level of evaporative demand, differences in root characteristics, leaf and tissue water relations, and crop development characteristics are all important in determining the differences between crops in the magnitude and time course of fraction p.

General information for different crops on rooting depth (D), on fraction p, and on $p(S_a)$ for different soil types has been reviewed by Doorenbos and Pruitt (1984) (Table 3). The data relate to ET of 5-6 mm day^{-1}; and rooting depth refers to crops with full canopy cover. In general when ET is 3 mm day^{-1} or less, $p(S_a)$ is greater by some 30%; when ET is 8 mm day^{-1} or more, it is lower by some 30%.

In practice crops are not freely supplied with water all of the time, and water supply varies within and between years. ICRISAT's crops are grown in environments that have marked dry seasons, and frequently experience dry spells within the rainy season itself. When water supply is not

Table 3. Generalized data on rooting depth (D) of crops with full canopy cover, fraction of available soil water (p), and readily available soil water ($p[S_a]$) for different soil types in mm m^{-1} when crop evapotranspiration is 5-6 mm day^{-1} (Doorenbos and Pruitt 1984).

Crop	Rooting depth (m)	Fraction of available soil water[1]	Readily available soil water (mm m^{-1})[1]		
			fine	medium	coarse
Alfalfa	1.0-2.0	0.55	110	75	35
Banana	0.5 - 0.9	0.35	70	50	20
Barley[2]	1.0-1.5	0.55	110	75	35
Beans[2]	0.5 - 0.7	0.45	90	65	30
Beets	0.6-1.0	0.5	100	70	35
Cabbage	0.4 - 0.5	0.45	90	65	30
Carrots	0.5 - 1.0	0.35	70	50	20
Celery	0.3 - 0.5	0.2	40	25	10
Citrus	1.2-1.5	0.5	100	70	30
Clover	0.6 - 0.9	0.35	70	50	20
Cacao		0.2	40	30	15
Cotton	1.0-1.7	0.65	130	90	40
Cucumber	0.7 - 1.2	0.5	100	70	30
Dates	1.5-2.5	0.5	100	70	30
Dec. orchards	1.0-2.0	0.5	100	70	30

Continued...

Table 3. *Continued.*

Crop	Rooting depth (m)	Fraction of available soil water[1]	Readily available soil water (mm m^{-1})[1]		
			fine	medium	coarse
Flax[2]	1.0-1.5	0.5	100	70	30
Grains small[2]	0.9 -1.5	0.6	120	80	40
winter[2]	1.5 - 2.0	0.6	120	80	40
Grapes	1.0-2.0	0.35	70	50	20
Grass	0.5 - 1.5	0.5	100	70	30
Groundnuts	0.5 -1.0	0.4	80	55	25
Lettuce	0.3 - 0.5	0.3	60	40	20
Maize[2]	1.0-1.7	0.6	120	80	40
silage		0.5	100	70	30
Melons	1.0-1.5	0.35	70	50	25
Olives	1.2-1.7	0.65	130	95	45
Onions	0.3 - 0.5	0.25	50	35	15
Palm trees	0.7-1.1	0.65	130	90	40
Peas	0.6 -1.0	0.35	70	50	25
Peppers	0.5 -1.0	0.25	50	35	15
Peppers	0.5 - 1.0	0.25	50	35	15
Pineapple	0.3 - 0.6	0.5	100	65	30
Potatoes	0.4 - 0.6	0.25	50	30	15
Safflower[2]	1.0-2.0	0.6	120	80	40
Sisal	0.5 -1.0	0.8	155	110	50
Sorghum[2]	1.0-2.0	0.55	110	75	35
Soybeans	0.6 -1.3	0.5	100	75	35
Spinach	0.3 - 0.5	0.2	40	30	15
Strawberries	0.2 - 0.3	0.15	30	20	10
Sugarbeet	0.7 - 1.2	0.5	100	70	30
Sugarcane[2]	1.2-2.0	0.65	130	90	40
Sunflower[2]	0.8 - 1.5	0.45	90	60	30
Sweet potatoes	1.0-1.5	0.65	130	90	40
Tobacco early	0.5 - 1.0	0.35	70	50	25
late		0.65	130	90	40
Tomatoes	0.7 - 1.5	0.4	180	60	25
Vegetables	0.3 - 0.6	0.2	40	30	15
Wheat	1.0-1.5	0.55	105	70	35
ripening		0.9	180	130	55
Total available soil water (S_a)		200	140	60	

1. When crop ET if 3 mm day^{-1} or smaller increase values by tome 30%; when crop ET if 8 mm day^{-1} or more reduce values by some 30%, assuming nonsaline conditions (ECe < 2 dS m^{-1}).
2. Higher values than those shown apply during ripening.

adequate, stomata tend to close and ET_a decreases. Once fraction p has been depleted, ET_a becomes increasingly smaller, and its magnitude depends on the remaining fraction of the available soil water, $(1-p)\ S_a \times D$.

It is inevitable that once the stomata are closed and ET_a decreases, net assimilation also decreases, often to zero during a significant fraction of the daylight hours, particularly in C_3 crops where low rates of assimilation are offset by photorespiration. The rates at which leaves are initiated and expand also decreases. As a result, both the rate and capacity components of crop growth are decreased. Moreover, plants in a long dry spell, particularly annual plants, may wilt, dry out, and die. In dry conditions, seeds will not germinate. These limitations determine the type of crops that can be grown and the timing of sowing and harvest, and they also affect crop yields depending on the magnitude of the plant water deficit and the development stage of the crop. We shall come back later to examine crop responses to water shortages, but first let us consider the ecological conditions which lead to water deficits in crops grown in seasonally arid areas of interest to ICRISAT.

Water Regime in the Seasonally Arid Tropics

The water relations of a crop depend on the attributes of the crop, but they depend even more on the seasonal climate of the place where it is grown—which determines how much water the crop will receive and when, and how fast the water will be used.

In areas in which ICRISAT has an active interest, the seasonal climates include a long and harsh dry season. During the season, which corresponds to the winter of temperate latitudes and may indeed be cool, precipitation is negligible or zero, and ET is 4-6 mm day^{-1} or more (Fig. 2). At the end of the dry season when the rains arrive, they fall on a dry profile from which all available water has been removed by crops or other vegetation during the previous season, often to a depth of several meters depending on the soil type. There is usually no water reserve in the soil and the uppermost layers approach air dryness. The first rains may be light or heavy, but they are usually scattered. As the upper layers of the soil become wet, microbiological processes begin to mineralize organic matter and liberate nitrate.

As the rains become established and the rate of precipitation exceeds ET (often referred to as the beginning the humid period), a wetting front begins to move down the profile in a manner determined by the daily balance of precipitation and crop water use. The wetting front carries with it the nitrate and any other readily soluble materials. The

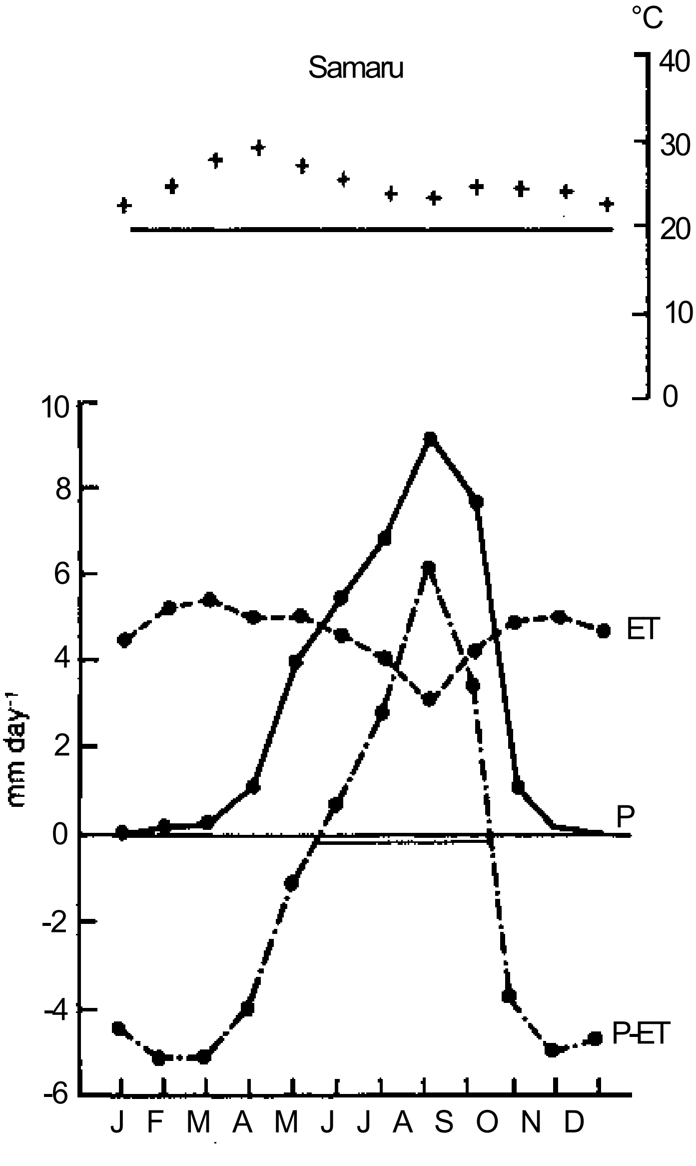

Figure 2. A seasonally-arid climate (Samaru, Nigeria). Monthly mean temperature (crosses); mean rates of precipitation (P) and potential evapotranspiration (ET) and the difference between them (P-ET) with mean duration of period in which P is greater than ET (horizontal line below zero axis). Period warmer than 20°C mean shown by horizontal line in temperature section.

extent of penetration of the wetting front determines the size of the water reserve accessible to the crop. If it is small, deep root penetration is not possible, and moreover there would be no water to tap if it were. However, at this stage, laterally spreading roots may be useful. The plants must be able to survive dry periods, often as long as 2 weeks or more, before the wetting front has penetrated deeper soil horizons.

As the season advances, and the wetting front moves further downwards, the profile may fill completely with water. Any additional water may be lost from the profile by seepage to lower ground and into water courses. If this cannot happen sufficiently rapidly, the profile may become waterlogged, excess water runs off from the surface (leading to surface wash), and low-lying parts of the field may be flooded.

Leaching of solubles is possible throughout the humid period, anaerobic losses of nitrogen may occur, and the roots may be substantially damaged, although the possible consequences have not been adequately studied.

As the rains decline toward the end of the rainy season, the rate of precipitation ultimately becomes less than that of ET. Thereafter crops begin to draw on the water reserve in the soil profile to complete their growth and yield-forming activities. If the root system has been damaged by the preceding wet conditions, the crop may not be able to extract water sufficiently rapidly. Presumably, in successful crops, the roots are damaged less, or new roots are formed rapidly as the profile dries. The latter is possible in cereals but less likely in primary-rooted legume crops. This is an area of considerable ignorance, but it may well be important for yield.

Moreover, it is important that the environmental physiology of the crops and crop mixtures fit appropriately into the time available for growth, and that crops are able to adjust their life cycles to match the unpredictable year-to-year variations in the length of the growing period. The ability to withstand diurnal water deficits, and to survive dry periods in a state of physiological (but not necessarily morphological) dormancy, seems likely to be important at this stage.

In the arid tropics, therefore, there can be both water deficits (or drought), and waterlogging (or even flooding) at different times of the year.

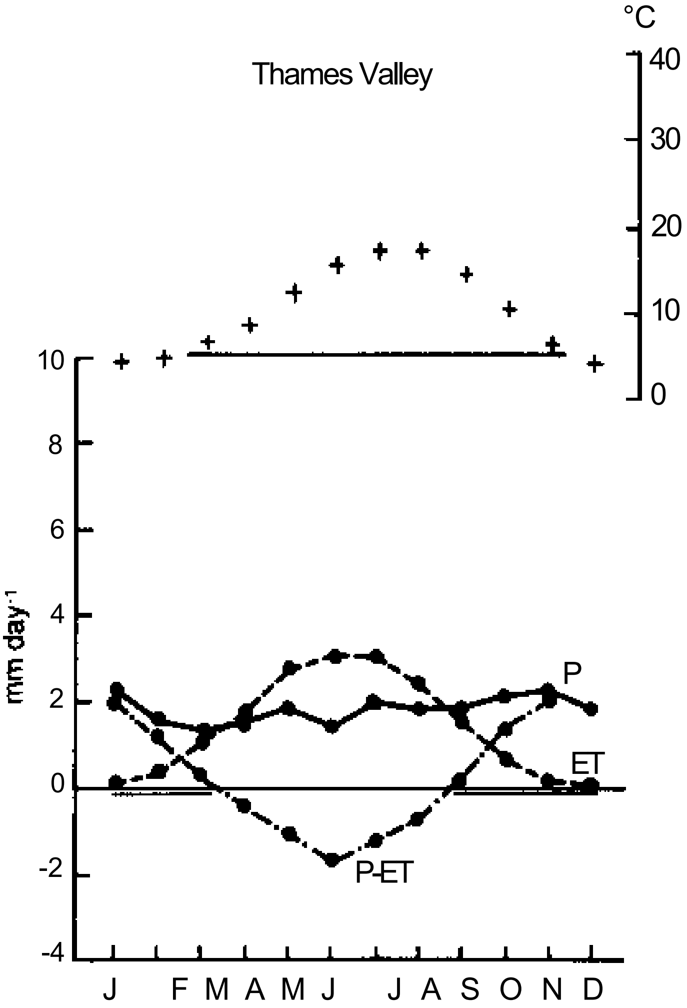

Figure 3. A temperature climate (Thames Valley, England). Monthly mean temperature (crosses); mean rates of precipitation (P) and potential evapotranspiration (ET) and the difference between them (P-ET) with mean duration of period in which P greater than ET (horizontal line below zero axis). Period warmer than 5°C mean shown by horizontal line in temperature section.

In contrast, the conditions of the typical water regime in the temperate regions (Fig. 3) are entirely different from those of the seasonally-arid tropics. The Deccan plateau or northern Nigeria or northeast Brazil are not simply hotter versions of Nebraska or Sasketchewan or Reading: they have totally different seasonal water regimes. In temperate regions, rain or snow may fall during every month of the year. Winters are wet, cold, and little radiation is received, so that the rate of ET is far lower than the rate of precipitation. As a result, the profile becomes saturated, and the surplus is often discharged at the end of the winter, particularly after the snow melts. Because the temperatures are cold, the rate of mineralization is very low and there is little or no nitrate to leach.

As the temperature rises, the days become longer, the growing season begins, and the rate of ET becomes greater than the rate of precipitation. Leaching is not generally possible during the growing season, and crops may have to draw increasingly (particularly where summers are hot) on the reserve of stored water in the soil. A soil water deficit develops, reaching a maximum in July or August (northern hemisphere). Cereals and several other winter- and spring-sown crops mature at or before this time. Deep root penetration enables a crop to tap the water of the fully-charged lower layers of the profile. As autumn advances, the rate of ET decreases and a wetting front begins to accumulate water in the soil, leading to recharge during the winter prior to the next annual cycle.

In every respect, the temperate and seasonally-arid tropical water regimes are mirror images of each other. The Mediterranean type of winter rainfall climate is intermediate. Scientists who study systems must think critically about which ideas and generalizations can be transferred from one region to another. These matters have been discussed more systematically elsewhere (Bunting 1975).

In the wetter parts of the seasonally-arid tropics, it may be possible, at least on heavier or deeper soils, to make more effective use of water by delaying the planting date until a sufficient reserve of water has been accumulated in the profile to offset the effects of dry gaps after the rains have begun. This requires skill, since it decreases the available growth period, but is often possible. On more sandy soils or in the drier parts of the seasonally-arid tropics, this management technique is usually not possible, and the early season dry gaps are critical for establishment, growth, and final yield.

Dry Matter Production

Most plant dry matter is produced as a consequence of photosynthetic uptake of carbon dioxide through the stomata. As suggested above, the assimilatory system by which the crop produces dry matter has two principal components: the size and the efficiency with which it works. Water shortage affects both.

When the water supply is adequate, the amount of dry matter produced by a crop per day depends on the number of hours during each day in which the stomata are open, the size and efficiency of the assimilating system, the level of radiation during those hours, and the temperature. The rate of uptake of carbon dioxide (and of loss of water) for a crop as a whole depends upon the expansion rate of the leaf surface and the rate of carbon dioxide uptake per unit of leaf area, which in turn depends on the number of hours during which the stomata are open.

Both the rates of assimilation and expansion are strongly affected by temperature, which also affects duration of the crop cycle and the evapotranspiration rate. In general, both plastochron and phyllochron are shorter, and leaf expansion is more rapid, at warmer temperatures.

The most important effect of water shortage is to limit the rate of leaf expansion before secondary thickening puts an end to the process. In most circumstances this is the principal way a water shortage affects the accumulation of dry matter and crop yield. It is not offset, in most cases, by the lower rate of actual evapotranspiration (ET_a) associated with a smaller leaf area index.

The next most important effect of a water deficit is a decrease in the length of time during the day when the stomata are open. Because diffusion of a gas through the stomata is involved in each process, it is not surprising that there is a linear relationship between dry matter production and water use in both C_3 and C_4 crops.

Reported seasonal water-use efficiencies (g dry matter kg^{-1} water) for dry matter production of C_3 rainfed crops in the warm, seasonally-arid tropics and subtropics are 1.2-3.3 g kg^{-1}, and 3.3-6.7 g kg^{-1} for C_4 rainfed crops (Kassam 1972; Kassam et al. 1976). These values correspond to seasonal rates of dry matter production in the range 50-130 kg ha^{-1} day^{-1} and 120-275 kg ha^{-1} day^{-1}. In the cool seasonally-arid tropics and subtropics (and in the cooler climates of the temperate regions), water-use efficiencies are comparatively greater (by 30-60%) because of the smaller ET, higher rates of dry matter production (due to a better radiation environment), and lower rates of respiration (due to a cooler thermal environment).

Dry Matter Partitioning and Yield

Once accumulated, dry matter is partitioned within a crop according to its inherent genetic programs. A plant with an indeterminate growth habit (e.g., groundnut, chickpea, or pigeonpea) in which reproductive and vegetative sinks, and nodules, compete through most of the crop life, differs from one with a determinate growth habit (e.g., pearl millet, sorghum, or maize) in which the vegetative and reproductive phases are separated. The life of an indeterminate annual ends because the partitioning system gives priority to the reproductive sinks so that the leaf to total growth ratio (LTGR, a reinvestment ratio) decreases to zero. In this case the crop is an annual for internal physiological, regulatory reasons. A cereal, on the other hand, is an annual because after the onset of the reproductive phase no more leaves can be formed on the main axis or tillers, because of the differentiation of the apical meristem from vegetative to reproductive. Hence, for morphological reasons, this is a different type of annual, and dry conditions have different critical effects on it than on the indeterminate annuals.

In all crops that have been examined, nearly if not all of the entire yield is produced as a net result of current assimilation during the time when the yield-accumulating organs are increasing in mass. In general, very little is transferred to these organs from previously accumulated reserves. The principal exception seems to be the dry matter necessarily transferred when previously-accumulated nitrogen moves from senescent leaves and other older parts of the crop into seeds or other yield organs. Some carbohydrate may sometimes move from culms to grain in some cereals; but usually yield is produced by current assimilation.

Among many things that are important for satisfactory dry matter partitioning and yield in a crop, it is necessary that:

- the life cycle of the crop should fit within those portions of the year which are favorable, and
- the crop should use as much as possible of the favorable season to produce its economic yield.

The length of the growing season (the time during which environmental conditions favor the accumulation of total dry matter in the crop as a whole) is determined by external limitations imposed by climate. The time used by crops to partition dry matter and to form their yield is determined by limitations imposed by plant structure and internal physiology. Let us briefly consider these limitations.

The Time Available: Limitations Imposed by Climate

We have already seen how in the seasonally-arid tropics, heat and dryness determine both the start and close of the season (Fig. 2). If we quantify the length of the growing season (reference length of growing period, LGP), as the period during which the rate of water supply from current rainfall and from 100 mm of water stored in the profile exceeds 0.5 ET, the areas generally referred to (in the agronomic definition) as the semi-arid tropics have a mean reference LGP of 60-240 days.

Year-to-year variability in the reference LGP is inversely related to length. In most countries in Asia, Africa, and South America where these relationships have been examined, coefficient of variation (CV) of mean reference LGP is 55-65% for areas with mean reference LGP of 60-90 days, and 10-15% for areas with 210-240 days. The dates of the beginning and end of the growing period are similarly variable.

The average period when precipitation exceeds ET, the humid period, is about two-thirds to three-quarters of the average total reference LGP. The CVs for the length of the humid period are generally similar to those for the total reference LGP, but for the quantity of total seasonal excess precipitation (i.e., the excess of the total amount of precipitation over the total of potential evapotranspiration), they are smaller. In other words, in the drier parts of the semi-arid tropics there are years that may not include a humid period, and therefore have no excess precipitation. In some instances the season may fail altogether, as in Kenya in 1983 and in Gujarat, India, in 1985. There are years in the wetter areas which are so wet that production of annual crops is adversely affected.

Furthermore, the frequency within and between years of dry spells long enough to lead to a soil moisture deficit of 100 mm or more within the growing season also varies substantially within and between the different reference LGP zones. It was necessary to quantify and map up to six different types of year-to-year moisture supply variations within each of the 11 reference LGP zones in the climatic resources inventory of Mozambique (Kassam et al. 1981-82), and up to 22 different types within each of the 15 reference LGP zones in the Kenya climatic resources inventory (Kassam and van Velthuizen 1983).

In some dryland regions (e.g., southern Africa, northwest India, northeast Brazil, central Argentina—the drier parts of the winter rainfall areas of the subtropics), there is no seasonal excess precipitation. Crop water requirements for full yields cannot be met from current rainfall alone. Thus fallowing to accumulate and conserve moisture in the soil from one year to the next to increase yields and their reliability is common on suitable soils.

Limitations Imposed by Plant Structure and Internal Physiology on Time to Form Yield

Whatever the environment, crops accumulate yield at different stages of their life cycles because of morphological differences. At the shoot apex, leaf and bud initials, which later are associated with nodes, are formed in a mathematically regular sequence in both space and time. At some point in this sequence, organs are differentiated in which starch or other carbohydrates, protein, oil, fiber, or other products are made (the sources) or accumulated (the sinks).

Crops fall into three broad phenological classes based on the number and location of node-in tern ode units which can be used to form yield:

- Yield may be produced throughout the period in which growth is possible because it consists of, or is accumulated in, the vegetative parts of a sufficiently long-lived, and often a perennial or biennial crop, e.g., many of the root and tuber crops, sugar cane, or fodder grasses.
- Botanically indeterminate-flowering plants produce yield during a variable fraction of the life of the crop, in fruits and seeds borne on lateral inflorescences, which may begin to form early in the life of the crop, e.g., pulses and leguminous oilseeds, sesame, and cotton.
- Yield is produced in terminal or late-formed inflorescences as the last phase in the life of an annual crop, or the annual shoot of a perennial crop, e.g., cereal crops, and banana. No more leaves are formed once the apical bud of the shoot has become reproductive. The sources for grain-filling are the latest-formed leaves, which follow each other into senescence.

The yield-forming organs are initiated and their number and size are determined during the vegetative phase, but evidently one of the main functions of the vegetative phase is to locate the grain-filling period at a particular stage of the season appropriate to the environmental circumstances and to the technology of the farming system.

In overall terms, therefore, four components work together to determine the mass of the dry matter accumulated in the yield organs during the yield-forming period:

- the size of the sources that produce the dry mass,
- the rate at which they work,
- the proportion of the product that is accumulated in the economically important parts, and
- the length of the yield-forming period during which these processes continue.

The first three combine to determine the growth rate of the yield organs; the fourth determines the duration of their growth.

Although crop improvement has changed the ways in which crops use time so that more of it is used to form yield, research on the physiology of yield has been concerned with the other three components: size, efficiency, and partition. Of course, these rate factors influence the duration of sink-filling and the length of the crop as a whole. Internal competition between developing fruits and other parts of the plant is the basis for the concept of the leaf to total growth ratio (LTGR). Where this ratio falls over time, the leaves age faster than they are replaced, and the crop stops growing because it lacks sources. Where LTGR continues to be large, the crop may continue to grow more or less indefinitely. These considerations determine the extent to which a crop behaves as an annual or a perennial.

Timing of Water Deficits

During the growth of many plants there are periods during which they are especially susceptible to drought stress—for example the time of transition from the vegetative to the reproductive phase in cereals. The magnitude of the water deficit is important in addition to its timing and duration.

A water deficit of a given magnitude may occur either continuously over the *total growing period* of the crop or it may occur during any one of the *individual growth periods,* i.e., establishment, vegetative, flowering, yield formation, or ripening. The effects on yield of a water shortage at different growth stages of a number of crops are reviewed in Doorenbos and Kassam (1979), where the response of yield to water supply was quantified through the yield response factor (k_y), which relates relative yield decrease to relative evapotranspiration deficit. Values of k_y for individual growth periods and for the total growth period for several crops are presented in Table 4.

In the case of deficits occurring continuously over the total growing period, effects of increasing water deficits on yields were less ($k_y < 1$) for alfalfa, groundnut, safflower, and sugar beet than in banana, maize, and sugar cane ($k_y > 1$). In the case of deficits occurring during the individual growth

Table 4. Yield response factor (k_y), the relative decrease in yield per relative deficit in evapotranspiration, for different crop growth periods (Doorenbos and Kassam 1979).

	Vegetative period						Total
Crop	early	late	total	Flowering period	Yield formation	Ripening	growing period
Alfalfa			0.7-1.1				0.7-1.1
Banana							1.2-1.35
Bean			0.2	1.1	0.75	0.2	1.15
Cabbage	0.2				0.45	0.6	0.95
Citrus							0.8-1.1
Cotton			0.2	0.5		0.25	0.85
Grape							0.85
Groundnut			0.2	0.8	0.6	0.2	0.7
Maize			0.4	1.5	0.5	0.2	1.25
Onion			0.45		0.8	0.3	1.1
Pea	0.2			0.9	0.7	0.2	1.15
Pepper							1.1
Potato	0.45	0.8			0.7	0.2	1.1
Safflower		0.3		0.55	0.6		0.8
Sorghum			0.2	0.55	0.45	0.2	0.9
Soybean			0.2	0.8	1.0		0.85
Sugarbeet							
beet							0.6 - 1.0
sugar							0.7 -1.1
Sugarcane			0.75		0.5	0.1	1.2
Sunflower	0.25	0.5		1.0	0.8		0.95
Tobacco	0.2	1.0			0.5		0.9
Tomato			0.4	1.1	0.8	0.4	1.05
Water melon	0.45	0.7		0.8	0.8	0.3	1.1
Wheat							
winter			0.2	0.6	0.5		1.0
spring			0.2	0.65	0.55		1.15

periods, the effect on yield is relatively small for the vegetative and ripening periods, and relatively large for the flowering and yield formation periods.

Although information about critical periods for plants can be obtained from formal field experiments (using a line sprinkler system, for example), it is valuable to compare this data with the variations in moisture regime and yields of crops over a number of years, as the following example of a groundnut crop illustrates.

Bunting et al. (1982) examined the relationship between the seasonal water balance and yields of long-season groundnuts at Kano Experiment Station, Kano, Nigeria, for most years from 1925 to 1980. Kano has a mean reference length growing period of 143 days, and its loessal soils are relatively light-textured.

In years of comparable total rainfall, yields ranged from zero to very satisfactory levels, depending largely on the characteristics of the first few weeks of the season. The correlations between yield and the dates of the start and end of the season, season length, and total annual rainfall were small and not significant.

For example, total rainfall was 716 mm in 1975 and 776 mm in 1966 (Fig. 4). Yield in 1975 was 3063 kg ha^{-1}, but in 1966 it was zero, presumably because of the stress during the first half of crop growth, which included establishment, the start of flowering, and peg formation.

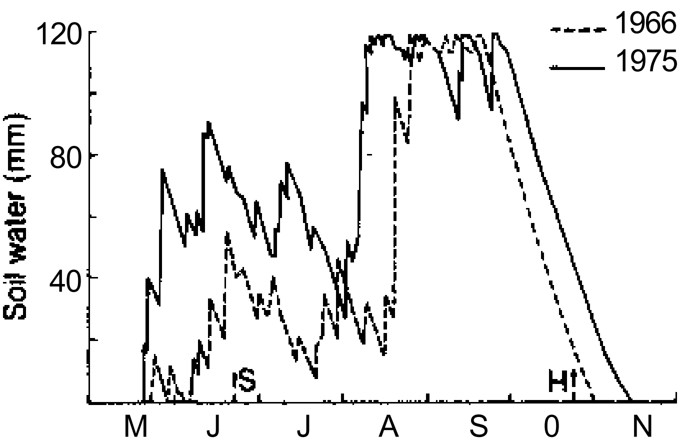

Figure 4. Calculated soil water contents (mm) at Kano, Nigeria, for 1975 (—) when groundnut yields were large and for 1966 (---) when yields were small; S and H indicate sowing and harvesting dates.

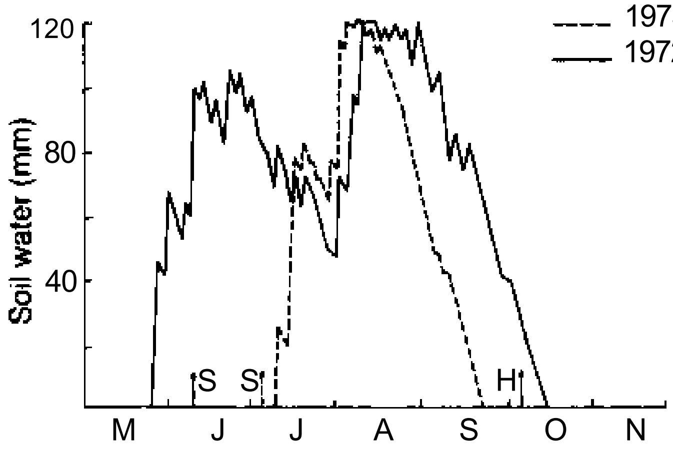

Figure 5. Calculated soil water contents (mm) at Kano, Nigeria, for 1972 (—) when groundnut yields were large and for 1973 (—) when yields were small.

The lowest total rainfall in the series was 416 mm in 1973 (Fig. 5). In this year, the rain began late and ended early, the profile was fully charged for only a few days, and the crop failed. In 1972 the relatively low rainfall (669 mm) was well distributed. The profile was nearly fully charged within the first month of the season, and this evidently enabled the crop to pass safely through a mid-season dry period, to give a final yield of 2809 kg ha^{-1}.

In 1979 (Fig. 6), the total rainfall was 580 mm, while in 1964 it was 753 mm (75 mm below the mean). In 1979 the season started very late and was also short (109 days). A dry period after sowing

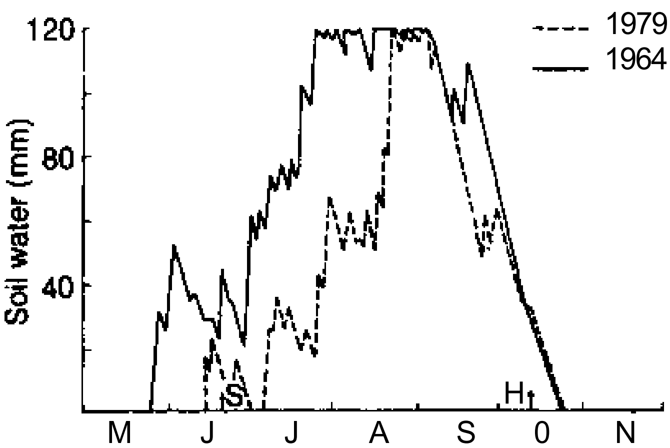

Figure 6. Calculated soil water contents (mm) at Kano, Nigeria, for 1964 (—) when groundnut yields were large and 1979 (---) when yields were small.

may have damaged the crop severely. The profile was fully charged only for a few days at the end of August and the crop was short of water through almost all of its life. The yield was 1032 kg ha^{-1}. In 1964 the rain began to fall early, the water balance was positive throughout the season, and the profile was fully charged for about 7 weeks from mid-July. The yield was 2539 kg ha^{-1}. In general, at Kano, it does not seem that the year-to-year variations in season length are a major factor determining yields, and water supply during pod-filling seems to have been adequate in all but the shortest seasons (1973, 1979). The most variable feature, and the one most likely to account for the yield variations, is the water balance during the first half of the season, including the first critical 40 days after sowing.

Adaptation to Drought

Definition and Levels of Drought

It is a condition of the life of land plants that during at least a part of their cycle they are able to obtain a sufficient supply of water to meet enough of the evaporative demand of the environment to permit growth and development. Most annual crops can tolerate considerable variations in the supply of water, usually at some cost in yield, but to achieve what producers would regard as a full yield, the supply of water must equal full crop water requirement throughout the cycle.

We may define drought as a period or periods during the life of the crop in which the supply of water is too small to meet the evaporative demand for sufficiently long that the loss of yield is economically unacceptable.

We may think about the definition of drought at two levels—at the level of climate and at the level of weather. At the level of climate, some places are characteristically drier or wetter than others, primarily because the growing season is too short. If the average or model length of growing periods is too short to accommodate the normal life cycle of an economic crop, sustained production will be impossible unless additional water can be supplied by runoff or irrigation.

At the level of weather, some seasons are wetter or drier than others because the length of the growing period departs from the longer term averages. In addition, the patterns of evapotranspiration and precipitation during the crop season itself also vary within and between seasons, as the examples from Kano amply illustrate.

The above two levels in the definition of drought form the basis of the quantitative inventories of the climatic resources compiled in the FAO agroecological zones assessments of crop, land, and population potentials at national and subnational levels (Kassam et al. 1981-82; Kassam and van Velthuizen 1983, 1984).

Adaptation to Drought at the Level of the Crop

There are three main ways in which the effects of dry periods on plants and crops are offset:

- The crop can *escape* them if its life cycle is short enough to enable it to mature safely during a continuously wet period: it behaves, in ecological terms, as a desert ephemerical.
- A crop can *endure or withstand* a dry period by extracting more stored water from the soil profile, by developing a bigger working range in water potential in leaves and other plant parts, and by storing water in its tissues so that wilting is delayed. By these means it can maintain a more or less normal water content, so that it can continue to assimilate carbon dioxide and grow.
- A crop may *survive and recover* from a dry period by losing water, so that much of the canopy wilts and dies, and then recover by producing new leaves from buds that were able to survive the dry spell. Surviving plant parts must be able to withstand intense heat and avoid total desiccation during the periods of severe stress.

Grain legume and cereal crops use all of these methods to some extent. For example, in the Sahel, where the annual rainfall may be less than 300 mm but the annual ET exceeds 2 m, very short season cowpeas avoid drought by maturing before any substantial stress develops, in less than 65 days. Similarly, short season groundnut ecotypes (in the spanish-valencia groups) mature early, particularly if they are densely sown (in 85-95 days from sowing at a mean temperature of 25°C). The primary root of groundnut grows rapidly, and can often penetrate the soil profile as deeply as soil water conditions will allow (120 cm, the depth of the wetting front, on montmorillonite clays of the Sudan rainlands). Groundnut leaves are reported to contain a layer of water-storing cells, which presumably helps to offset the effects of water loss by delaying the day-time closing of the stomata and wilting of the leaves. The alternately branched forms of groundnuts bear large numbers of terminal vegetative buds, which may help them to produce more new leaves more rapidly after damaging dry periods.

In cereals, the 60-70 day Indian pearl millet varieties are an example of a plant type that can cope satisfactorily in most years in the drier parts of the semi-arid tropics. Like their African counterparts, they can root deeply in soils where water is available at depth, grow vigorously, and also endure a dry period by a combination of mechanisms, and recover by producing fertile tillers either from the basal nodes or from the upper nodes of elongated tillers.

Adaptation to Drought at the Level of the Production System

A second level of adaptation to drought exists at the level of the diversity in the farmers' production systems that have sustained human populations in dry regions, often over many years. The main purpose of this section is to suggest that a part of the solution for the problems of arid and seasonally arid environments is to be found in a study of the rationale of the adaptation of the existing systems of production in seasonally arid areas, and that we need to think about individual crops in the context of the systems in which they are grown.

The first plantings in the production systems of the wetter parts of seasonally-arid northern Nigeria are of short-season pearl millet. It is sown at wide spacing so that it can make best use of the limited and uncertain supplies of water to become established and survive until the onset of the main rains. This provides an early supply of food, often in late July or early August, to break the hungry gap which is a predominant feature of rural life in many years.

When the main rains appear to be assured, the main staple crop of sorghum is sown among the early millets. These sorghums are photoperiod sensitive so that whenever the uncertain start of the main rains allows them to be sown, they will come to flower at a time closely related to the average date of the end of the rains (Curtis 1968). Since this date is far more constant from year to year than the date of the onset of the rains, this sequence of production activities provides an inbuilt measure of insurance against effects of rainfall variation at the beginning of the season.

When the gaps in the sorghum crop have been filled and the weeding has been completed, often around the end of July or early August, long-season, photoperiodic cowpeas are sown amongst the sorghum, including the space vacated by the millet. The cowpea canopy helps to protect the surface of the soil from the impact of the heavy August rains and, by preventing erosion and surface sealing, it may help to maximize the accumulation of water in the profile as a reserve for the maturation period of the crop.

Further north in Nigeria, in more arid areas, the production systems are based more and more on day-neutral plant materials, which flower in a determined time after emergence irrespective of daylength, and so maximize the chances that the crop will produce at least some yield. Many of these desert ephemeral types complete their life cycles extremely early. The well-known 60-day cowpeas of Nigeria are an example.

In the traditional groundnut-producing areas of Gujarat, India, adaptation to the uncertain dryland environment has been achieved through growing both sequential and alternately branched cultivars, ranging in duration from 85 to 125 days. In recent years farmers have experimented with the deeper rooting sunflower as an intercrop with groundnut to add further adaptability to the system. In the arid areas of western Gujarat and Rajasthan, the practice of fallow to accumulate water in the soil, in combination with early maturing millet sown at wide spacings, is a popular strategy with farmers.

In other systems of the seasonally-dry tropics in Asia and Africa, producers capture and distribute runoff from higher ground by a wide variety of methods. The ultimate development of these systems is recycling water stored in dams by means of canal irrigation, or stored below ground by means of pump and tubewell irrigation, as commonly seen in the drier parts in the Indian subcontinent, and in some areas in Nigeria and Zimbabwe.

In all regions in which agriculture is conducted in an uncertain and unpredictable environment, production systems seem always to include an element of storage—of water, food, cattle and other livestock on the hoof, or valuables and money hidden in the house, or more securely deposited in the bank. One of the most important means of offsetting the risk of drought is to store food, and particularly to store excess production from a good year for use in the year or two ahead. This means than an important task in offsetting the effects of drought is to ensure that storage losses are minimized.

Studies on the indigenous storage systems of the drier parts of Mali found that the average storehouse constructed by a family for its own use was large enough to hold 3 years' requirement (Gillman quoted in Bunting 1985). The store could be filled in a good year, and after that the family had some insurance against climatic difficulty for several years to come. This was assured by the mode of construction of the store and by heritable, inbuilt resistance to storage pests in the grain. Gilman found that traditional varieties of grain, stored in the traditional way, lost on average no more than 2% to insects in the course of a year. The largest loss he measured was 5%. By contrast, the improved, high-yielding varieties promoted by government, stored in the traditional store, lost 30% in a year. They had no resistance to storage pests because they had not been bred for this attribute.

Summary

Principles governing the choices of crops dry cropping systems for use in the seasonally dry tropics are based on:

- the nature of the water regime in these areas and the soil water availability to crops as supply factors;
- the evaporative demand of the air and the extent of crop cover as demand factors;
- the relationships of transpiration and dry matter production, as circumscribed by the limits of season length and partitioning of dry matter to economic yield and production factors; and
- adaptations to moisture deficits both at the crop and the production system level as specific opportunities or requirements for individual systems or crops.

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Applications of, and Limitations to, Crop Growth Simulation Models to Fit Crops and Cropping Systems to Semi-Arid Environments

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Abstract

Crop growth simulation models have considerable potential for evaluating crops, crop varieties, and cropping practices in arid and semi-arid regions. Models for many of the world's major crops have been developed and are available for such applications. The selection of a candidate model should be based on its sensitivity to factors of interest to the researcher, the availability of inputs, the ease with which the model can be used, and the model credibility (is it validated?). If a suitable model for the crop of interest does not exist, present models can be adapted to simulate the crop. We describe here a systematic approach followed to convert our soybean crop growth model (SOYGRO) to simulate growth and yield of groundnut (PNUTGRO). To illustrate plant breeding applications of crop growth simulation, sensitivity analysis was conducted on various crop genetic traits simulated by PNUTGRO using 21 years of Gainesville weather and 3 planting dates. Simulations with PNUTGRO were done with 4 years of weather from Niamey, Niger, to demonstrate management applications: optimum sowing date, cultivar choice, and sowing density for a semi-arid environment.

Résumé

Applications et limitations des modèles de simulation de la croissance des cultures dans le but de l'adaptation des cultures et des systèmes culturaux aux milieux semi-arides : Des modèles de simulation de la croissance des cultures peuvent être particulièrement utiles pour l'évaluation des cultures, des variétés et des pratiques culturales dans les régions arides et semi-arides. Des modèles ont été développés pour les principales cultures mondiales et sont disponibles pour telles applications. Les bases de la sélection d'un modèle devraient tenir compte surtout de la disponibilité des intrants, l'utilisation facile du modèle, sa validité et sa sensibilité pour les facteurs étudiés. Des modèles actuels peuvent être adaptés pour la simulation pour une culture donnée en l'absence d'un modèle approprié. Une approche systématique est décrite dans cette communication qui a été suivie en vue d'adapter le modèle de croissance de la culture de soja (SOYGRO) pour la simulation de la croissance et du rendement des arachides (PNUTGRO). L'application de la croissance des cultures à l'amélioration des plantes est illustrée par l'analyse de la sensibilité de différentes caractéristiques génétiques simulées par PNUTGRO. La simulation a été effectuée avec les données climatiques de 21 années de Gainesville, aux Etats-Unis et trois dates de semis. Des simulations avec PNUTGRO pour démontrer les applications de gestion—la date de semis, le cultivar ainsi que la densité optimaux dans un environnement semi-aride—ont été basées sur des données climatiques d'une période de quatre années de Niamey au Niger.

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Selection and Testing

The objective of this paper is to present the potential and limitations of crop growth simulation models to evaluate various crops, crop varieties, and cropping systems for arid and semi-arid regions.

Model Suitability

In the selection of a crop model, several critical factors should be evaluated. First, does the model respond to the factors of interest and over the range of values expected in this environment? For studies that involve fitting crops to semi-arid environments, the model should, at a minimum, respond to temperature, radiation, and drought stress (e.g., rainfall and soil water-holding traits) as it predicts the crop duration, growth, and yield. Typical studies and factors of interest might involve sowing dates, sowing patterns, and crop varieties. As suggested by van Keulen and de Wit (1984), there are several levels of analysis for which models might provide answers:

1. genetic potential response to radiation and temperature (water and nutrients not limiting);
2. growth and yield response to radiation, temperature, and water (water limiting, nutrients not limiting); and
3. growth and yield response to radiation, temperature, water, and nutrients (water and nutrients limiting).

Answers to level 2 questions will require the model to have a soil water balance subroutine and drought stress effects on growth processes. Answers to level 3 questions will require adding effects of nutrient balance and stress from inadequate nutrients on growth processes (Virmani et al. 1977). To be suitable for semi-arid regions, we believe candidate models must include:

1. soil water balance and rooting traits, preferably by layers;
2. sensitivity of photosynthesis, transpiration, root-shoot partitioning, leaf expansion, leaf senescence, and seedset to a modeled plant water status parameter; and
3. responsiveness to planting density, row spacing, and planting dates.

Input Availability, Simplicity, and Credibility

A second factor is the availability of inputs to run the model. Some models require so much data which are not available for a site that it may be impractical to use them. A third factor is whether the model is simple to use? This relates more to availability of inputs than to the level of detail in the model. A model could be very complex but require readily available data. A fourth factor is the credibility of the model. Has it been validated in enough places and for similar types of environments? If not, can it easily be validated for a given site so that results can have credibility?

What degree of detail or simplicity is necessary in models for fitting crops and systems to the environments? Simplicity in a model may be desirable; however, highly simplified models frequently cannot answer the questions of interest. Moreover, they often require careful recalibration for each new application or site. Detail or complexity in the model may be desirable to allow many ideas to be tested, but there is also a "degrees of freedom" problem in which the greater the number of variables and parameters in the model, the less certainty there is which ones must be changed in order to correct a problem in the simulation. Also, as the complexity of the model is increased, there is often an increase in the amount of information requested by the model in order to run the simulation. Can the required values for parameters be easily obtained? What are the requirements for soils and weather information? If the input requirements are readily available, then a more complex model may be suitable if the model is credible.

Problems of Limited Data Availability

There are two ways in which limited data availability can have an impact. First, are sufficient data available to run the crop growth model? This includes all necessary weather inputs, soil water-holding characteristics, soil fertility attributes, and the crop genetic attributes. With such information, the model can be run for a region; however, the model's credibility cannot be determined until measured data on crop output are taken.

Because crop models are very sensitive to weather conditions, limitations in the availability or quality of weather inputs can restrict the use of models for a given area. When a crop model is to be compared with experimental data for a particular year and site, weather data for that site and crop growing season are essential. Errors in the data or the use of uncalibrated sensors for data collection could lead to poor comparisons between simulated and measured crop outputs even if the model itself is accurate. When a crop model is to be used for analysis of management options for sites where experiments have not been conducted, good quality weather data are still necessary. Usually, several years of accurate weather data are needed to allow analysis of the year-to-year variability in crop yield for different management practices associated with weather variability (Boggess et al. 1983).

A second problem is the limited availability of data on intermediate in-season measurements of crop growth and soil water status for comparing with simulated predictions. For example, if only final yield information is available, the modeler has very little information on which to improve the model. Thus, there should be a limited number of very complete data sets, to allow the simulations to be internally calibrated versus intermediate measurements of soil water and crop state variables such as leaf area index, crop mass, mass of component parts, pod numbers, seed numbers, and seed size. Once such a calibration is completed, we can have more confidence in using the model in a summary mode, when only final yield information is available. In such summary simulations, model parameters should not be blindly changed in order to obtain a fit to the experimental data.

Extension of Single-Crop Models to Other Relevant Crops

What is the adaptability of a given crop model? Can a given crop model be adapted for another crop? How transportable is the model, i.e., can it be used in a highly different cropping system and different area? For example, how easy is it to transfer a given groundnut model developed for full season, high technology cropping systems in the USA, to short season, low technology, semi-arid cropping systems in India?

We will illustrate how a simulation model of soybean (SOYGRO) has been adapted to simulate another crop, groundnut. An early adaptation of SOYGRO V4.2 to simulate groundnut (Boote et al. 1983) demonstrated a hypothetical coupling to effects of leaf-spot disease injury. A detailed description of the subsequent conversion of SOYGRO V5.0 to simulate groundnut (PNUTGRO) is given by Boote et al. (1986). We started with SOYGRO V5.0 (and V5.3) because it has user-friendly interfaces and user-friendly graphics output, runs on IBM-PC compatible microcomputers, has a transportable soil water balance subroutine, and has modular code structure. Modular structure allows easy adaptation of one subroutine at a time. The model also has input files of crop-specific and cultivar-specific traits which are easily changed with no need to recompile the code. The most recent SOYGRO version (V5.3) also has a file input structure that provides simple and separate input files for soil water characteristics, weather inputs, crop management information, and fertility practices. In fact, we have attempted as much as possible to remove from the code, coefficients for crop-specific, genotype-specific, soil-specific, and management-specific traits, and to place them separately into input files. This makes the code more generic in contrast to having coefficients "hard-wired" into the code.

Our approach to adapt the model for groundnut was to use as much of the SOYGRO Version 5.3 code as possible, and to change only those parameters that are species or variety specific. The majority of changes were to two input files which pertain to species and variety characteristics; however, minor code changes were made in some subroutines. PNUTGRO uses the same differential equations as SOYGRO to describe crop growth (Wilkerson et al. 1983, Wilkerson et al. 1985). Important processes considered include: photosynthesis, synthesis and maintenance respiration, partitioning, Nremobilization, pod addition, senescence, soil water balance, and evapotranspiration. Data collected at Gainesville, Florida in 1981 (Boote, unpublished) were used to calibrate PNUTGRO and to estimate parameters not available in the literature. The data set consisted of daily weather information and periodic dry matter samples for an irrigated crop of cultivar 'Florunner' planted 1 Apr 1981.

During the adaption of SOYGRO to simulate Florunner groundnut, we developed a systematic procedure which we believe has important implications for anyone who wishes to adapt an existing model for a new crop. Important features to adapt and the suggested order of adaptation are:

1. Before running any simulations, estimate the cost of tissue synthesis for each plant part based on approximate tissue composition using the method of Penning de Vries and van Laar (1982).
2. Estimate parameters associated with protein mobilization: initial and final fraction protein in vegetative tissue.
3. Develop parameters to predict phenological development (V and R stage) as a function of temperature and photoperiod.
4. Obtain initial weights per plant at emergence, initial fraction leaf, stem and root, and initial specific leaf area (SLA).
5. Develop coefficients that describe dry matter partitioning among vegetative plant parts (leaf, stem, root) as a function of V stage up to flowering, and subsequently, as a function of R stage.
6. Describe changes in SLA versus crop life cycle (growth stage).
7. Develop coefficients for photosynthesis response to solar radiation, LAI, temperature, and water status. For a given data set, response to solar radiation interception can be calibrated to give the approximately correct slope to total dry matter accumulation in the linear phase, up to 80-90 days.
8. Develop parameters for pod addition rate, growth rates, and growth durations per shell and per seed. The reason for calibrating pod addition here, is that pods have first priority for assimilate, thus rate of pod addition establishes the rate of switchover to reproductive growth. The remaining fraction goes to vegetative growth.
9. Determine the upper limit of assimilate partitioning to pod and seed growth (soybean is 100% whereas groundnut can be 50-90%).
10. Determine whether fruiting will be determinate or indeterminate. Can more fruits add after early ones mature?
11. Determine whether leaf area growth will be determinate or indeterminate.
12. Carefully set and adjust shell growth rate, shell growth duration, seed growth rate, seeds per pod, and maximum shell-out, because they are interrelated and together define the seed filling period, seed size, and weight per pod.
13. Determine the rate of protein remobilization from vegetative parts and the amount of associated leaf abscission.

All these parameters should be initially determined for a well-irrigated crop. Then, drought and fertility effects can be determined, especially for items 3, 5, 6, 7, 8, 12, and 13. Moreover, rooting and other response to drought should be developed from data observed on paired treatment studies on drought-stressed versus irrigated plots.

Our experience showed that several iterations are needed to calibrate and set the above parameters, especially those related to photosynthesis, partitioning, pod addition, pod growth, and seed growth characteristics. However, if sufficient intermediate growth data are available, there are logical reasons for the decision on which parameter(s) to change. It is also important to use the actual irrigation record rather than to assume adequate irrigation.

The PNUTGRO model has been successfully adapted from the SOYGRO V5.3 code and uses the IBSNAT-input-output file system (IBSNAT In press). We have calibrated the model based on Florunner groundnut at Gainesville, Florida. Boote et al. (1985) describe the above conversion process and show simulated results versus experimentally- measured LAI, dry matter accumulation, pod numbers, and shelling percentage for Florunner groundnut. We plan to validate PNUTGRO against independent data sets for Florunner groundnut collected in the southeastern United States. We also plan to adapt it for simulating short-season groundnuts grown in semi-arid regions. The code has several improvements over the original PNUTGRO code. We now grow individual cohorts of fruits from shell addition though to seed maturation, and can now simulate individual fruit maturation and percent mature (100% filled) pods.

How can PNUTGRO or another existing model be adapted to a new cropping system? What is different about the new system versus the one for which the model was developed? Are the crop cultivars the same and have they been described in terms of climatic effects on life cycle progression? The most common situation will be that the cultivars are different and that they have not been described. If so, genetics parameters would need to be measured for the cultivar of interest. These parameters should define the life cycle and length of growth phases for the cultivar relative to temperature and photoperiod.

Are the soils the same? If the soils are highly different, can the different characteristics of water flow, water-holding capacity, and water uptake be adequately described in the soil water subroutines of the model? Is the available soils information described in a standard way accepted by the modeling or scientific community? All modelers hope their models have the proper responsiveness to soil and aerial environment. Often the latter is not true and coded relationships in the model as a function of temperature or drought stress, for example, may need improvement.

Finding such discrepancies in the model leads to improvement of the model, especially if appropriate research is conducted to determine the correct relationship to a soil or aerial environmental factor. Crop genetic parameters and growth process relationships to aerial or soil environment should not be considered infallible, because the specific coefficients for some of these relationships depend on how the modeler defines the relationships. Coefficients for response to photoperiod are a prime example. Phenological equations in response to photoperiod have been developed, but the exact coefficients will depend on how the mathematical relationships are envisioned by the modeler.

Models to Select Crop Variety Attributes Under Different Water-deficit Situations

Crop growth models can be used for plant breeding applications. The models can be used to vary crop genetic traits hypothesized to influence crop growth and yield response to various water-deficit situations. An important principle to recognize is that a model can be sensitive to a given trait only if the modeler uses that trait in a manner that influences yield or that influences yield response to soil and aerial environment. Given this premise, the modeler can sometimes change the coding to make the model sensitive to the trait; nevertheless, this should be recognized as being the modeler's concept of how that trait influences yield in his model.

Given the above precautions, there are a number of crop and cultivar traits that can be hypothetically changed which could influence yield response of a SOYGRO- or PNUTGRO-type model to water-deficit situations. The soil water-holding traits and the water- deficit situation (daily rainfall amounts and length of rainy season) should also be defined, because they will influence the impact of various cultivar traits. We have done this type of genetic sensitivity analysis with PNUTGRO under natural rainfall conditions for Gainesville, Florida with 21 years of weather data.

To make the simulations relevant to semi-arid regions, life cycle and partitioning coefficients representative of a short-season cultivar were used. Phenological progression toward R stages was similar to the Starr cultivar reported by Boote (1982) and partitioning was similar to that reported by Duncan et al. (1978). A 180-cm deep sandy soil profile was used with a lower limit plant extractable water content of 0.045 (volumetric), a drained upper limit water-holding capacity of 0.11, and a saturated upper limit of 0.23. At Gainesville, the profile is very likely recharged prior to planting by fall-winter rains, unless a significant crop had grown on the plots until shortly before planting. Moreover, Florida producers wait for rains to wet the topsoil prior to planting. Thus, for sensitivity analyses at Gainesville, the simulations began with a full soil water profile (0.11 volumetric) prior to sowing. For Gainesville, three sowing dates (15 Apr, 15 May, and 15 Jun) were used for each of the 21 years of weather data. This was to span the range of typical sowing dates and to obtain different weather profiles even within years.

In order to be quantitative, we evaluated the percentage yield response of PNUTGRO to a

10% change in a given genetic coefficient. The traits that were varied include:

- a 10% increase in rate of root depth growth;
- altered root profile: a 10% decrease in root length density above 30 cm and a 10% increase in root length density below 30 cm;
- a 10% increase in root length to mass ratio;
- altered root:shoot partitioning, with a 10% increase in the fraction allocation to roots at any point in the life cycle;
- a 10% increase in ATOP which shifts partitioning to root as plant water status (TURFAC) decreases;
- a 10% increase in SENDAY, rate of leaf abscision in response to decrease in TURFAC;
- a 10% greater fraction of life cycle devoted to R4-R8 but within the same total life cycle;
- a 10% longer duration from V1 to R4 stage (longer vegetative);
- a 10% longer duration from R4 to R8 (pod-set to maturity);
- a 10% longer total life cycle (V1 to R8);
- a 10% increase in canopy photosynthesis rate;
- a 10% increase in the maximum limit of partitioning to fruits;
- a 10% increase in pod addition rate;
- a 10% change in shelling percentage;
- a 10% increase in N mobilization rate; and
- a 10% increase in senesced leaf per g of protein mobilized.

The results of this sensitivity analysis are shown in Table 1.

Increasing the rate of root depth progression increased the yield by 2.42%, averaged over three sowing dates for 21 years of weather data at Gainesville. The increased water uptake increased seasonal transpiration by 1.70%, and allowed higher LAI (2.81%) and higher biomass yield. Altering the shape of the rooting profile (10% more below 30 cm and 10% less above 30 cm) was even more beneficial to yield increase (2.92%) for essentially the same reasons: greater canopy transpiration (2.24%), greater LAI (4.21%), and greater biomass and yield. Similarly, increasing the root length to mass ratio allowed more water uptake for the same amount of root mass. Seasonal transpiration was increased 1.20% and allowed 1.61% higher yield. In PNUTGRO, these three characteristics only occasionally caused yield reductions among the 63 cases simulated. For real plants, we might speculate that there may be a cost to the plant for growing roots deeper, having fewer roots in the topsoil (less nutrient uptake?), or for having thinner roots (greater resistance?).

Increasing the partitioning to the root decreased pod yield by 1.43%, on average, although yield increases and decreases were present in the 63 cases. The reason for the yield reduction is that increasing the partitioning to root resulted in lower LAI (2.99%) which reduced light interception and photosynthesis, which in turn reduced biomass and yield. PNUTGRO has an ATOP function which increases partitioning to roots as a function of turgor. A value of 0.5 for ATOP means that 0.5 of the expected shoot growth can be diverted to root growth as plant water status (TURFAC) declines from 1.0 to 0. Increasing ATOP from 0.5 to 0.55 resulted in a 0.17 % yield increase. There is no doubt that shifts in partitioning are part of a survival mechanism, but they may have minor effects on pod yield in Florida, because benefits of additional water extraction are offset by reductions in LAI for light capture. Another drought stress-related function, SENDAY, is the maximum fraction of leaf area that can be lost per day due to drought stress (when TURFAC is at 0.). SENDAY had orginally been reduced from 0.05 for soybean in SOYGRO to 0.03 for PNUTGRO. Increasing the sensitivity of leaf loss to drought stress (0.03 to 0.033) decreased yield 0.31 %. Since our uncertainty about these last two traits is great, the range of yield response could be 5- to 10-fold greater than the 0.17% increase or 0.31% decrease simulated.

The life cycle traits are fairly obvious in importance to plant breeders. Increased duration of the reproductive period is a trait frequently associated with increased yield in many crops. Early maturity is also desired by breeders and producers. Thus, a simulation of similar life cycle, but earlier onset of pod addition (R4) was done to increase by 10% the fraction of life cycle devoted to reproductive growth. The simulated effect was a 2.54% decrease in pod yield for the short-season, Spanish-type cultivar at Gainesville. The early onset of pod addition limited LAI (14.82% less), which limited light capture and biomass production (8.33% less). There is likely an optimum

Table 1. Percentage pod yield responses to 10% changes in crop and genetic characteristics in PNUTGRO, simulated with 21 years of weather data at Gainesville, Florida, USA.

	Pod yield (kg ha^{-1})				Change in pod yield (%)		
		Range				Range	
Characteristic[1]	Mean	Min.	Max.	CV(%)	Mean	Min.	Max.
Standard run	3475	1749	4383	19.6			
Drought stress and rooting							
Rate of root depth increase	3550	1781	4409	18.4	+ 2.42	-0.45	+ 8.39
Root profile[2]	3571	1776	4427	18.8	+ 2.92	-0.14	+ 9.36
Partitioning to root	3426	1699	4306	19.7	-1.43	-5.22	+ 2.15
Root length to mass ratio	3527	1787	4411	19.1	+ 1.61	-0.43	+ 4.56
Partitioning to root vs. TURFAC	3481	1754	4383	19.5	+ 0.17	-0.62	+ 1.22
Leaf loss vs. TURFAC	3467	1744	4383	19.9	-0.31	-2.55	+ 0.00
Life cycle traits[3]							
Same R8, 10% increase in reproductive phase	3408	1733	4554	22.6	-2.54	-20.81	+ 5.29
Increase vegetative phase (VI to R4)	3648	1691	4456	17.9	+ 5.38	-3.30	+ 16.05
Increase reproductive phase (R4 to R8)	3858	1766	4834	19.2	+ 11.14	+ 0.95	+ 18.98
Increase vegetative and reproductive phases (V1 to R8)	3991	1705	4939	18.1	+15.41	-2.49	+31.67
Other traits							
Maximum canopy PG	4021	2150	4930	16.7	+ 16.51	+ 9.10	+30.52
Maximum partitioning to pod	3658	1857	4704	20.9	+ 4.97	-0.40	+ 8.11
Pod addition rate	3515	1811	4493	20.4	+ 0.95	-3.71	+ 3.55
10% decrease in shelling percentage[4]	3392	1723	4284	20.3	-2.55	-11.75	+ 0.86
Vegetative protein mobilization rate	3420	1734	4308	19.7	- 1.61	-3.49	-0.87
Leaf loss per gram of protein	3474	1749	4389	19.7	-0.07	-0.51	+ 0.62

1. 10% increase except as noted below.
2. Same total root length, but 10% more below 30 cm and 10% less above 30 cm soil depth.
3. Days after planting (DAP) to RI, R4, and R8 were 31.4, 49.3, and 117.3, respectively, for the standard simulation, over 21 years and 3 dates. The DAP to R1, R4, and R8 were 31.4, 42.4, and 117.3 for the early R4 (same R8 maturity) simulation. The DAP to R1, R4, and R8 were 33.3, 52.9, and 121.2 for the increased vegetative phase (V1 to R4) simulation. The DAP to RI, R4, and R8 were 31.4, 49.3, and 124.8 for the increased reproductive phase (R4 to R8) simulation. The DAP to RI, R4, and R8 were 33.3, 52.9, and 128.8 for the increased total life cycle (V1 to R8) simulation.
4. Maximum shelling percentage was decreased from 78% to 71.8%.

combination between the start of pod addition and LAI establishment relative to increased pod-fill duration, within a fixed life cycle.

Allowing a 10% increase in the vegetative phase (V1 to R4) increased yield 5.38%, even with the same duration of pod-fill. The yield increase was associated with increased LAI (9.09%) and increased production of biomass (7.58%). Seasonal canopy transpiration was increased 5.67% because the total life cycle was increased from 117.3 to 121.3 days. Keeping the time to R4 unchanged, but increasing the duration from R4 to R8 by 10% gave a 11.14% increase in yield. Seasonal canopy transpiration was increased by 8.07% because of longer crop duration (117.3 days to 124.8%).

Allowing both longer vegetative and ionger reproductive phases to occur together (10% increase in time from V1 to R8) gave a combination increase in yield of 15.41%, which is almost additive of the benefits of increased LAI and the increased pod-fill duration. The increased LAI, biomass, and seasonal transpiration were 9.97, 13.34, and 13.33%, respectively. The simulated longer life cycle was 33.3, 52.9, and 128.8 days to R1, R4, and R8, respectively. By contrast, Florunner has an even longer life cycle (7 days longer to R4 and 7 days longer to R8). Moreover, Florunner has higher partitioning than the short-season type; thus its increased yield potential is even greater than the 15.41% difference shown here.

A 10% increase in canopy photosynthetic response to solar radiation increased yield 16.51%. The effect on yield is large; however, part of the effect is from the feedback loop whereby greater photosynthesis increased LAI (26.58%), which in turn increased light interception and dry matter production. Moreover, simple simulations of canopy photosynthesis show that a 10% change in maximum canopy photosynthesis requires much larger changes in leaf photosynthesis (25-30%).

Increasing the maximum fraction partitioned to pods from 77.0 to 84.7%, increased yield by 4.97% and resulted in 12.33% lower LAI at maturity. It is particularly interesting that this change, characteristic of the yield improvement of groundnut in the southeast USA (Duncan et al. 1978), resulted in the highest coefficient of yield variability compared with all other sensitivity parameters changed. Apparently, making the plant more determinant during pod growth and reducing concurrent vegetative growth, created lower yield stability. This simulation verifies the adage that low-yielding plants have the most yield stability. Increasing the rate of pod addition by 10% increased yield 0.95%. Adding pods faster also resulted in 5.13% lower LAI and also increased the CV for yield. The effect of decreasing shelling percentage from 79 to 71.82% was to reduce yield by 2.55%. This difference in shelling percentage approximates the difference between small-podded types and large-podded (Virginia) types.

Protein mobilization from vegetative tissue is assumed to occur as soon as there are seeds to use the mobilized N; nevertheless, the rate of mobilization is assumed to be a vegetative trait, not created by "sink demand". A 10% increase in rate of protein mobilization (a more self-destructing crop) reduced yield by 1.61% and reduced final LAI by 2.75%. We presently assume that for every g of protein mobilized from the leaf, 1 g of leaf (no available protein) is abscised. Increasing that to 1.1 caused a negligible reduction in yield (0.07%). Nevertheless, we have considerable uncertainty (a two- to three-fold range) regarding the choice of a value of 1.0.

Other sensitivities possible, but not attempted, include varying the turgor sensitivity for duration or rate of progress through various reproductive phases and varying the turgor sensitivity for pod addition beyond any effect on photosynthetic reduction. We plan to do such hypothetical simulations in the future, but we have virtually no experience or data on which to check whether the outputs of such simulations are realistic.

Use of Models for Testing Crop Management Practices to Minimize the Effects of Rainfall Variability

For a given climatic region with years of weather and rainfall data, hypothetical simulations to optimize the yield response and stability relative to management practices are possible with crop growth models. Management practices available to test with crop growth models may include: varying sowing dates, varying row spacing and sowing density, and varying cultivars if different cultivars are an option. In order to do a valid evaluation, a substantial number of weather years for a given location is best. We used 21 years at Gainesville for such simulations in this paper. Alternatively, a weather simulator could be used (Richardson, 1985).

We simulated the response of PNUTGRO to sowing every 15 days from 15 Mar though 1 Aug for the 21 years of weather at Gainesville, Florida. The short-season cultivar type and soil characteristics were described previously in the sensitivity analysis section, except that the initial soil water profile was at 0.045 for 0-15 cm, 0.077 for 15-30 cm, and at 0.11 for depths below 30 cm. Simulations were initiated 15 days prior to sowing, so that rains within the 15 days prior to sowing could recharge the profile. Sowing on 15 May resulted in the greatest simulated yields (3577 kg ha^{-1}) with the lowest coefficient of variation (CV) across years (16.9%) (Table 2). This high yield occurred despite having nearly the shortest life cycle duration (114.7 days) compared with earlier or much later plantings. Maximum yields attained (good rainfall years) were quite stable (4121-4646 kg ha^{-1}) over all planting dates. However, the minimum yield (low rainfall years) was stable only between 15 Mar to 15 May sowings, then it declined slightly to 1851 and 1749 kg ha^{-1} for 1 Jun and 15 Jun sowings, and collapsed to 938 and 819 kg ha^{-1} for 1 Jul and 15 Jul sowings, respectively.

The lowest CVs for yield occurred for sowings between 15 Apr to 1 Jun. This generally coincides with the recommended sowing dates in Florida. The CV for yield generally followed the pattern of CV for rainfall received during the crop life cycle, which was lowest for Apr and May sowings and higher for very early or late sowings. These simulations are consistent with the weather pattern in Gainesville of dry periods in Apr-May or in Sep-Oct bracketing a generally rainy Jun-Aug. These simulations suggest that sowing after 1 Jul without irrigation would be risky in the Gainesville area. It is risky for another reason. For 15 Jul sowings, freezing temperatures were encountered in 3 of the 21 years at 6, 7, and 10 days prior to simulated maturity. A temperature of -2.2°C or less causes LAI to go to zero in PNUTGRO. For 1 Aug sowings, leaf-killing temperatures (-2.2°C or below) occurred in 17 of 21 years prior to simulated maturity. Further results for 1 Aug sowings are not shown because normal maturity was not reached.

Simulated sowing date had an interesting effect on life cycle progress (Table 2). Early and late sowings caused longer life cycle durations but for different reasons. Early sowings delayed flowering and onset of pod-set, whereas late sowings had rapid flowering and pod-set, but were slower developing during pod-fill. Sowing on 15 Mar resulted in 48 and 69 days to R1 and R4 stages, whereas 1 Jul and 15 Jul sowings flowered in 27 days and reached first full-sized pod at 44 days. The simulated later maturation (137 days) for 15 Jul sowing, is qualitatively correct, but is probably too drastic a delay because we use air temperature to drive development. Actual development is probably also a partial function of fruit and root zone temperature which lags the seasonal cycle in air temperature.

The predicted average canopy transpiration (T) over the crop life cycle was nearly the same at 303-295 mm for rainfed crops planted 15 Mar through 15 May at Gainesville. Transpiration began to decline slowly for later sowings and reached its lowest level at 243 mm for 15 Jul sowings. The predicted seasonal evapotranspiration (ET) was very stable across sowing dates: declining slowly from 419 mm for 15 Mar sowings to 381 mm for 15 Jul plantings. This stability in T and ET occurred inspite of crop life cycle duration changing from 138 days for 15 Mar sowing to 113 days for 1 Jun planting to 137 days for 15 Jul sowing. Apparently the longer life cycle for early and late sowings (caused by cooler temperature), mostly offset the lower energy available for T and ET in early spring or late fall. These values for T and ET are simulated under rainfed conditions and do not represent the crop water requirement.

Optimum sowing date was simulated for each of 4 years of Niamey weather, beginning 1 Jan with a dry profile (0.045% volumetric soil water for all depths to 180 cm). Other soil and cultivar characteristics were the same as for Gainesville simulations. To emulate the farmer's decision to sow after significant rainfall, sowings were triggered 1 day after receipt of 20+ mm of rain received in a 5-day period, or after receipt of 28 or more mm of rain received in a 20-day period. As

Table 2. Maturity, pod yield, leaf area index (LAI), biomass, and water balance characteristics for different simulated sowing dates using PNUTGRO with 21 years of weather data at Gainesville, Florida, USA.

	Simulated sowing date								
	March	April		May		June		July	
Characteristic	15	1	15	1	15	1	15	1	15
RI (days)	47.5	40.9	36.6	32.8	30.1	28.1	27.4	26.7	26.6
R4 (days)	69.1	60.9	55.7	50.8	47.7	45.2	44.5	43.7	43.7
R8 (days)	138.2	129.0	123.2	117.8	114.7	113.0	114.1	120.4	136.8
Mean yield (kg ha^{-1})	3194	3283	3408	3491	3577	3473	3402	3237	3258
Minimum yield (kg ha^{-1})	2176	2027	2171	2225	2223	1851	1749	938	819
CV—yield (%)	21.3	20.5	18.5	18.8	16.9	19.2	22.5	25.8	26.5
Rainfall (mm)	647	655	668	671	695	730	712	692	656
CV—rainfall (%)	20.9	18.2	15.1	18.7	17.7	21.4	24.7	21.9	22.6
Transpiration (mm)	303	302	301	297	295	277	264	246	243
Evapotranspiration (mm)	419	415	412	412	414	408	397	386	381
LAI at R8	3.06	3.13	3.34	3.41	3.44	3.27	3.18	2.70	2.51
CV—LAI(%)	24.8	24.3	20.4	21.5	22.1	22.4	26.1	31.6	37.5
R8 biomass (kg ha^{-1})	7215	7330	7646	7741	7882	7624	7503	6931	6748
CV—biomass (%)	19.3	19.6	17.9	18.7	17.7	18.2	21.4	25.0	27.0

shown in Table 3, early sowing was advantageous for this short-season, semi-arid climate. Optimum yield was predicted for the first sowing in 1983 and 1984 (16 Jun and 2 Jun), and for the second sowing in 1981 and 1982 (24 Jun and 22 Jun). Yield declined rapidly as sowing was delayed. Delays of 30 or more days, frequently resulted in less than half of the yield potential of the optimum sowing date.

Deciding on the amount of available water initially in the soil profile is a potential problem for simulations in these semi-arid regions. For the second sowing date above for the 4 years, the simulated crop left about 27 mm of available soil water in the profile, mostly below 90 cm. Simulations were done starting with 27 mm of available water in the profile (0.045% at 0-30 cm, 0.06% at 30-90 cm, and 0.065% at 90-180 cm depths). Based on simulation with this greater initial soil water, the yield was increased in 3 of 4 years (Table 3). Average yield was increased 10.9% from 1185 to 1315 kg ha^{-1}. This average yield oc-

Table 3. Simulated pod yield response to sowing date, cultivar, initial soil water profile, and sowing density, using 4 years of weather data at Niamey, Niger[1].

Sowing date and year	Yield ($kg\ ha^{-1}$) Standard cultivar Starr	Cultivar Florunner	+27 mm of initial soil water	Yield at optimum density	Optimum plant density (plants m^{-2})
1981					
27 May	1654				
24 Jun	1943	1907	2011	2358	13.0
7 Jul	1268				
10 Jul	1128				
12 Jul	1057				
17 Jul	813				
26 Jul	488				
4 Aug	239				
1982					
11 Jun	849				
22 Jun	925	912	1135	1238	60.0
29 Jun	820				
4 Jul	690				
5 Aug	207				
7 Aug	213				
1983					
16 Jun	1412				
22 Jun	1248	1209	1487	1549	11.0
12 Jul	674				
17 Jul	483				
21 Jul	385				
30 Jul	253				
1 Aug	242				
1984					
2 Jun	850				
6 Jul	626	553	625	899	1.0
11 Jul	569				
13 Jul	550				
16 Jul	549				
21 Jul	540				
2 Aug	387				

[1] If not otherwise noted, cultivar is Starr at 0.762 by 0.102 m spacing (12.9 plantsm^{-2}), and soil water profile begins 1 Jan at 0.045% (v/v) volumetric soil water content (no available water).

curred with 316 mm actual seasonal rainfall and 298 mm predicted ET. The average "steady state" amount of soil water simulated to remain in the 180 cm profile was about 31 mm.

Another management decision is the choice of cultivar. This is illustrated by growing two cultivars planted at the second sowing date with the Niamey, Niger, weather. The standard short-season cultivar Starr was compared with the Florunner cultivar (Table 3). With the Niamey weather, Florunner was simulated to begin pod-set at 49.25 days and to mature at 120.5 days. The simulated Starr cultivar reached R4 at 41.75 days and R8 at 106.25 days. In each year, the Florunner simulation produced higher LAI, but lower yields (1145 versus 1185 kg ha^{-1}). Not only was yield lower, but seed size was 13% smaller, and shelling percentage was lower (67.0% versus 69.3%). Unlike the Gainesville sensitivity analysis, the longer-season cultivar did not yield more because of limiting water.

Simulated LAI, biomass, and pod growth are compared for Florunner versus the Starr cultivar for 1983 and 1984 Niamey weather (Figures 1A, 1B, and 1C). As before, the simulated sowing dates were 22 Jun 1983 and 6 Jul 1984. Simulations were started 1 Jan with a dry profile. The increase in LAI, biomass, and pod yield were much greater in 1983 which had more optimum rainfall distribution. The longer vegetative phase of Florunner allowed it to produce a higher LAI in both years (Figure 1 A). Nevertheless, its later start of pod addition pushed the period of pod-fill further into the end of the rainy season, and resulted in lower yield and quality. We are satisfied with the qualitative response of PNUTGRO to semi-arid environments and are anxious to test it against actual field data.

Another management decision is the row spacing and plant spacing in the row. All the previous simulations were done with a 0.762-m row spacing and a 0.102-m spacing in the row to give a plant population of 12.87 plants m^{-2}. PNUTGRO was used to simulate yield response to plant population in equidistant spacing from 1 to 60 plants m^{2} for the second sowing date for the 4 years of Niamey weather. The simulated optimum plant population differed from year to year. Optimum sowing density was 13, 60, 11, and 1 plants m^{-2} in 1981, 1982, 1983, and 1984, respectively (Table 3). In the two drier, unusual years (1982 and 1984), the optimum yields (1238 and 899 kg ha^{-1}) were not far from the yield (1195 and 703 kg ha^{-1}) at 13 plants m^{-2}.

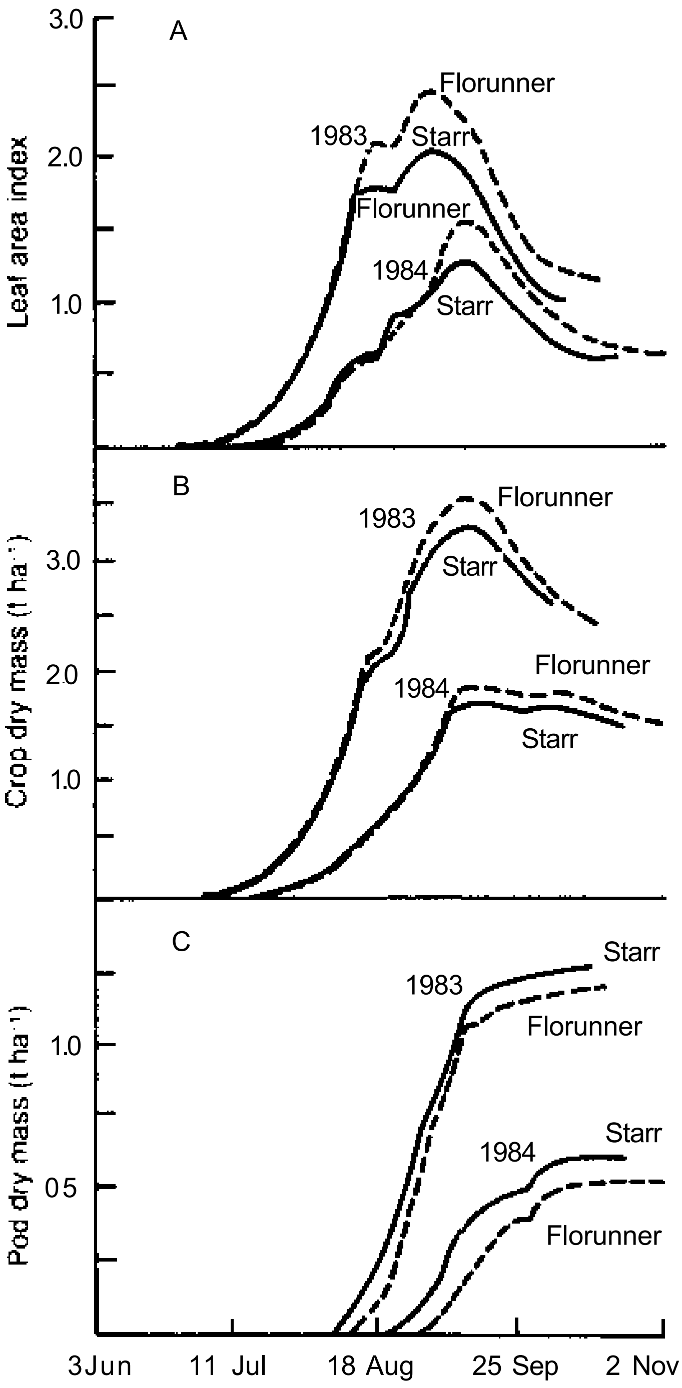

Figure 1. Simulated pod dry mass, crop dry mass, and leaf area index of Starr and Florunner groundnuts for Niamey, Niger, 1983 and 1984.

Several concluding comments and cautions are in order. The yield simulations of a given cultivar versus sowing date will be reasonable only if the model can properly predict growth and phenological response of that cultivar to sowing date (via temperature, photoperiod, and radiation effects). Simulated effects of row spacing and sowing density are likewise somewhat dependent on how the model handles row spacing and population effects on light interception and photosynthesis.

A soil fertility effect on growth and yield would be desirable for its impact on LAI, water consumption, and yield in an analysis of rainfall variability effects. Our models presently do not respond to soil fertility or fertilizer applications, thus we have not done such simulations.

Integration of Single-Crop Models with Multiple-cropping Systems and Farm-decision Models

Can the model be adapted as a subroutine of a larger multicropping, farm management model? Can it be used as one component in a linear programming system to help make decisions on optimum combinations of crops for a given farm or farming region?

In areas where multiple cropping may be practiced, the crop-growth models could be used to study the optimal timing of different crops and the selections of appropriate varieties for a farm. Tsai (1985) developed a structure to run four crop models for selection of the cropping sequence that maximizes profit and the yield stability for North Florida conditions. Other studies have used crop models as inputs to farm management models in which crops, sowing dates, and the time and space arrangement of crops are determined. Such studies could also include any constraints, preferences, or other considerations of the farmer in a particular socioeconomic setting, but this remains to be done.

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Identifying Crops and Cropping Systems with Greater Production Stability in Water-deficit Environments

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Abstract

Water-deficit environments are unfavorable for the growth and development of rainfed crops, and often produce low and unstable yields. The effective cropping season in the rainy season is restricted by both rainfall quantity and distribution, thereby setting limits on choice of crops, cultivars, and cropping systems. For postrainy-season crops grown on conserved soil moisture, it is the moisture storage at sowing time that determines the choice of crops and cultivars.

There is a need to characterize crop growth environments in the arid and semi-arid tropics: rainfall pattern; soil type, depth, moisture-storage capacity, and moisture-release characteristics; and temperature regime. Stability of productivity at a reasonable economic level should be the objective in improving the traditional cropping systems. Under dryland situations, intercropping systems have proved to be more stable than either sole-crop or sequential-crop systems. Crops, cultivars, and cropping systems should be selected so that their growth characteristics fit into the period of moisture availability.

Résumé

Identification des cultures et des systèmes de culture avec une stabilité plus importante de la production dans des milieux déficitaires en eau : Des milieux déficitaires en eau sont défavorables à la croissance et au développement des cultures pluviales et souvent produisent des rendements faibles et instables. La campagne agricole effective est restreinte par la pluviométrie, tant quantité que répartition. Ces facteurs limitent le choix des cultures, des variétés et des systèmes de culture. Quant à la saison post-pluviale, la rétention de l'humidité au moment du semis détermine le choix des cultures et des variétés.

L'environnement de la croissance des cultures dans les tropiques arides et semi-arides devrait être caractérisé : le régime des pluies, le type, la profondeur, et la capacité de rétention d'eau du sol, les caractéristiques de la disponibilité de l'humidité et le régime des températures. La stabilisation de la productivité à un niveau économique raisonnable devrait être l'objectif de l'amélioration des systèmes de culture traditionnels. Le système des cultures associées sous conditions arides s'est avéré plus stable que les systèmes des cultures pures ou séquentielles. Les cultures, les variétés et les systèmes de culture devraient être soigneusement choisis; leurs caractéristiques de croissance doivent être adaptées à la période de disponibilité de l'humidité.

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Constraints to Production

Problems and Approaches

In many arid and semi-arid areas, crop production problems follow a familiar sequence:

- unfavorable crop growth environment;
- limited choice of crops and cultivars, particularly in water-deficit environments and aberrant weather situations;
- low cropping intensity; and
- low and unstable productivity.

Water deficits are responsible for low and unstable crop yields in both arid and semi-arid areas. In addition, nutrient stress and/or environmental stresses may take the water-deficit environment even more unfavorable for crop growth. Land degradation is frequently a serious problem. The arid zones are characterized by harsh climatic conditions, coupled with wind-deposited soils low in organic matter which retain little moisture. Vegetative cover is sparse, and crop yields are low and unstable. Consistant remunerative crop production is diffcult.

The crops and cultivars currently grown in dryland areas are not necessarily the most stable and efficient in terms of moisture use. Many of the existing cultivars of sorghum, pearl millet, pigeonpea, groundnut, castor, cotton, and other crops are not adapted to the rainfall pattern where they are grown. For example, the crop duration is often longer than the effective cropping season. They usually experience drought stress at the most critical stage of their life cycle, which leads to low and uneconomic yields. In order to achieve yield stability, it is necessary to grow crops and cultivars with water-requirement patterns that match the effective growing season. The food needs of the farmer, storability and marketability of the produce, the price at harvest, and susceptibility to diseases and insect pests also govern the choice.

Moisture Availability Periods

The moisture availability period determines the effective cropping season. Based on the analysis of long-term rainfall data in the arid and semi-arid areas of India, effective cropping seasons have been delineated for a number of locations (Table 1). In arid regions, the effective cropping season is normally 11-17 weeks, which restricts the choice of crops, and limits the farmer to a single crop in the rainy season. In semi-arid regions, the effective cropping season is normally longer (22-32 weeks), with the exceptions of 8 weeks in Bellary (Karnataka) and 17 weeks in Bijapur

Table 1. Effective cropping season at various locations in arid and semi-arid tropics of India.

			Rainfall (mm)	
Zone	Location	Growing seasons (weeks)	Monsoon season (weeks 23-39)[1]	Postmonsoon season (weeks 40-48)
Arid	Jodhpur	11	353	8
	Hisar	13	395	19
	Anantapur	13	305	149
	Rajkot	17	572	36
Semi-arid	Hyderabad	22	603	108
	Bangalore	32	400	226
	Bijapur	17	381	130
	Sholapur	23	494	101
	Bellary	8	261	133

1. Standard meteorological weeks: week 1 = 1-7 January.

(Karnataka) regions. Rainy-season crops are grown in shallow to medium Vertisols at Bijapur, while postrainy-season crops are commonly grown in deep Vertisols at Bellary. The rainfall pattern and soil depth together determine the moisture availability period and thereby the choice of crops and cropping systems. In shallow to medium Alfisols and related soils, only single-season cropping, mostly during the rainy season, is possible. On deep Alfisols and Vertisols, double cropping is possible. The amount of rain received in May determines whether or not double cropping is possible on deep Alfisols.

Traditional Crops and Cropping Systems

The traditional crops and cropping systems in arid and semi-arid regions of India are mostly based on farmers' subsistence requirements. They are not necessarily the most efficient for productivity, moisture use, monetary returns, and labor-use potential.

In the arid regions, crops follow a long fallow period (Oct-Jun) and are grown during the rainy season only. Mixed cropping as a means of risk reduction is very common.

On deep Vertisols in the semi-arid tropics of India about 12 million ha are left fallow during the major part of the rainy season (Ryan and Sarin 1981), and a postrainy-season crop is grown on the moisture stored in the soil profile. Sorghum, chickpea, and to a lesser extent, safflower, are commonly grown in central India, either as sole crops or in combinations. The cropping period is underutilized in this system, especially in the medium- to high-rainfall (750-1250 mm) areas. In the north central plains the main crop is wheat, grown mostly as a sole crop, but sometimes intercropped with chickpea. In some Vertisol areas the most common systems are based on cotton. The cotton systems are found on the higher, better drained areas of the toposequence, whereas at the other extreme, rice might be found in flooded areas. Cotton is commonly intercropped with occasional rows of pigeonpea.

In Alfisols, cropping in the rainy season (Jun-Sep/Oct) is common, except in deeper soils where double cropping with a short-duration pulse crop followed by a cereal crop is practiced in good rainfall years.

Basis of Improved Crops and Systems

Stability of Production

A distinction should be made between stability of production and stability of productivity. We are more concerned here with stability of productivity at a reasonable economic level in water-deficit environments. The use of stable crops and cultivars, combined with improved management of cropping systems, imparts stability to production in a given season, and to productivity in a given environment. In an intercrop system, it is often one particular crop component which is more stable than the other components over seasons and years. For example, in the sorghum/pigeonpea, pearl millet/pigeonpea, and groundnut/pigeonpea intercrop systems, it is the pigeonpea that is more stable over environments and seasons than is the cereal or groundnut crop. Similarly, in sequential cropping systems, the crop grown during the rainy season usually has more stable productivity than the crop grown on receding soil moisture.

Rao and Willey (1980) examined the stability of sorghum/pigeonpea intercrop systems from 51 experiments. Based on the coefficient of variation for grain yield, sole pigeonpea (cv 44%) was more stable than sole sorghum (cv 49%), but intercropping was more stable than either (cv 39%). When regressions of yield against an environmental index were computed, sole pigeonpea would fail 1 year in 5, sole sorghum 1 year in 8, but intercropping only 1 year in 36.

Selection of Crops and Varieties

There are various approaches to the selection of crops and varieties. Land-use capability is the ideal concept but is rarely followed in dryland areas. It is the moisture-storage capacity of the soil and water availability that govern land-use capability in dry areas, in addition to factors such as topography, erosion hazard, soil fertility, etc. Moisture-storage capacity depends on the depth and texture of the soil. In shallow, medium, and deep soils having available moisture of about 100,150, and 200 mm, single (sole) cropping.

intercropping, and double cropping, respectively, are possible.

For postrainy-season crops grown on conserved soil moisture, it is the available moisture in the soil profile at sowing time that dictates the choice of crops. As an example, studies at the Dry Farming Research Center of Haryana Agricultural University, Hisar, India, have shown that the choice of postrainy-season crops changes with the conserved soil moisture available (Table 2). Results suggest that short-duration and low-water requiring crops and cultivars should be preferred under receding soil moisture situations.

Table 2. Suggested cropping strategies for different amounts of stored soil moisture at sowing, Hisar, India.

Stored moisture (mm)	Suggested crops
300	Wheat, pea, chickpea
200-300	Wheat (Desi), barley, lentil, chickpea
150-200	Chickpea, barley, raya (*Brassica juncea*), sarson (*Brassica campestris* cv brown sarson), chickpea
75-150	Raya, chickpea, possible in better-catchment areas
50-75	Taramira (*Eruca saliva*)

In shallow to medium-deep Vertisols at Sholapur, there is not a great choice among sorghum, chickpea, and safflower since the water-use efficiency (WUE) is almost the same (6.6 to 7.6 kg grain mm^{-1} water used). However, chickpea and safflower prices are higher. Safflower grown at Bellary on a deep Vertisol was higher yielding and

Table 3. Yield, water use, and water-use efficiency (WUE) of different varieties of postrainy- and rainy-season crops, Sholapur, India. Data are means of 5 (postrainy season) or 4 (rainy season) years.

Crop	Variety	Yield ($t\ ha^{-1}$)	Water use (mm)	WUE ($kg\ mm^{-1}$)
Postrainy season				
Sorghum	M 35-1	1.75	247	7.0
	CSH 8R[1]	2.32	220	10.5
Chickpea	N 59	1.38	199	7.8
	Chafa	1.36	212	6.6
Safflower	N 62-8	1.44	212	6.7
	7-13-3	1.54	227	7.3
Rainy season				
Sunflower	EC-68414	1.09	239	4.5
	Mordan	0.96	241	4.0
	EC-69874	1.17	238	4.9
Groundnut	SB XI	1.05	295	3.8
	TMV-10	1.02	274	3.7
	K-4-11	1.03	316	3.3
Pigeonpea	Prabhat	0.75	295	2.5
	S-5	0.92	324	2.8
	No. 148	1.22	325	3.7

1. Data for 2 years only.

more profitable than cotton. Genotypes may differ in their yield potential and moisture-use efficiency. CSH 8R sorghum hybrid used moisture more efficiently than M 35-1 (local) (Table 3). Among rainy-season crops, sunflower was more moisture-efficient than groundnut and pigeonpea.

Table 4. Potential cropping systems in relation to rainfall and soil type, for arid and semi-arid zones in India.

Rainfall (mm)	Soil type	Effective growing season (weeks)	Suggested cropping system
350-600	Alfisols and shallow Vertisols	20	Single rainy-season crop
350-600	Deep Aridisols and Entisols	20	Single cropping with either a rainy- or post-rainy-season crop
350-600	Deep Vertisols	20	Single postrainy-season crop
600-750	Alfisols, Vertisols, and Entisols	20-30	Intercropping
750-900	Entisols, deep Vertisols, deep Alfisols, Inccptisols	30	Double cropping with monitoring
900	Entisols, deep Vertisols, deep Alfisols, and Inceptisols	30	Double cropping assured

Table 5. Crop growth environments in selected locations in the arid tropics of India.

Location	Latitude and longitude	Mean annual rainfall (mm)	Mean annual PET (mm)	Soil		Moisture storage capacity (mm)	Effective growing season (weeks)
				Type	Depth (m)		
Rainy-season cropping							
Jodhpur	26° 18'N 73°01'E	380	1843	Aridisols	0.90	80-90 $(90\ \text{cm})^{-1}$	11
Hissar	29°10'N 75°46'E	400	1616	Aridisols	0.90	80-90 $(90\ \text{cm})^{-1}$	13
Anantapur	14°41'N 77°40'E	570	1857	Alfisols	0.45	40-70 $(45\ \text{cm})^{-1}$	14
Rajkot	22° 18'N 70°47'E	625	2145	Vertisols	0.45	135-145 $(45\ \text{cm})^{-1}$	17

Among pigeonpea varieties, No. 148 had a higher WUE (3.7 kg grain mm^{-1}) than S 5 (2.8 kg grain mm^{-1}), and Prabhat (2.5 kg grain mm^{-1}).

Not all crop cultivars are suitable for all seasons. Some cultivars yield well when sown on time, while others perform better when sown late. Shorter-duration cultivars are preferred for late-sown conditions. With sorghum, for instance, CSH 5 should be sown at the normal (break of the monsoon) sowing time, while CSH 6 (a hybrid that matures 10 d earlier than CSH 5), should be sown when sowing is delayed by 10-15 d.

Cropping Systems Strategy

Rainfall pattern and effective growing season are the most commonly used parameters for the selection of cropping systems. Based on these two parameters, and soil type, different cropping strategies are suggested for different regions (Table 4). In regions receiving 350-600 mm rainfall with an effective growing season of 20 weeks, only single cropping (100% cropping intensity) is possible in Alfisols, shallow Vertisols, deep Alfisols, and Entisols. In deep Vertisols, single postrainy-season cropping is possible in areas receiving 350-600 mm rainfall with a 20-week effective growing season. Intercropping (150% cropping intensity) is possible in regions having 20-30 weeks of effective growing season. In areas receiving more than 750 mm rainfall and having an effective growing season of 30 weeks or more, double cropping (200% cropping intensity) is a distinct possibility.

Table 6. Crop growth environments in selected locations in the semi-arid tropics of India.

Location	Latitude and longitude	Mean annual rainfall (mm)	Mean annual PET (mm)	Soil		Moisture storage capacity (mm)	Effective growing season (weeks)
				Type	Depth (m)		
Rainy- and postrainy-season cropping							
Hyderabad	17°-27'N 78°28'E	770	1757	Alfisols	0.15-0.30	40-75 $(45\ cm)^{-1}$	17
				Deep Vertisols	0.90	300 $(100\ cm)^{-1}$	25
Bangalore	12°58'N 77° 58'E	890	1500	Alfisols	0.90	180-200 $(90\ cm)^{-1}$	32
Sholapur	17°40'N 75°54'E	722	1802	Shallow to medium-deep Vertisols	0.45	135-145 $(45\ cm)^{-1}$	23
Bijapur	16°83'N 75°76'E	680	1650	Shallow to medium-deep Vertisols	0.45	135-145 $(45\ cm)^{-1}$	17
Postrainy-season cropping							
Bellary	15°09'N 76°51'E	500	1738	Deep Vertisols	0.45-0.90	145-270 $(90\ cm)^{-1}$	8

Matching Crops and Cropping System with Crop Growth Environments

Description of Crop Growth Environments

Typical crop growth environments in the arid and semi-arid tropics of India are described in Tables 5 and 6. The moisture storage capacity of the Aridisols of Jodhpur and Hissar is 80-90 mm (90 cm depth)$^{-1}$, while that of shallow Alfisols of Anantapur is 40-70 mm (45 cm depth)$^{-1}$ (Table 5). The crop growth environment is relatively more favorable in Rajkot because of higher rainfall and heavier textured soils. In the deep Alfisols of the Bangalore region and the Vertisols of the Hyderabad region, the crop growth environment is quite

Table 7. Traditional and improved crops and cropping systems for selected locations in the arid tropics of India.

	Crops		Stable cropping systems	
Location	Traditional	Improved	Intercrop	Sequential
Aridisols				
Jodhpur	Pearl millet Moth bean Cluster bean Mung bean Sesame Rapeseed-mustard	Hybrid pearl millet Improved mung bean Castor bean Cluster bean Sunflower Safflower	Green gram or cluster bean/ pearl millet (BJ 104) *Cenchrus ciliaris*/ mung bean (T 44) (normal rainfall) *Cenchrus ciliaris*/ cluster bean (FS277) (for > 500 mm rain)	Pearl millet-fallow Pearl millet (BJ 104)-mustard (T 59) (for > 500 mm rain)
Hisar	Pearl millet Cluster bean Mung bean Chickpea	Hybrid pearl millet Cluster bean Improved mung bean Rapeseed-mustard	Pearl millet/ mung bean Pearl millet/ cowpea (fodder)	Pearl millet-chickpea Mung bean-mustard
Shallow Alfisols				
Anantapur	Groundnut Pigeonpea Foxtail millet Sorghum	Groundnut Castor Pearl millet or sorghum Pigeonpea Mesta (rozella)	Groundnut (Kadiri-1)/ pigeonpea (PDM 1) Groundnut/castor bean Pearl millet/pigeonpea	—
Medium Vertisols				
Rajkot	Pearl millet Cotton Sorghum Groundnut	Sorghum Cotton Castor Groundnut	Groundnut (J-11)/ Groundnut (J-11)/ pigeonpea Cotton/green gram	—

Table 8. Traditional and improved crops and cropping systems for selected locations in the semi-arid tropics of India.

	Crops		Stable cropping systems	
Location	Traditional	Improved	Intercrop	Sequential
Shallow Alfisols				
Hyderabad	Sorghum Castor bean Pearl millet	Castor bean Sorghum Foxtail millet Pearl millet	Sorghum/pigeonpea Pearl millet/ pigeonpea Castor bean/ cluster bean Pigeonpea/ mung bean	—
Deep Alfisols				
Bangalore	Finger millet Maize Groundnut Horse gram	Finger millet Maize Groundnut	Finger millet (PR 202)/soybean Groundnut/ pigeonpea Finger millet/ maize or pearl millet (fodder)	Cowpea-finger millet
Shallow to medium Vertisols				
Solapur	Pearl millet Sorghum Safflower Chickpea	Hybrid pearl millet Sorghum Groundnut Chickpea	Pearl millet/ pigeonpea	Pearl millet-chickpea Mung bean-rabi sorghum
Bijapur	Pearl millet Groundnut Cotton	Hybrid pearl millet Foxtail millet Sunflower Green gram Safflower	Groundnut/ pigeonpea Pearl millet/ pigeonpea Chickpea/ safflower	Green gram - rabi sorghum Green gram - safflower
Deep Vertisols				
Hyderabad	Sorghum Maize Safflower Chickpea	Sorghum Safflower Chickpea	Sorghum/ pigeonpea	Sorghum-safflower Sorghum-chickpea Maize-chickpea
Bellary	Cotton Rabi sorghum Safflower Coriander	Rabi sorghum Safflower Field beans Chickpea Cotton/setaria	Sorghum/coriander Cotton/chickpea	—

favorable for a double-cropping system (Table 6). In Sholapur and Bijapur regions which receive 680 to 720 mm of annual rainfall and have shallow to medium-deep Vertisols, only a single crop is possible during the rainy season. In deep Vertisols, however, a double-cropping system could be adopted. In the deep Vertisols of Bellary which receive 500 mm annual rainfall, the crop growth environment is not favorable for a double-cropping system; only a short-duration postrainy-season crop is taken under such situations.

Selection of Stable Crops and Cropping Systems

The stable traditional crops and more stable crops and cropping systems (intercropping and sequential crops) for selected parts of the arid and semi-arid tropics of India in varied soil types are presented in Tables 7 and 8. In the arid-zone Aridisols, a short-duration (65-70 d) pulse crop grown in association with pearl millet is a more stable system than growing sole pearl millet (Table 7). In good rainfall years, a longer duration crop (cluster bean) could be grown. For shallow Alfisols of Anantapur and medium Vertisols of Rajkot region, groundnut/pigeonpea or castor bean and pearl millet/pigeonpea were stable intercropping systems.

For the semi-arid zones a sorghum/pigeonpca intercropping system is the most stable system both for Alfisols and Vertisols (Table 8). In Vertisols with a moisture-storage capacity of 300 mm, double crops (sorghum-safflower, sorghum-chickpea, and maize-chickpea) form stable cropping systems. On deep Alfisols, a cowpea-finger millet system has good potential. In the Sholapur and Bijapur regions, a pearl millet/pigeonpea system is most stable for light-textured soils. A double-crop system is possible in deep Vertisols, except in Bellary where sequence cropping is not possible, but an intercrop system with sorghum or cotton as a principal crop is possible. The cotton/chickpea intercrop system appeared to be least risky with a LER of 1.3 and 107% return compared with sole cotton.

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Interpretive Summary of Part 2:

Selecting Crops and Cropping Systems for Water-limited Environments

T.R. Sinclair[1]

Introduction

Considerable information and technology has been developed in the effort to match crops and environments. However, this technology is at many levels of complexity and sophistication so that synthesizing widely applicable recommendations is still very complex, but there appears to be some consensus on the approaches required to match crops and cropping systems to their environments.

Three major problem areas need to be resolved in the semi-arid tropics. First, a complete environmental assessment, including quantification of soil water storage and the various water loss processes, is required. Second, the problems of growing crops primarily on stored soil water, usually during the postrainy season when they will be subjected to terminal drought, must be considered. Third, the problems of variable periods and duration of drought during the rainy season need to be evaluated. Each of these problem areas has a set of applicable technologies and potential solutions which are discussed in an effort to identify those approaches having the greatest potential to improve yields.

Assessment of the Crop Environment

The technologies and approaches to assess crops and their environments are immense. Models for these assessments range from empirical evaluations of historical weather records to very detailed and complex models formulated from a mechanistic approach (for discussion see Landsberg 1988). As discussed below, each of these has serious drawbacks to evaluate crop performance under adverse conditions. An intermediate approach between these extremes is also discussed from the perspective of identifying the major constraints to crop productivity.

While analysis of weather records is unquestionably of great importance, unless these data are put in the context of the variables influencing a cropping system, they have minimum value. Rainfall patterns by themselves are not particularly useful unless the soil water-storage capacity, crop-water consumption rate, direct water losses from the soil, and crop response characteristics are known. Further, statistical models may not be of much help in making management decisions for the unique, individual year currently in production. It can be the unusual season (which generally seems to be the current one) that determines the ultimate success or failure of an individual farmer.

Complex models certainly offer a tool to study the mechanisms of the many hypothesized interactions between crops and the environment. For example, the PNUTGRO model (Boote and Jones 1988) incorporates a great deal of the available physiological information on the growth and yield potential of a groundnut crop. The model is used to quantitatively assess the impact on poten-

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tial yield of altered environmental or crop variables (Boote and Jones 1988). However, caution is essential when attempting to extrapolate these complex models to new environments. Many of the relationships and their coefficients are derived empirically from specific growth conditions. In many cases the behavior of specific empirical coefficients, or even the nature of the interactions among relationships, have not been evaluated under a range of drought conditions. Further, these complex models are technically difficult to transfer to new conditions because the background information and data input requirements are usually quite extensive. These complex models are appropriately used to explore the potential effects of altering individual physiological traits under reasonably stable environmental conditions, but are much less appropriate to evaluate cropping systems under adverse conditions.

A possible alternative to the extreme approaches discussed above, is to model the major processes determining crop yield with generalizations about the responses of these processes to the weather. Simple response functions to light and temperature can account for a great deal of the yield variability that is environmentally dependent (Monteith and Scott 1982, Spaeth et al. 1987). An essential feature of this simplified, mechanistic approach to modeling crop production in the semi-arid tropics would be the incorporation of a soil water-balance model.

One of the simplest approaches to account for the soil water balance is to consider the soil as a bulk water-storage reservoir described by the available soil water (Veihmeyer and Hendrickson 1950). It is assumed that soil water is available to the plants between two limits of volumetric soil water content. While the upper limit has been fairly well defined, definition of the lower limit has been ambiguous and difficult to determine experimentally. Commonly the permanent wilting point is used as the lower limit, but it is observed to be highly variable among species (and even varieties) because of variability in the physiology of the various survival traits. As a consequence, compilations of available soil water result in a whole range of values for individual soils (illustrated in Table 3 of Bunting and Kassam 1988).

An alternative recently suggested by Sinclair and Ludlow (1986) is to define the lower limit of available soil water in terms of the decrease in transpiration rate. They suggested the lower limit for biomass accumulation is reached when stomata have closed and transpiration has become negligible. Such a definition is of more direct physiological relevance to crop production because water used after stomatal closure does not support the accumulation of new biomass, and it averts including the soil water extracted during a protracted, survival phase.

Sinclair and Ludlow (1986) suggested that plant use of stored soil water could be divided into three physiologically distinct phases using the concept of transpirable soil water. In Stage I the soil moisture content is high and the availability of water to roots generally causes no inhibition of transpiration rates and photosynthesis. Stomata are open during Stage I and the transpiration is determined primarily by meteorological conditions. Stage II begins when the water supply rate to the roots from the soil is inadequate to meet the transpirational demand. During Stage II the stomatal conductance is decreased to maintain a balance between transpirational water loss rate and the supply rate from the soil. Interestingly for many crops, Stage II begins when 0.2-0.3 fraction of transpirable water remains in the soil.

Stage III begins when little or no additional decreases in stomatal conductance are possible and thus transpirable soil water has been exhausted. Virtually no leaf gas exchange occurs during Stage III and the crop is in a survival mode. In Stage III water loss rate is greater than the supply rate from the soil so the relative water content of the plants slowly decreases. Flower and Ludlow (1986) showed that, in pigeonpea, plant senesence finally occurs when a critical relative water content is reached.

In the scheme outlined above a fairly simple model can be used to account for bulk water storage and the crop response to fraction of transpirable soil water. In simple models of grain legume growth, Sinclair (1986) and Sinclair et al. (1987) also incorporated response functions for leaf growth and symbiotic nitrogen fixation rates to transpirable soil water. These simple models illustrated the importance of the soil water balance, crop ontogeny, and ontogenetic flexibility on crop yields in response to droughts.

In conclusion, a fairly complete assessment of the total crop environment is required to truly evaluate various cropping options for a particular locale in the semi-arid tropics. Certainly soil water storage must be incorporated to be able to evaluate the severity of the drought and its effect on crop production. The total potential water storage in the soil and the extent of soil dehydration have major effects on crop productivity. Variability among cropping systems in the soil water depletion rate and the response functions to the stored water are key assessments to improve crop productivity.

Terminal Drought Environment

The assessment of crop production potential in the terminal drought or postrainy-season environment is relatively straightforward. The amount of water available to support crop production is defined at the beginning of the postrainy season by the amount of available (or transpirable) water stored in the soil. Consequently, the maximum crop production is limited to the amount of stored soil water.

Using the approach of Tanner and Sinclair (1983), it is possible to quantitatively define the maximum crop biomass that can be produced from the stored soil water. They derived a mechanistic expression relating biomass accumulated to the amount of evapotranspiration, i.e., water-use efficiency. By assuming a postrainy season of uniform vapor pressure deficit, the derivation of Tanner and Sinclair (1983) leads to:

$$B \leq (W-E)\frac{k}{(e^*-e)} \qquad (1)$$

where:

B = crop biomass produced (g m^{-2}),
W = total available water (g m^{-2}),
E = total soil evaporation (g m^{-2}),
k = explicit coefficient defined by physiology of crop species or variety (Pa),
(e^*-e) = average daily atmospheric vapor pressure deficit (Pa).

Sinclair et al. (1984) extended equation (1) to define specifically the potential grain production of a crop (Y) by including the harvest index (H = ratio of grain yield to total crop biomass):

$$\frac{k}{(e^*-e)} \qquad (2)$$

In both equations (1) and (2), if evapotranspiration (ET) is substituted for W, then the equations become identities. Consequently, theoretical considerations suggest a linear relationship between crop yield and evapotranspiration. This conclusion has been shown a number of times including studies with sorghum (Garrity et al. 1982b, Stewart et al. 1983), cowpea (Turk and Hall 1980b), and soybean, black gram, green gram, and cowpea (Lawn 1982b).

Equation (2) can be used to estimate directly the yield potential during the postrainy season. As an illustration, estimates are made for crop yield when the stored transpirable soil water is 100, 150, and 200 mm (x 10^3 g m^{-2}). Yield estimates (Table 1) can be calculated for both a C_4 crop (k = 11 Pa) and a C_3 grain legume (k = 5 Pa) by assuming (e*-e) is constant at 2.5 x 10^3 Pa, E/ET for the season equals 0.3, and both crop types achieve a harvest index of 0.5. Clearly, both the amount of stored soil water and the crop species have a large effect on the potential yield (Table 1).

The yield estimates in Table 1 would be increased if the relative amount of soil evaporation during the postrainy season was decreased. Various options exist for minimizing soil evaporation (see Unger et al. 1988). However, it should be noted that incremental yield increases from decreases in E/ET diminish rapidly in equation (2). At some point, the economics of decreasing E will not be fully justified by increased yields.

In addition to the total water storage, the key variable suggested by equation (2) for obtaining yields in terminal drought environments is the harvest index. It is essential in the selection of cropping systems and crops for the postrainy season to attain a high harvest index; that is, the fraction of harvestable component must be large.

Table 1. Maximum seed yield estimated from various amounts of stored transpirable soil water during the postrainy season.

Stored water	Maximum seed yield (g m^{-2})	
(mm)	C_4 Crop	Grain legume
100	154	70
150	231	105
200	308	140

Passioura (1977) demonstrated that harvest index was increased as the percentage of soil water used after anthesis was increased, and suggested altering rooting properties to retard water extraction rate during the vegetative stages of the crop. A similar effect is also achieved by selecting crops with early anthesis to insure water availability for reproductive growth and for the completion of the growth cycle. Hall and Grantz (1981) found in cowpea grown on stored water that the selection of earlier anthesis led to greater harvest indices and yields. Similarly, Saxena (1987) found in chickpeas growing under terminal drought stress that yields were negatively correlated with the days to flowering.

A correlative approach to maximizing water use during the postanthesis period is to identify lines that initiate flowering at an early date and have sequential initiation of seed growth over a fairly long period. Such an indeterminate growth habit allows the number of growing seeds to increase gradually so that the number of seeds reaching maturity is maximized before drought-induced senescence occurs. As a consequence, harvest index and crop yield relative to the stored water is also maximized. The indeterminate growth habit of pigeonpea and chickpea are seemingly examples of the advantageous use of this developmental pattern under terminal drought.

Another approach to maximizing harvest index is to develop crops that can continue to fill seeds during Stage III drought when the crop is in the survival mode. Even though no biomass is being accumulated during Stage III, it would be advantageous to have a crop that can continue seed growth from stored plant reserves during a prolonged survival phase (Blum 1983). At this time, little information exists about seed growth potential during Stage HI drought. However, several mechanisms exist to increase the duration of this survival phase (Ludlow and Muchow 1988) so that increasing the time available to complete seed growth and increased harvest index may be possible.

Consequently, several important options are available to sustain crop production during the postrainy season. Important among these options are the selection of crop species and cropping practices that lead to a completion of the plant life cycle before drought-induced senesence. As a result, high harvest indices and maximized yields for the amount of available water can be achieved. Important cropping practices currently used to take advantage of these concepts are reviewed by Singh and Reddy (1988).

Intermittent Drought Environment

Intermittent drought is a potential stress for nearly all rainfed crops in all types of climates. During the rainy season in the semi-arid tropics, there are clearly episodes of decreased or no rainfall. Whether these periods of deficit rainfall inhibit crop production is an important problem in the environmental assessment, as discussed earlier. Germination and crop establishment is one of the most obvious periods when an intermittent drought can have devastating consequences on crop production. Analysis of historical meteorological records may produce important clues on when to sow crops to take full advantage of early rains, but not subject germinating seeds to drought stress (see review by Stewart, 1988). In addition, genetic material that has improved germination capability under limited soil moisture may be identifiable. Saxena (1987) found superior lines of chickpea that germinate under drought conditions imposed in both the greenhouse and field.

Subsequent to crop establishment, a decrease in stored soil water resulting from an intermittent drought will become important when the crop progresses from Sinclair and Ludlow's (1986) Stage I to Stage II in its use of transpirable soil water. The amount of stored water at the beginning of the drought and the length of the period without rainfall dictate how quickly Stage II is reached and how long the crop is subjected to this condition. A prolonged lack of rainfall will subject crops under intermittent drought to Stage III and crop survival is jeopardized.

Assuming that much of the impact of intermittent drought occurs during Stage II and early stage III, then biomass production is clearly retarded as described by equation (2). Decreases in stomatal conductance and the lack of water to support CO_2 assimilation lower crop productivity. While this loss in productivity once Stage II is reached can occur at any time during crop development, the overall impact on crop yield will vary with growth stage. Stress during crop growth stages of high leaf area indices will have the greatest decrease in yield. At high leaf area indices, the crop gas exchange rates are greatest, so water is lost at the highest rate and Stage II drought is reached more quickly. Further, during periods of high leaf area indices the crop has the greatest potential CO_2 accumulation rates so that inhibited gas exchange at this time results in the greatest productivity loss. This is highlighted in soybean production simulations of Muchow and Sinclair (1986), which showed that 20 days of drought at the beginning of seed growth resulted in much more severe decreases in seed yield than at any other crop growth stage. Yet the model contained no features causing the crop to be uniquely sensitive at the beginning of seed growth.

Aside from the interaction of leaf area and water use, are there any unique crop growth stages that make the crop especially sensitive to drought? Commonly it is suggested that crops at anthesis are especially sensitive. Surprisingly, the evidence suggests this is true only when the crops are subjected to very severe drought stress. To assess whether drought-induced yield decreases are due to overall restricted biomass accumulation or are attributable to some unique sensitivities of reproductive growth and development, harvest index can be used as an indicator. If harvest index remains nearly unaffected by intermittent drought, then there is little special sensitivity of drought on reproductive processes beyond the effect on overall biomass accumulation.

In four grain legumes (cowpea, soybean, black gram, and green gram), Lawn (1982b) found that harvest index was not decreased by drought until the total biomass accumulation was decreased to less than one-third of the irrigated treatment. Spaeth et al. (1984) found harvest index within soybean to be constant when subjected either to various irrigation rates or to drought at various crop growth stages. However, none of their drought treatments decreased total biomass below one-third of the fully irrigated treatment. Turk and Hall (1980a) found the harvest index in cowpea was constant over a wide variation in total biomass production resulting from drought stress.

Similar to the grain legumes, the harvest index of sorghum does not appear to decrease until quite severe drought stresses are imposed. Garrity et al. (1982a) found no decreases in harvest index within sorghum genotypes at differing irrigation rates and at differing growth stages. The maximum decreases in total biomass production were about 40%. In a comparison of fully irrigated and rainfed treatment for two sorghum varieties, Wright et al. (1983) found no decrease in harvest index even though total dry matter production was decreased by more than 40%. On the other hand, Bond et al. (1964) showed some decreases in harvest index in dryland sorghum; but before the harvest indices declined total biomass accumulation was decreased to less than half of the treatment that received the most water.

Consequently under all but very severe intermittent drought stress, the apparent sensitivity of crop growth stage may be more directly attributable to inhibited gas exchange capability than any unique physiology of the anthesis and early seed-growth stages. However, to avoid the potential risk of the very severe intermittent drought on reproductive growth, it is possible to conserve water for the drought episode by altering crop management and/or physiology. If the timing of the drought is quite predictable, then management practices—later sowing dates or lower plant populations—would effectively conserve water to minimize the severity of the intermittent drought. Plant traits may also be altered to conserve water for the drought periods. Lower stomatal conductances, either decreased leaf area or leaf loss during drought, and less dense rooting patterns would all retard water use from the soil (Ludlow and Muchow 1988). Of course each of these water conservation approaches is achieved through decreases in crop gas exchange preceeding the intermittent drought event. No net gain in potential crop biomass accumulation is achieved, but the deleterious effects of late Stage II or Stage III drought on reproductive growth may be avoided.

Since the management practices and physiological alterations required to conserve water for the intermittent drought may actually decrease yield potential, especially during wet years, an attractive alternative is to increase the total soil water store available to the crop. In a simulation study of drought adaptive mechanisms, Jones and Zur (1984) found that increased rooting depth was by far the most effective approach to maintain plant turgor during drought. Experimentally Bhan et al. (1973) found in a comparison among eight sorghum varieties grown during the rainy season that those varieties with roots penetrating more deeply into the soil also had the greatest production of shoot weight. Blum (1974) demonstrated there was considerable genetic variability among sorghum lines in the amount of extracted soil water although no data on possible variation in rooting depth were obtained.

Additionally, in situations where very severe, intermittent drought stress is possible at the initiation of reproductive growth, special consideration of the crop growth pattern may be required. Ontogenetic flexibility within crop plants would be especially desirable for crops subjected to very severe droughts so that reproductive growth can resume after the drought is relieved. Bidinger et al. (1982) found an important advantage of pearl millet in droughty climates is its developmental plasticity. Cultivars have been found that enhance this characteristic by delayed flowering and by the stimulation of secondary tiller growth when subjected to drought. In grain legumes, Lawn (1982a) and Sinclair et al. (1987) concluded that an important advantage of cowpea over other grain legumes when subjected to drought was the ability of cowpea to delay development so that flowering and reproductive growth can resume when the crop is rewatered. Indeterminancy may be a desired trait to confer ontogenetic flexibility when crops are subjected to severe drought.

If the intermittent drought lasts sufficiently long so that prolonged Stage III drought is experienced by the crop, then crop survival is in jeopardy. Ludlow and Muchow (1988) itemized some of the physiological traits that would be desirable to enhance the probability of survival during Stage II drought. These traits include a minimization of water loss by means of leaf shedding and a small epidermal conductance, and a low relative water content at which sensescence occurs. Physiological traits that allow the crop to recover production potential after rewatering and suriving Stage HI drought would also be important.

Conclusions

No matter how sophisticated the technology applied to the cropping system, it is clear crop yields in semi-arid climates are inherently limited by the amount of soil water available to support crop gas exchange. Environmental assessments are crucial to determine when and how much water is available to the crop. However, this is not a small task because quantification of soil water storage capability in terms of availability to support transpiration, and quantification of the various water loss processes, must be an integral part of this assessment.

For terminal drought situations in the postrainy season, assessment of the available (transpirable) soil water allows maximum biomass production to be estimated. The challenge in the application of technology is to optimize the fraction of that biomass that is converted into harvestable plant components. Crop selection strategies and management practices are available to achieve a high fraction of harvestable components during the postrainy season climate (Singh and Reddy 1988).

The intermittent drought of the rainy season is a much more variable and complex situation. Given that soil water is inadequate during intermittent drought periods to sustain maximum crop gas exchange, one of the main effects of these droughts is simply the lack of water to sustain biomass accumulation. Without the possibility of irrigation, an important objective in the application of technology for these intermittent droughts is to maintain the potential for high harvest indices. Certainly several management options and physiological improvements of the crops may be exploited to maintain a high harvest index. If it is possible to have intermittent droughts sufficiently severe to jeopardize the survival of the crop, then additional technologies to improve crop management and physiology are required to minimize the risk. Flexibility in management schemes and ontogenetic development of the crop are both important to minimize the effects of very severe drought.

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Part 3.

Possibilities for modifying crop and soil management practices to maximize production per unit rainfall

Principles of Crop and Soil Management Procedures for Maximizing Production per Unit Rainfall

P. W. Unger, O. R. Jones, and J. L. Steiner[1]

Abstract

Under rainfed cropping conditions, much of the rainfall is not used effectively. Objectives of this report are to discuss reasons for low rainfall-use efficiency and opportunities to improve efficiency through adoption of improved soil and crop management practices. Low rainfall-use efficiencies occur because crop evapotranspiration (ET) is a small part of total rainfall, transpiration (T) is a small part of total ET, and yields are low relative to the amount of water transpired. Practices to improve rainfall use efficiency include those that increase water infiltration and reduce runoff (tillage, residue management, controlled traffic, contouring, terracing, land leveling), increase soil water-storage capacity (profile modification, deep tillage, adding organic matter), reduce evaporation (mulches; tillage; timely, rapid, and uniform crop establishment), reduce deep percolation of water (using deep-rooted crops, installing barriers), reduce ET by noncrop plants (control weeds, volunteer crop plants), and increase yields relative to the amount of water transpired (timely crop establishment, controlling insects and diseases, providing adequate nutrients, timely crop harvest).

Résumé

Principes des pratiques culturales et de l'aménagement du sol pour la production maximale par unité de pluviométrie : Une grande partie de la pluviométrie sous conditions pluviales n'est pas efficacement utilisée pour la production des cultures. Ce rapport essaye d'étudier les raisons de la faible efficacité dans l'exploitation de la pluviométrie ainsi que le potentiel pour améliorer l'efficacité à l'aide des pratiques culturales et l'aménagement améliorés du sol. La faible exploitation de la pluviométrie résulte de trois facteurs essentiels : l'évapotranspiration (ET) des cultures, une petite partie de la pluviométrie totale; la transpiration (T), une petite partie de l'évapotranspiration totale (ET); et les rendements, qui sont faibles par rapport à la quantité d'eau transpirée. L'efficacité de l'utilisation de la pluviométrie peut être améliorée par les pratiques qui augmentent l'infiltration de l'eau tout en réduisant le ruissellement (travail du sol, exploitation des résidus, courbes de niveau, terrasses, nivellement); qui augmentent la capacité de rétention d'eau du sol (modification de profil, travail profond du sol, apport de la matière organique); qui réduisent

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l'évaporation (mulch, travail du sol, établissement rapide et uniforme des plants); qui réduisent la percolation profonde de l'eau (cultures à racines profondes, installation des barrières); qui réduisent l'évapotranspiration (ET) par l'usage des plantes non-cultivées (mauvaises herbes, plantes accidentelles); et qui augmentent les rendements par rapport à la quantité d'eau transpirée (établissement opportun des cultures, lutte contre les ravageurs et les maladies, apport d'éléments nutritifs adéquats, récolte en temps opportun).

Introduction

The crop selected for a given set of environmental conditions, along with its management and the management of the soil in which it is grown, have a major impact on how efficiently rainfall (and other forms of precipitation) are used to produce an economic yield. Other papers at this meeting pertain to crop selection based on analyses of environmental conditions. Therefore, we assume that well-adapted crops have been selected, and will not stress crop adaptation. Our emphasis will be on crop and soil management practices to achieve maximum production of an economic yield per unit of rainfall. Our objectives are to discuss the reasons for low rainfall-use efficiency and the opportunities to improve efficiency through adoption of improved crop and soil management practices. In addition, we will discuss some other factors to be considered when determining which management practices are appropriate for a given crop production situation.

Reasons for Low Rainfall-use Efficiencies

Low rainfall-use efficiencies occur because crop evapotranspiration (ET) is a small part of total rainfall for the crop production cycle (harvest to harvest), transpiration (T) is a small part of total ET for the crop under consideration, and yields are low relative to the amount of water transpired. Soil, crop, and environmental conditions are responsible for low ET to total rainfall, low T to ET, and low yield to T ratios.

Ratio of Crop ET to Rainfall Level

Rainfall potentially available for crop ET is that which falls during the period from harvest of the most recent crop to harvest of the crop under consideration. Water loss from the system other than by crop ET lowers rainfall-use efficiency. Low infiltration and high rainfall runoff, low soil water storage capacity, evaporation (E) of soil water before crop establishment, and ET by noncrop plants all contribute to water losses. Also, crops with limited root systems may not use water from the soil profile effectively, thus contributing to low rainfall-use efficiencies.

Rainfall, soil, and crop characteristics influence water infiltration and runoff. Runoff occurs when rainfall rates and amounts exceed the surface storage capacity and infiltration rate of a soil. This is often the case with intense rainstorms or where rainfall occurs frequently. Under such conditions, a soil may not be filled to capacity because of low infiltration rates due to steep slopes, soil aggregate dispersion and surface sealing, and slowly permeable or impervious horizons in the soil profile. Infiltration may be especially low when the soil surface is smooth, bare, and devoid of crop residues prior to crop establishment or canopy development.

The water infiltration rate of some soils may be sufficiently high to avoid excessive runoff and to fill the soil to capacity, but the plant-available water storage capacity may be low, and therefore contribute to low ratios of crop ET to rainfall levels. Low water storage capacities occur on shallow soils (bedrock or other unfavorable soil conditions at a shallow depth) and on soils with low water retention capabilities. Retention of plant-available water is low on sandy and high clay content soils (Fig. 1). On permeable soils without restricting layers, infiltrated water may be lost from the profile by deep percolation.

Evaporation of soil water is a natural process, but such loss before crop establishment reduces the amount available for subsequent ET by the crop. The amount of water lost by E is influenced by climatic and soil conditions. Losses are greatest where the evaporative demand of the envi-

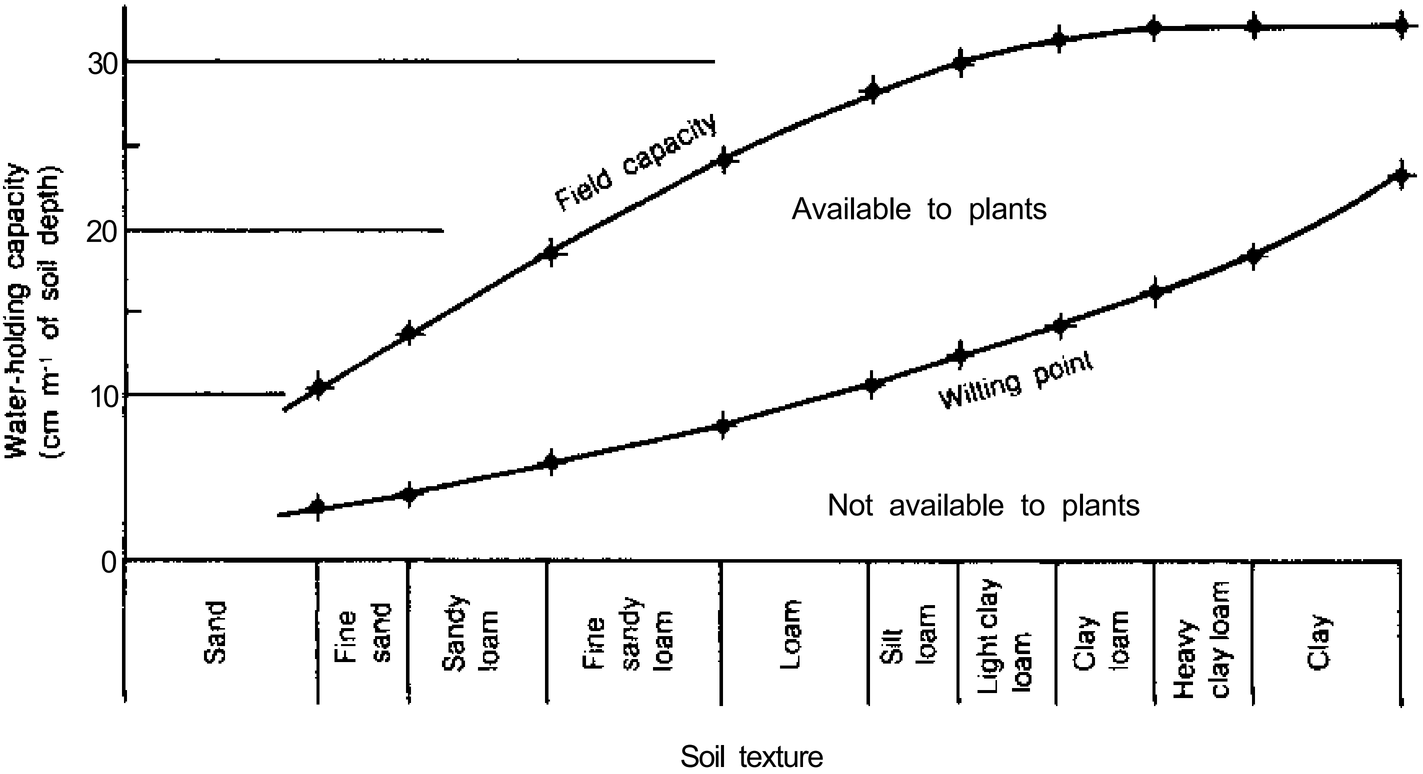

Figure 1. Typical water-holding capacities for soils of different textures (adapted from USDA 1955).

ronment is highest (warm, dry, windy climate) and where soils retain a large amount of water at or near the surface or where the water readily moves to the surface by unsaturated flow or in the vapor phase. Evaporation as a part of total rainfall may be especially high in arid and semi-arid regions where much of the rainfall may occur in small storms. Evaporation is increased when inversion tillage exposes moist subsurface soil to the atmosphere.

Transpiration by noncrop plants is another major means by which soil water that could benefit crops is lost. Losses may occur before crop establishment or during the crop growing season due to the growth of weeds, volunteer crop plants, trees, or shrubs. Uncontrolled weeds and volunteer plants are especially detrimental to soil water storage during noncropped periods (Figs. 2 and 3), and strongly compete for water with crops during the growing season. Additional competition for water occurs where trees or shrubs grow in fields or at the field borders. However, these plants may be useful in some instances as forage for animals, windbreaks, and firewood.

Some soil water potentially available for ET may not be used because the crop plants have a limited root system or because a given crop may not extract water to the same soil matric potential as another crop. In either case, the remaining water may be potentially available to a subsequent crop with a more extensive root system or one that extracts water to a lower matric potential. This remaining water, however, lowers the ratio of ET to rainfall level for the current crop and may reduce the ratio for a subsequent crop because of lower infiltration, lower potential for storing additional soil water, increased percolation and E, and possible loss of the water through ET by noncrop plants.

Ratio of Crop T to ET Level

The T to ET ratio may be relatively low when plant canopies are incomplete due to low and erratic plant populations and poor plant growth. The ratio also may be relatively low when crop growth is poor due to stresses during the growing season.

Numerous factors can lead to low and erratic plant populations, which can result in E being a significant part of crop ET. To assure satisfactory populations, adequate rates of viable seeds and satisfactory seeding methods must be used.

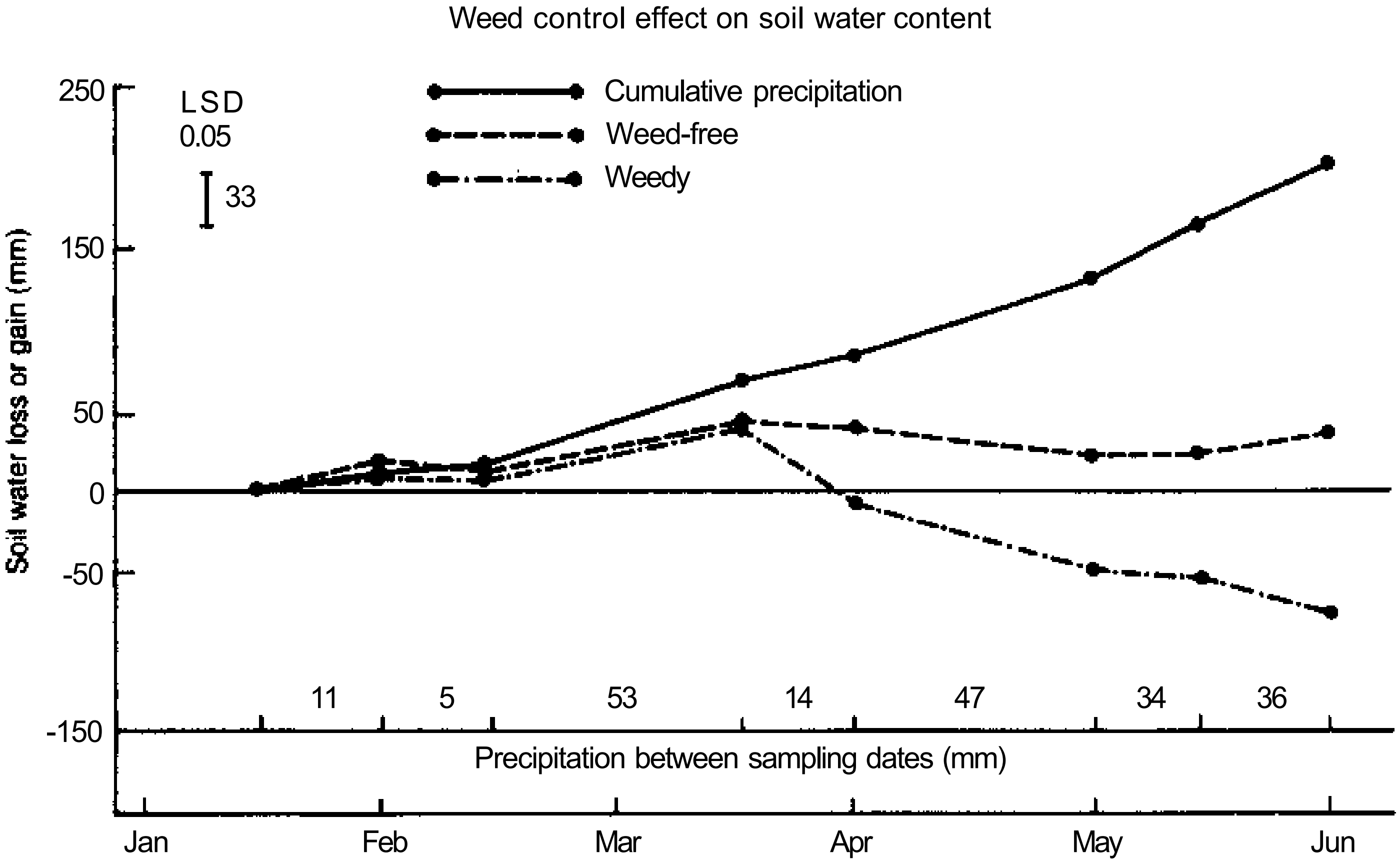

Figure 2. Cumulative precipitation and soil water gains or losses from weedy and weed-free plots during the fallow period (adapted from Wiese 1960).

However, even with adequate seeding rates and methods, low and erratic populations may result from poor seed germination and poor seedling emergence and survival.

Germination and seedling emergence and survival are critical stages in a plant's life cycle. These may be adversely affected when soil conditions are unfavorable due to poorly prepared seedbeds, high salt or alkali levels, aluminum toxicity, an unfavorable pH, and low or nonuniform water content. Germination and especially emergence may also be adversely affected by soil dispersion by rainfall and subsequent crusting when the soil dries. Further, seeds and seedlings may be damaged or destroyed by insects, diseases, rodents, birds or other organisms, or by weather-related factors such as hail, intense rainstorms, or wind-borne soil particles.

Even when adequate plant populations have been established through satisfactory germination and seedling establishment, ratios of T to ET may still be low because canopies are incomplete due to poor plant growth. This poor growth may result from many of the same factors that adversely affect germination and seedling emergence and establishment. In addition, plant growth may also be poor because of poor soil aeration; dense or compacted soil horizons; low soil fertility (macro and micronutrients); competition from noncrop plants for space, water, light, and nutrients; and, of course, low plant-available soil water level.

Transpiration-use Efficiency Level

There is a simple linear correlation between T and dry-matter production (de Wit 1958, Tanner and Sinclair 1983). Generally, only severe production problems reduce the amount of dry matter produced per unit of T. In crop production systems, transpiration-use efficiency (TUE) is often based on the portion of the crop that is of economic or marketable importance rather than on total dry-matter production.

The theoretical relationship of potential economic crop yield to T is also linear (Fig. 4), with the slope and intercept dependent on climatic

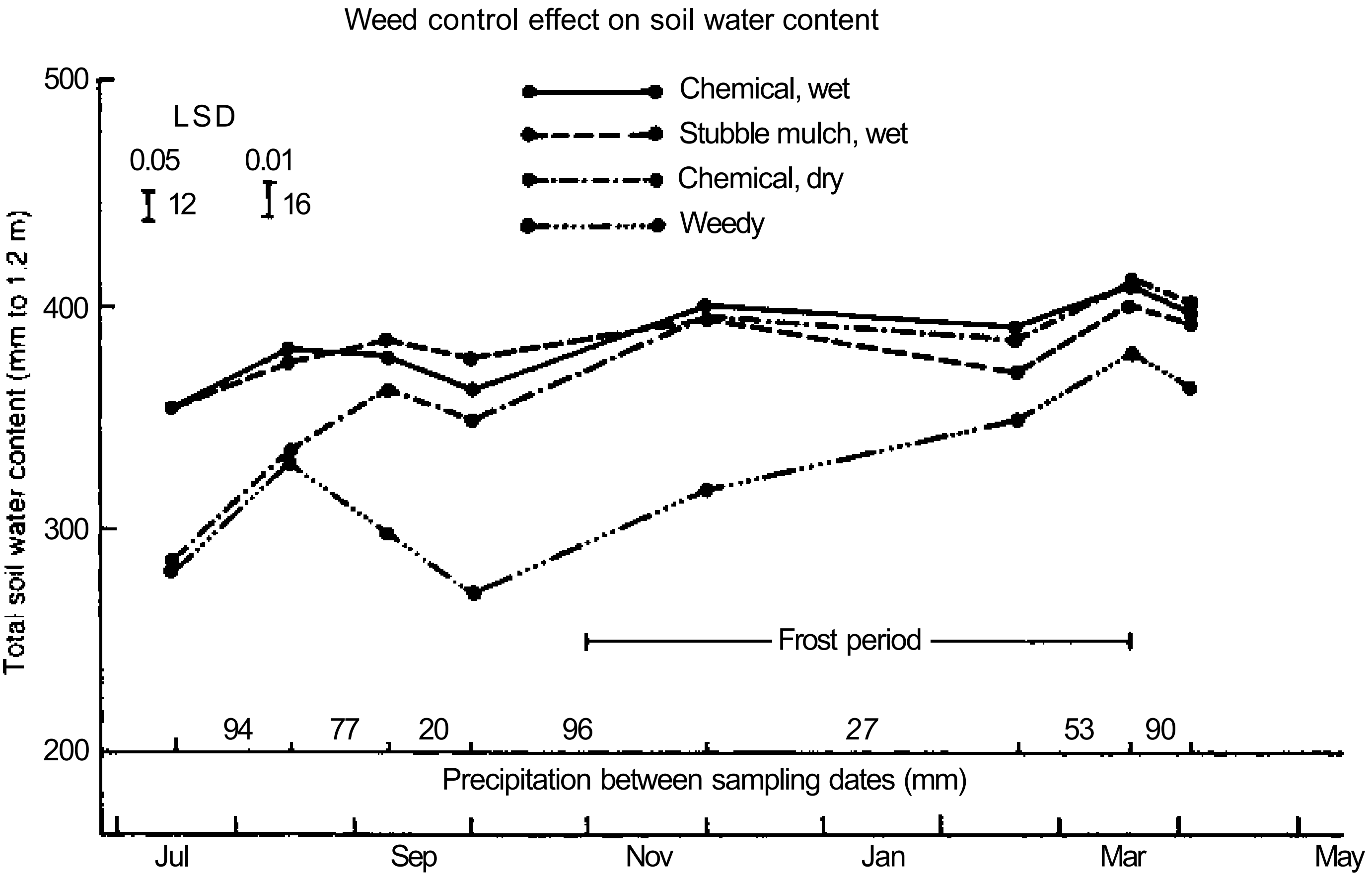

Figure 3. Total soil water content in a 1.2-meter profile at various sampling dates under different tillage methods (adapted from Wiese and Army 1960).

conditions such as temperature, vapor pressure deficit, or potential ET (ETp); on differences between crops; and on genotypic differences within a crop. To achieve yields that are above the line requires major changes in the crop such as an increase in the proportion of total dry matter being partitioned to marketable yield or superior yield quality. Such changes are generally achieved through genetic improvements or major modification of growing conditions such as mist irrigation for temperature modification.

Yields that fall below the line occur when drought stress occurs during a sensitive growth period, or when factors other than water such as severe stress caused by lack of nutrients, diseases, insects, or other factors, limit yields.

Water -use efficiencies (WUEs) based on field data deal with the relationships of yield to ET because making independent measurements of E and T under field conditions over a growing season is virtually impossible.

Stewart (1988) showed that the relationship of sorghum grain yield to growing season ET was remarkably stable over a range of conditions at semi-arid locations in the USA, India, and Israel. The E portion of seasonal ET is often estimated by crop growth models, but the E estimates have not been validated under partial canopy cover. However, data of Ritchie and Burnett (1971) indicated that T was about 0.5 ETp when cotton (*Gossypium hirsutum* L.) and grain sorghum [*Sorghum bicolor* (L.) Moench] plants had leaf area indexes (LAIs) of 1.0 (Fig. 5). At LAIs of about 2.5, T became greater than 0.8 ETp for the two crops when soil water was nonlimiting.

The amount of T rather than E is the factor that influences crop yields. Thus, T at or near potential T (Tp) for the prevailing conditions is desirable. However, seasonal T near seasonal Tp does not assure high TUEs because crop yields can be greatly reduced by short-term stresses at critical growth stages. Crop TUE also can be lowered by delaying crop harvest beyond physiological maturity, which results in continued water use without increasing yields of crops such as grain sorghum, cotton, or maize (*Zea mays* L.).

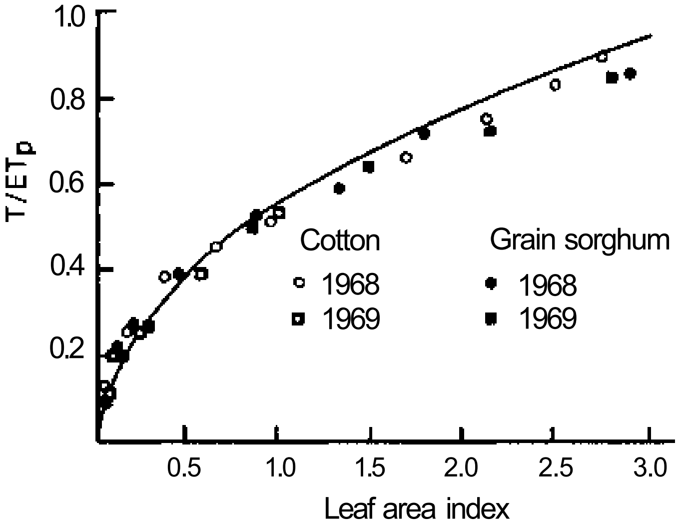

Figure 4. Generalized transpiration efficiency relationship based on the economic yield of a crop.

Most crops experience stresses during a growing season, with those due to drought and sometimes temperature generally most prominent in tropical and subtropical arid and semi-arid regions. Stress at any time may reduce plant growth and harvestable yield. However, stress at critical stages, even for short periods, can drastically reduce the yield of harvestable product of some crops, with total T by the crop reduced only slightly. The relative sensitivities of selected crops to drought stress at different growth stages are given in Table 1. When yield is reduced without a concomitant reduction in T, the TUE for the crop is sharply reduced. Sharp reductions in TUE may occur also when harvestable crop products are damaged or destroyed near or at maturity by insects, diseases, other organisms, or climatic (hail, wind, etc.) factors.

Many crops reach a growth stage, physiological maturity, beyond which no further yield increase occurs even though T continues until the crop has completed its life cycle. Seed or grain crops such as wheat (*Triticum aestivum* L.), rice (Oryza sativa), maize, sorghum, and sunflower (*Helianthus annuus* L.) are in this category. Harvest at some time after physiological maturity is common and largely unavoidable because the seed or grain of such crops must dry sufficiently to avoid harvest and storage problems, and because of the time required to complete the harvesting operation. However, permitting complete plant drying before harvest may unnecessarily permit water use and, hence, reduce TUE. Crop harvest as soon as practical after physiological maturity, along with harvest, uprooting, or destruction of the remaining plant material, not only enhances crop TUE but the water retained in the soil could be used by a subsequent crop or may be sufficient to permit early and more timely tillage and seedbed preparation for the next crop.

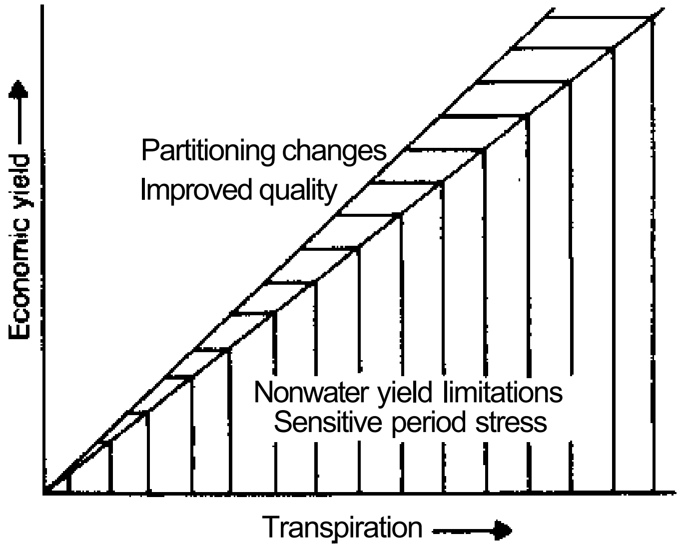

Figure 5. Transpiration (T) as a fraction of potential evapotranspiration (ETp) as influenced by the leaf area index, with soil water nonlimiting (adapted Ritchie and Burnett 1971).

Management Opportunities to Improve Rainfall-use Efficiency

Because soil and crop management factors affect rainfall-use efficiency, adoption of improved management practices should lead to more efficient use of rainfall for crop production.

Ratio of Crop ET to Rainfall Level

Soil Considerations

Management techniques that increase soil water storage and decrease water losses by E and by ET of noncrop plants increase the amount of water retained in the soil for subsequent use by crops.

Table 1. Sensitive growth periods for water deficit (Doorenbos and Kassam 1979).

Crop	Sensitive period
Alfalfa	just after cutting (and for seed production at flowering)
Bean	flowering and pod filling; vegetative period not sensitive when followed by ample water supply
Cotton	flowering and boll formation
Groundnut	flowering and yield formation, particularly during pod setting
Maize	flowering > grain filling; flowering very sensitive if no prior water deficit
Onion	bulb enlargement, particularly during rapid bulb growth >vegetative period (and for seed production at flowering)
Pepper	throughout, but particularly just prior to and at start of flowering
Safflower	seed filling and flowering > vegetative
Sorghum	flowering, yield formation > vegetative; vegetative period less sensitive when followed by ample water supply
Soybean	yield formation and flowering, particularly during pod development
Sunflower	flowering > yield formation > late vegetative, particularly period of bud development
Tobacco	period of rapid growth > yield formation and ripening
Tomato	flowering > yield formation > vegetative period, particularly during and just after transplanting
Water melon	flowering, fruit filling > vegetative period, particularly during vine development
Wheat	flowering > yield formation > vegetative period; winter wheat less sensitive than spring wheat

Under rainfed conditions, soils are refilled with water from the top. On swelling clay soils, fully wetting the soil profile is difficult, especially when a high clay content layer is near the surface. Other problem soils are those containing fragipans, tillage pans, and clay pans. Practices such as profile modification, deep plowing, paraplowing, and vertical mulching can increase water infiltration and, hence, deeper and more uniform soil wetting and subsequent root proliferation and growth occur.

Although these practices are energy intensive, the results, if properly done, are beneficial for a number of years. For example, deep tillage and profile modification on the slowly permeable clay loam soil at Bushland, Texas, USA, in the early- to mid-1960s still increases water infiltration rates (Eck 1986). Provided finer-textured materials are brought to the surface or mixed with sand by the deep tillage operation, deep tillage can increase the water-holding capacity of sandy soils and reduce their susceptibility to erosion. Infiltration, crop yield, and water-use efficiency benefits from soil profile modification and deep tillage were greater under conditions of limited precipitation and irrigation than under adequately watered conditions when a dense clay was disrupted by mixing to 0.9 or 1.5-m depths (Unger 1979, Eck and Unger 1985).

Recent research in India on coarse-textured soils showed deep tillage improved plant rooting by reducing soil mechanical resistance, although no high-density layers were present (Chaudhary et al. 1985).

Deep soil loosening with implements such as chisels or a paraplow is often more practical than deep tillage with inversion-type implements such as moldboard or disk plows because less disruption reduces the power requirement. Mukhtar et al. (1985) reported increased infiltration on loam, silt loam, and silty clay loam soils in Iowa, USA, following tillage to a 25- to 30-cm depth with a paraplow in comparison to 15- to 20-cm deep moldboard tillage, because the maize residues remaining on the soil surface prevented surface sealing during subsequent intense rainstorms.

When rainfall intensity greatly exceeds a soil's infiltration rate, storm runoff and soil erosion may occur. Soil and water conservation practices, such as land leveling and grading, furrow diking, contour tillage, and terracing, can be used to increase surface storage, reduce slope gradient and/or length, and conduct water from fields at nonerosive velocities. While storm runoff often constitutes only a small fraction of total precipitation, runoff conservation in water-deficit areas can greatly increase crop yields (Table 2).

Contour furrowing for row crops is an effective runoff control and conservation practice. By combining contour furrows with level terracing, water can often be stored in the furrows during most storms, while terraces protect against erosion from heavy rains that may overflow furrows. At Spur, Texas, USA, plots with sloping furrows, contour furrows, and contour furrows supplemented with closed-end level terraces had an average annual runoff of 70, 50, and 0 mm, and average cotton lint yields of 130, 160, and 210 kg ha^{-1},respectively (Fisher and Burnett 1953).

In some climates and on some soils, excess water runoff is necessary to provide optimum conditions for crop growth and development. In such cases, graded furrows are effective to conduct excess water from fields and prevent ponding and soil aeration problems. A graded broadbed-and-furrow (BBF) system developed at ICRISAT has been particularly successful in controlling erosion and improving drainage and soil aeration of Vertisols during rainy-season cropping. The BBF system is laid out on a grade of 0.4-0.5%. However, a grade of 0.1% may be adequate for optimum performance (personal communication, J. T. Musick, Bushland, Texas). The crop in the BBF system is planted on broad, flat beds 100 cm wide,

Table 2. Effect of runoff conservation with land leveling on soil water content at seeding and sorghum yield, Bushland, Texas, USA, 1958-72 (Jones 1975).

Conservation practice	Cropping system	Grain yield (kg ha^{-1})	Available soil water content at seedling (cm)	Runoff (mm)
1% slope	Annual sorghum	1240	9.8	-[1]
Bench terrace	Annual sorghum	1780	16.3	0
CBT[2] level bench	Annual sorghum	2230	18.1	+ 68[3]
CBT watershed	Wheat-sorghum-fallow	1890	14.8	-34

1. Runoff not measured.
2. CBT (conservation bench terrace).
3. CBT received a runoff contribution from the 1.5% slope CBT watershed. CBT watershed:CBT bench ratio = 2:1.

with a furrow 50 cm wide and 15 cm deep between the beds (Kampen 1982, El-Swaify et al. 1985). On soils where rooting depth is restricted by a high water table, drainage ditches or tile drains can effectively lower the water table and increase the root zone depth.

Establishing or maintaining a crop residue mulch on the soil surface usually will increase soil water through improved infiltration and/or decreased evaporation. The mulch dissipates raindrop energy, thus preventing or reducing soil particle detachment, which blocks soil pores and drastically reduces infiltration rates. Mulches also can retard runoff, permitting more time for infiltration. Soil erosion by wind and water is also reduced when a mulch is present. Mulches can be maintained on the soil surface with stubble mulch tillage (sweeps or chisels) or by using herbicides to control weeds and volunteer plants.

Sandy soils have a low water-holding capacity but are readily refilled because infiltration rates are usually quite high. The water-holding capacity of coarse-textured soils can be improved by adding organic materials to the soil, provided such materials are available, or by deep-tillage to bring finer soil materials to the surface (Miller and Aarstad 1972). Increasing the water-holding capacity of sandy soils also has the advantage of reducing deep percolation, thus potentially increasing ET. Deep percolation on coarse-textured soils also may be eliminated or reduced by installing a bituminous or other impermeable layer at the bottom of the root zone to restrict downward movement of water (Erickson et al. 1968, Robertson et al. 1973). This is practical on a limited scale for production of high-value crops.

Evaporation accounts for the major loss of water in arid and semi-arid climates. In the Great Plains (USA), approximately 60% of the average annual precipitation is lost from soil by E in cropping systems involving fallow periods (Bertrand 1966). Evaporation decreases and T increases as plant canopies develop. Also, E can be reduced by maintaining a crop residue or mulch cover on the soil surface (Fig. 6). The mulched soil will contain more water than the bare soil until the curves meet, provided both soils initially contained equal amounts of water. The effectiveness of a mulch in decreasing E is dependent, among other factors, on the thickness of the mulch. Low density straws, such as wheat, are much more effective on a weight basis than sorghum or cotton in reducing E. Compared with wheat straw, twice as much sorghum stubble and four times as much cotton residue (stalks) were needed to achieve similar decreases in E (Unger and Parker 1976).

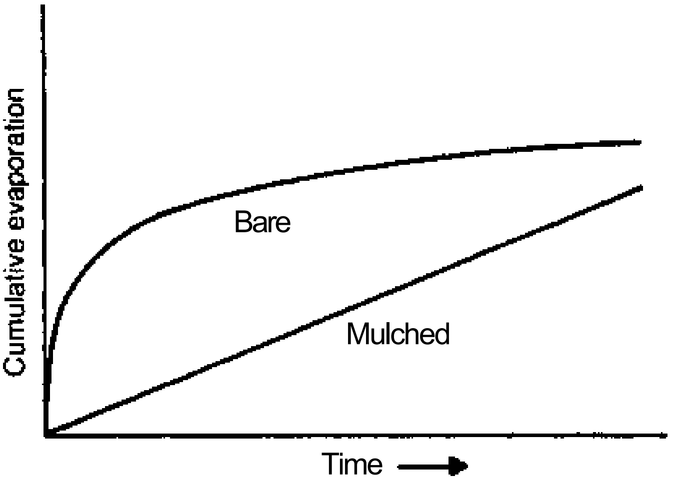

Figure 6. Schematic diagram showing cumulative evaporation from a bare and a mulched soil over time (from Unger and Phillips 1973).

To demonstrate the effectiveness of a mulch in conserving water, Unger (1978) placed 0, 1,2, 4, 8, and 12 Mg ha^{-1} of wheat straw on a clay loam at the start of an 11-month fallow period at Bushland, Texas, USA. Fallow-season precipitation storage efficiencies were 23, 31, 31, 37, 44, and 46%, respectively. Increased soil water storage with heavy mulch rates was attributed to increased infiltration and lower E but the increase was not proportioned between the two factors. As compared with the 0 Mg ha^{-1} mulch treatment, the 8 and 12 Mg ha^{-1} mulch treatments more than doubled the grain yields of sorghum planted after the fallow period.

Shallow tillage to pulverize the surface soil and create a dust mulch potentially could reduce E by disrupting the continuity of capillary pores to the surface. However, by the time soil has dried sufficiently to allow traffic and tillage, most E has already occurred. Also, the dust mulch may reduce infiltration if rainfall occurs, but an additional operation would be required after each significant rainstorm, and the clean tillage necessary to form a dust mulch leaves the soil unprotected against wind and water erosion (Unger 1984).

Weeds and volunteer crop plants use water before crops are planted (Figs. 2 and 3) and compete with crops for water, nutrients, and light during the growing season. Effective weed control is essential to achieve maximum crop yields. According to Wiese (1983), perennial weeds can reduce crop yields as much as 75% and infestation of annual weeds can significantly lower yields. Eleven plants per m^2 of tansy mustard [*Descurainia pinnata* (Walt.) Britt.] reduced wheat yields by 10% in the Texas High Plains. In other regions, annual weeds reduced corn yields by 13-85%, depending on weed species, weed populations, and crop growing conditions. Weeds can be controlled by tillage or with herbicides. The most effective weed control is obtained by exploiting differences in the biological characteristics of crops and competing weeds (Wiese 1983).

In areas with less than about 250 mm of growing-season rainfall, water harvesting using salted, sealed beds to shed water and skip-row planting to concentrate the plants and water, has considerable potential on soils with relatively high clay content (personal communication, Dale Fuehring, Clovis, New Mexico). An example given by Fuehring showed that regular cropping of sorghum with 250 mm of total rainfall required 150 mm for plant use until seed initiation, which left 100 mm for grain production. Grain yield was 1570 kg ha^{-1}. By using 50% of the area for water harvesting, water available for the crop was doubled. Again, 150 mm were required for plant use until seed initiation, but 350 mm were available for grain production. The yield was 5490 kg ha^{-1} cm a harvested-area basis or 2740 kg ha^{-1} on a total-area basis. According to Fuehring, the advantage is even greater where rainfall is lower. The amount of salt initially applied was about 2240 kg ha^{-1}, but the benefits still occur after 8 years without adding any additional salt. Hence, the adverse effect of the salt on crops appears to be negligible.

Crop Considerations

Cropping strategies to obtain high precipitation-use efficiencies vary, depending on climate, resources available, and the farmers' needs. Attaining the maximum possible yield may not be the most economical or practical goal. Higher precipitation-use efficiencies usually occur with annual, intercropping, or double-cropping systems because crops are on the land when water is available. Noncropped or fallow periods should be kept to a minimum, except in cool climates with low E where yields are increased 100% or more by fallowing.

An example of a system that uses water efficiently by extending the cropping period is the improved management system that has been developed at ICRISAT for cropping Vertisols in the semi-arid tropics. With the improved system, a rainy-season crop (sorghum or maize) is dry-sown in a graded BBF system immediately prior to the onset of the monsoon season. After harvest of that crop, a postrainy-season crop of chickpea [*Cicer arietinum* (L.)] is grown utilizing stored soil water. Alternatively, pigeonpea (*Cajanus cajan* (L.) Millsp.) is intercropped with the rainy-season crop. Intercropping is the preferred means for extending cropping during the postrainy season on Vertisols because it eliminates the need for a second land preparation between crops (El-Swaify et al. 1985).

Another example of extending the cropping period is the "opportunity" system utilized by some farmers in the USA Great Plains. Typically, a wheat-fallow or a wheat-fallow-sorghum-fallow sequence is used. With opportunity cropping, the fallow period may be omitted and another crop is seeded when soil water contents are adequate. For instance, a farmer harvests wheat in June and may immediately plant a short-season sorghum hybrid because late May-early June rainfall largely refilled the soil water reservoir. Alternatively, the farmer may wait 3 months and seed another crop of wheat. If the soil profile has not been recharged, then the land is fallowed until the next May or June, when sorghum is seeded.

A similar system, called "response" farming, was reported by Stewart (1985). This system relies on a strong correlation between seasonal rainfall and (a) the date of onset of the rainy season and (b) the rainfall amount during the first 30 days. The farmer selects the crop and a management strategy based on the onset of the rainy season and can adjust the production inputs by adding fertilizer or by thinning the crop after the first 30 days, depending on whether a favorable or poor season is indicated. According to Stewart (1986a and 1986b) the system showed promise for introduction to wheat production areas in Mediterranean climatic zones of North Africa and the Near East.

A practical method of utilizing soil water and nutrients stored below the normal rooting zone of most crops is to rotate occasionally to a deeper-rooted crop, such as sunflower or alfalfa (*Medicago sativa* L.). Sunflower roots may extend to a 3-m depth, and alfalfa roots may penetrate to 6 or 7 m under favorable conditions.

Ratio of Crop T to ET Level

To maximize the T to ET ratio, E must be minimized. The E component of ET can be minimized by applying well-adapted soil and crop-management practices.

Soil Considerations

Ideally, to minimize E, the soil should be covered with a crop at all times. This may be possible with perennial crops but not with annual crops that must be established each year. Because ET is only E until crop T begins, it is important that soil conditions be favorable for timely and rapid seed germination and seedling establishment when conditions are otherwise suitable for plant establishment.

Germination and seedling establishment are enhanced when seeds are planted in well-prepared seedbeds with properly operated and suitable planting equipment. Factors include seedbeds having suitable water content, temperature, soil aeration, soil aggregate size relative to seed size, etc.; and planting equipment capable of placing seed at the proper depth, so that spacing between seeds is proper and uniform, and seed-soil contact is favorable. Under such favorable conditions, the potential need for replanting is minimized and, thus, T becomes an increasing part of ET on a timely basis.

Other factors favoring rapid and timely germination and seedling establishment, and which also affect subsequent plant growth, are the control of pests (insects, diseases, rodents, birds, weeds, volunteer plants), the control of unfavorable soil chemical conditions (salinity, alkalinity, pH, toxic substances), and the availability and/or application of an adequate amount of plant nutrients (both macro- and micronutrients). When all conditions are favorable, plant canopies develop rapidly and T then becomes the major component of ET.

Crop Considerations

Once a crop canopy completely covers the soil surface, ET is predominantly T. However, many dryland crops do not provide complete cover over a large part of the growing season. As long as an appreciable amount of the soil surface is exposed to radiation and soil-air interchange with the atmosphere is possible, E from the surface can be large. To maximize the T component of seasonal ET, early plant growth and establishment are important, especially in areas that receive frequent, light rainfall, as compared with less-frequent storms. As discussed above, seedling establishment is enhanced by preparation of a good seedbed and use of effective planting equipment.

In addition, use of high-quality, uniform seed will improve the uniformity of crop establishment. Adoption of reduced-tillage or high-residue systems changes the micro-environment in which the young crop grows. Aston and Fischer (1986) reported that cooler soil temperatures associated with high residue levels at sowing were associated with reduced early season growth of wheat in southeastern Australia. In the semi-arid climate at Bushland, Texas, USA, sorghum planted into high levels of standing wheat residue grew more vigorously than sorghum planted into fields with little or no residue (Unger and Wiese 1979), possibly due to an improved microclimate within the standing residue. Little difference in barley (*Hordeum vulgare* L.) growth occurred under different tillage systems where the climate was moderate (Sharma 1985).

Strategies for managing the early season growth and water use of the crop depend on the nature of the water supply. If crop growth depends mostly on growing season precipitation, then quick establishment of a crop canopy can reduce the solar energy reaching the soil surface, thereby reducing E from the soil. This is particularly important if the rain occurs as frequent, small events and the water does not infiltrate deeply into the profile. Steiner (1986) proposed using narrow-row spacing to reduce the portion of growing-season ET that occurs as E in a dryland grain sorghum crop. More total dry matter was produced in a favorable growing season but not a higher grain yield. Bond et al. (1964), at the same location, showed that narrow-row spacing of sorghum could lower yields when the soil water content at planting was low. Both studies showed that narrow-row crops used more soil water during the vegetative portion of the growing season than did wide-row crops, and that a high population level, particularly with narrow rows, was more likely to have a lower yield under severe water-deficit conditions.

When the crop relies primarily on water stored in the soil at sowing time, the depletion rate of water with time is important. If depletion of soil water is excessive early in the growing season, the crop may undergo extreme stress during the reproductive and seed-filling growth stages. Passioura (1976, 1983) showed that the harvest index of wheat (grain yield:above-ground total dry matter) was a function of the seasonal ET % that occurred after anthesis. He proposed that plants with a high axial resistance to flow in roots and reduced partitioning of assimilate to roots would allow the crop to extend the period of water use over the growing season.

Other researchers propose that root systems that extract water more efficiently from the soil profile, either through deeper rooting (Wright and Smith 1983), or through differences in root physiology (B. L. McMichael, personal communication, USDA Plant Stress Laboratory, Lubbock, Texas), can expand the soil water supply. Johnson and Davis (1980) analyzed data from a 10-year period and reported that favorable soil water at planting was essential for adequate root development by winter wheat if the crop was to fully extract the water supply in a clay loam soil at Bushland, Texas, USA.

Where successful cropping depends both on stored soil water and on highly variable growing-season rainfall, then the two management options—rapid development of the plant canopy and slow depletion of the soil-water supply—are in opposition. Unger et al. (1986) have shown that high residue levels from previous wheat crops improve the response of sorghum to growing-season precipitation. This and other mulching practices reduce E as a portion of growing-season ET without excessive early-season depletion of stored soil water.

Researchers have long proposed the use of antitranspirants to control the rate of water use in water-limited situations. There are three basic types of antitranspirants—compounds that cause stomatal closure, film-forming compounds, and reflectants (Rosenberg 1974, Das and Raghavendra 1979). The compounds that cause stomatal closure act on physiological processes such as turgor regulation of the stomata guard cells or cell permeability.

Unfortunately, these types of substances generally have not been effective as antitranspirants in field applications and many of them have shown toxic effects to the plants. All film materials tested have a greater permeability to H_2O molecules than to CO_2 and, therefore, seriously reduce water-use efficiency (Jones 1983). An ideal reflectant would transmit light in the photosynthetic bands and reflect light of other wavelengths. However, kaolinite-treated soybeans *(Glycine max* L.) showed a large increase (up to 300%) in reflectance in the photosynthetic range and little effect on reflectance at other wavelengths (Doraiswamy and Rosenburg 1974). Therefore, kaolinite would be most useful for a crop that was light-saturated for a major portion of the growing season, such as soybeans, but not for crops such as sorghum, millet *(Pennisetum* sp and *Panicum* sp), or maize. Although new materials may be developed with more satisfactory properties for use as antitranspirants, they are currently too expensive and/or have too negative an impact on dry-matter production to be useful for field crop production (Das and Raghavendra 1979).

The highest T:ET ratios are generally in crops grown under a high level of management. If crop growth is limited by factors other than water or if water is used by noncrop species, then the efficiency of the system is reduced. As mentioned before, timely harvesting is important to maintain high TUEs. Once physiological maturity is reached in grain and pulse crops, it is important to stop T of the crop to conserve water for the next crop. This can be done by timely grain (or seed) harvest followed by cutting off or uprooting the remaining plant materials. In addition, yield will be lower due to lodging, birds, or rodents, or quality deterioration can occur if the crop remains in the field too long.

Transpiration-use Efficiency

The TUE generally is subject to manipulation only when referring to the production of harvestable or marketable yield. However, there are some indications that variability exists in the CO_2:H_2O flux ratios in cotton leaves (J. E. Quisenberry and J. L. Hatfield, personal communication, USDA Plant Stress Laboratory, Lubbock, Texas). While it is important that researchers pursue the goal of improving crop TUEs through strong breeding programs and through an improved understanding of the physiological and environmental limitations to TUE, a producer can maximize TUE through use of good agronomic management practices as discussed above.

Under semi-arid dryland production, a range of management options is required. Because the farmer often is operating under marginal conditions, the crop type, variety, and management need to be carefully matched to the conditions at planting time as well as to probable conditions during the growing season. Van Staveren and Stoop (1985) analyzed traditional cropping patterns that had developed in West Africa around toposequences that affect the water available for crop production. They found that improved cultivars could be introduced into the traditional systems but that no single cultivar responded well across the range of soil types and planting dates.

Other Factors Affecting the Selection of Management Practices to Maximize Rainfall-use Efficiency

Crop production often is only a part of the overall farming enterprise, and may be integrated with other production on many farms: large animals or poultry, lumber or wood, or fish. When this is the case, competition for soil and water, space, time, and/or crop products may reduce efficient use of rainfall for crop production, but favor the overall farming enterprise and general well-being of the farmer's family.

Crop Residue Uses

Well-managed crop residues are highly effective to control erosion by water and wind and also conserve water and increase crop yields. Crop residues also have value as livestock feed and bedding and as fuel in many countries. However, the value of residues from mature crops as livestock feed generally is low unless the residues are chemically treated, as with sodium hydroxide or anhydrous ammonia, to improve their digestibility. Wheat straw, for example, is so low in nutrients and digestibility that beef animals cannot eat a sufficient amount of the material to maintain body weight unless a nutrient supplement is provided (personal communication, N. A. Cole, Bushland, Texas).

Residues of some other crops have higher nutrient values. However, for crops with low nutrient values when mature, use as livestock feed is not beneficial. In such' cases, a more practical alternative would be to use a portion of the land to grow a forage crop for livestock. By harvesting the crop at its most nutritious growth stage, much less forage would be required. Then the low-quality residues could be retained on the land for soil and water conservation purposes. Where residues have value for livestock bedding and fuel, the removal of only part of the residues is suggested so that sufficient residues remain on the land to conserve the soil and water resources.

Weeds as Livestock Forage

In some countries, weeds that grow after harvest of the primary crop provide forage for grazing animals. Where rainfall is adequate, this practice has no major adverse effect on water conservation for subsequent crops. However, weeds use soil water and nutrients and, where rainfall is limited, may severely reduce growth and yields of the next crop. Devoting a portion of the land area to a high-quality forage crop could provide adequate forage for the livestock and allow timely weed control on the remaining area so that subsequent crop growth would not be adversely affected.

Capture of Runoff in Water Ponds

In many regions, excess rainfall is lost as storm runoff. Runoff water can be stored in farm ponds or reservoirs and used to irrigate part of the cropland during water-deficient periods. For efficient storage, the ponds must be constructed in soils having very low permeability or where the soil has been treated or liners have been installed to reduce seepage. The pond may also be used to store water for livestock and, if a minimum depth of about 1 m can be maintained, it can be used for fish production to provide food for the farmer (Gil 1979).

Rotating Crops and Tillage

Crop rotations are used widely to control insect, disease, and weed problems and to better use water stored in the soil. Rotation of crops having different nutrient requirements also could improve nutrient availability to plants and, hence, increase production with the same amount of water.

Crop rotations using different tillage methods can improve pest control (especially weeds). In addition, some types of tillage, such as chiseling or sweep plowing, may make soil conditions more favorable for water infiltration than another type (for example, disking); hence, water-use efficiency can be increased.

Conclusions

While water management for crop production must be integrated into management objectives for the overall farm enterprise, this paper has focused primarily on maximizing water-use efficiency of cropping systems. Management objectives which will help achieve this goal include:

- increase the infiltration of precipitation into the soil through tillage and residue management, and land surface engineering;
- store runoff water for later use;
- increase the soil water storage capacity through profile modification and increased organic matter;
- reduce evaporation by maintaining a mulch over the surface, limiting tillage, and achieving timely, rapid, and uniform crop establishment to shade the soil surface;
- reduce deep percolation of water through use of deep-rooted crops or installation of impermeable barriers;
- reduce water use by noncrop plants such as weeds, and volunteer crop plants; and
- maximize yields relative to water use by using well-adapted crops and genotypes, timely crop establishment and harvest, and good agronomic practices.

Water is a severely limiting resource for crop production in the semi-arid and arid tropics. Improved soil- and crop-management practices outlined in this paper that increase soil water storage and efficient crop-water use can stabilize production in highly variable precipitation zones.

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Opportunities for the Productive Use of Rainfall Normally Lost to Cropping for Temporal or Spatial Reasons

E. R. Perrier

Abstract

The use of supplemental irrigation and water harvesting farming can alleviate climatic risk factors in arid and semi-arid regions by increasing choices for soil and crop management, which in turn can stabilize crop-water requirements and, therefore, yields. The analysis of rainfall and evapotranspiration data shows that variability is a constraint to agronomic production, but the potential for system design to control drought is within manageable limits. Analyses show that with systematic conservation, surplus water from wet years could be made available during dry periods or drought years. Water harvesting to maximize or minimize runoff is a stabilizing factor for farming systems which depend on natural precipitation. Runoff can be used directly on cultivated fields or stored in soil, or used with supplemental irrigation when stored in excavated ponds or small check dams. Infrastructural parameters required in the support environment when supplemental irrigation and water harvesting farming are implemented must be evaluated if changes are to succeed.

Résumé

***Possibilités pour l'utilisation productive de la pluviométrie perdue en conditions normales pour les cultures à cause des facteurs temporels ou spatiaux :** L'usage de l'irrigation d'appoint et de l'aménagement de l'eau peut alléger les facteurs du risque climatique dans les régions arides et semi-arides en augmentant les options pour l'aménagement du sol et des cultures. Ceci, à son tour, peut stabiliser les besoins en eau des cultures et ainsi les rendements. L'analyse de la pluviométrie et des données de l'évapotranspiration montre que la variabilité est une contrainte pour la production agronomique. Mais, le potentiel de l'approche des systèmes pour une lutte adéquate contre la sécheresse existe. Les donnees montrent que l'excès d'eau a partir des années humides avec le stockage systématique peut être utilisé pendant des périodes sèches ou des années avec la sécheresse. L'aménagement de l'eau pour maximiser ou minimiser le ruissellement est un facteur stabilisant pour les systèmes de culture pluviaux. Le ruissellement peut directement être utilisé dans des champs cultivés ou stocké dans le sol. Le ruissellement peut également être utilisé avec l'irrigation d'appoint quand l'eau est entreposée dans des étangs creusés ou dans de petits barrages. Le succès de nouvelles méthodes dépend de l'évaluation des paramètres d'infrastructure requis dans l'environnement lorsque l'irrigation d'appoint et la culture avec l'aménagement de l'eau sont effectuées.*

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Introduction

Immanuel Kant (1781), the famous German philosopher, stated that all scientific observations must be shaped by two dimensions of reason: space and time. The logic of inquiring systems, a methodological approach used in planning and development, requires a theory of space and a theory of time (Churchman 1971). The domain of time implies an examination of the process of events within a system, just as the domain of space involves examination of the magnitude of design. Some necessary linkage between these dimensions must be assumed by the inquiring system to sustain a natural order for agricultural development.

Relative to space and time, the stochastic nature of rainfall in semi-arid regions compels the setting of manageable boundaries that permit crop production to the limit of existing natural resources. Each year, on each hectare, a given volume of rainfall is received. It should be the goal of every farm and village to permit no water to escape its boundaries as runoff (Perrier 1984). The conceptual understanding of water supply is that of an uncontrollable natural constraint to agriculture. Water supply may be a natural constraint, but it is a constraint that can be modified, conserved, and managed.

To modify agricultural development within a region requires assessment of a country's human population, land and water resources, development potential, and degradation hazards. Because water is a primary limiting resource in semi-arid regions, water conservation means improved water management to promote higher and more stable yields. Water management techniques do not change the nature of weather, but rather the effect of weather on rainfed agriculture is less devastating using these techniques. They are attempts to convert the stochasticity of rainfall into a manageable, deterministic, methodological technology.

Agronomists, engineers, and economists proceed from a consideration of natural factors, including population demands, to view water conservation technology as yet another means for adapting to a specific environment. All problem definitions must proceed from the reality of water scarcity. Rainfall is the principal water source in the semi-arid and arid regions, and all other resource needs diminish in importance beside this constraint to agricultural production. Any method that will increase the amount of rainfall infiltrating into the soil will increase productivity in these regions.

The objectives of moisture conservation technologies are to reduce runoff to negligible amounts, retard direct evaporation from the soil surface, limit transpiration by weeds, and use the bulk of the rainfall for crop transpiration or water storage within the soil profile for later use by a crop. Optimal water storage in soil requires that an adequate amount of rainfall infiltrate to root depth for immediate use by crops, with surplus water diverted to a storage facility or aquifer for later distribution and application by supplemental irrigation. The purpose of this paper is to examine the potential to increase agricultural production through water conservation technologies which estimate crop water requirements for designing both supplemental irrigation and water harvesting farming.

Supplemental Irrigation

The potential for increasing food production from rainfed agriculture in semi-arid regions may be high, but the risk involved with the amount, frequency, and duration of rainfall requires implementation of supplemental irrigation to stabilize production. Uncertainties of rainfall-runoff events are difficult to reconcile with crop water requirements but the use of supplemental irrigation reduces risk uncertainty. In an area where a crop can be grown by natural rainfall alone, but additional water by irrigation stabilizes and improves yields, this irrigation is termed supplemental. The effective and efficient implementation of supplemental irrigation requires scheduling by consumptive use with the quantity of water required for continued plant growth based on minimal demand, i.e., the total volume of water applied as well as timing of irrigations at critical plant growth stages and during drought periods. Supplemental irrigation is that component of conservation technology which harnesses the domain of time to restrain the effects of stochasticity for management of crop production at deterministic levels.

To irrigate, an economic source of water must be explored. In semi-arid conditions, a water supply for supplemental irrigation is usually in a tenuous condition and alternative water sources must be identified. Check dams, catchment basins, wells, pumpback systems, and intermittent or regular streamflows are important alternative water sources for supplemental irrigation. These sources can reduce the risk of a poor harvest by supplying water for plant growth during periods of low rainfall or drought. To ensure that time and money are not wasted, alternative methods of water supply should be considered in the design, before installation of a supplemental irrigation system.

The crop water requirement necessary for optimal production is the quantity of water needed to replace moisture used by a crop growing under specific environmental conditions, applied in a timely manner. The water balance method is calculated to determine the crop water requirement under local conditions to ensure efficient water use with a given irrigation system design. In general, climatic methods for predicting the water balance are used because of the difficulty in obtaining and analyzing field measurements from equipment such as soil-moisture samplers, tensiometers, neutron probe apparatus, or weighing lysimetcrs, which can all be used for data verification. Because climatic conditions vary for each year, rainfall and evaporation records can be used to estimate the water balance for irrigation scheduling (Doorenbos and Pruitt 1984), and these measurements can be used to ease technology transfer when determining crop water requirements by local farmers.

Whenever possible, and for more efficient use of limited water supplies, supplemental irrigation should be scheduled at the moisture-sensitive stages of plant growth. For example, for rainfed spring wheat in the Near East, the three most sensitive periods for supplemental irrigation are:

- at planting time, near mid-November;
- at tillering, from mid-February to mid-March; and
- at heading, from mid-March to mid-April.

When irrigation scheduling using climatic factors coincides with these sensitive periods, water should be applied to return the soil moisture to field capacity in the root zone.

Water balance calculations for irrigation scheduling are determined by measuring movement of major input and output water components. Rainfall and water quantities are usually expressed by water depth, therefore it is convenient to express the water balance in similar terms, millimeters (mm). The equation is:

$$R + I = ET + RO + S$$

where

R = rainfall on a field (mm)
I = water added by irrigation (mm)
ET = evapotranspiration (mm)
RO = runoff (mm)
S = soil-water storage (mm)

Simple calculations estimate the water requirements and time of irrigation for a particular crop (Perrier 1986).

To illustrate the computation of the water balance technique, 1984 climatic data for Aleppo, Syria, are used: daily rainfall and pan evaporation data, as well as soil and plant growth characteristics. A field was selected which had an expanding clay soil 1.05 m deep, with a clay content of 70%, a bulk density of 1.01 g cm^{-3}, and an infiltration rate of 8.5 mm h^{-1}. Table 1 shows the computations of water balance for 11 days following sowing to time of germination.

The computations for the required variables are as follows:

Daily Rainfall. Rain (mm) is measured using standard rain gauges, which are monitored daily at 0800.

Evaporation Data. E_{pan} (mm) is measured using Class A pans (usually on nongrassed sites), which are surrounded by a short crop or bare, noncultivatcd area to provide standard measurements. This galvanized pan, painted annually with aluminum or white paint, has fixed dimensions: 121 cm diameter by 25.5 cm deep. The pan is mounted level on a 15 cm high open-frame platform (pallet) with a water level 7.5 cm below the rim. Large open screens cover the pan to discourage birds, dogs, and farm animals from drinking.

Potential Evapotranspiration. ET_o (mm) is calculated by multiplying the pan coefficient, k_p, which is estimated for each location, by the pan evaporation, E_{pan}. The pan coefficient, k_p, is determined by direct measurement of the potential evapotranspiration, ET_o, at the site of the evaporation pan by use of a lysimeter or by using Penman's equation (Frere and Popov 1979). The ET_o is the maximum quantity of water that may be evaporated by a uniform cover of dense short grass when the water supply to the soil is not limited. Different ground covers, relative humidity, and wind affect k_p. For the Aleppo example, a pan coefficient of $k_p = 0.7$ was used throughout the growing season for spring wheat; therefore,

$$ET_o = 0.7 \times E_{pan}.$$

Crop Coefficient. K_c, determined for each study site, is the ratio of the evapotranspiration, ET_{cr}, to the potential evaporation, ET_o, which is related to various stages of plant growth. K_c is affected by the method of determining ET_o, as well as site-specific factors such as crop characteristics, sowing date, plant development, growing season length, and climate. During the growing season, K_c can be adjusted by taking consecutive soil moisture samples to measure ET_{cr} and back-calculate to adjust estimated K_c values. Figure 1 shows the crop coefficient for wheat, which was not under stress, planted on 6 Dec and harvested about 1 Jul.

Crop Evapotranspiration. ET_{cr} (mm) is the actual amount of water used by the crop, and can be measured directly or can be calculated using the potential evapotranspiration, ET_o, and a crop coefficient, K_c, where:

$$ET_{cr} = K_c \times ET_o.$$

However, with this equation, at the start of the season when there are no plants (RD [root depth] and RZM [root zone moisture] = 0), then ET_{cr} must be computed using K_c without a crop, e.g., $K_c = 0.1$ for the Aleppo example during this early period.

Root Depth. RD (mm) or effective depth of water use as a function of time, can be determined by collecting root samples in the soil profile, estimating from plant height measurements and other plant characteristics, or measuring soil moisture desorption patterns in the soil profile. The root depth as a function of time for spring wheat at Aleppo is shown in Figure 2.

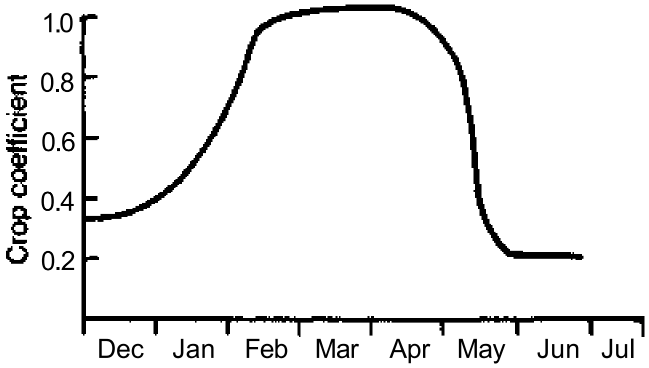


Figure 1. Crop coefficient, K_c, for spring wheat sown on 6 Dec 1984, and harvested in Jul 1985 at Aleppo, Syria.

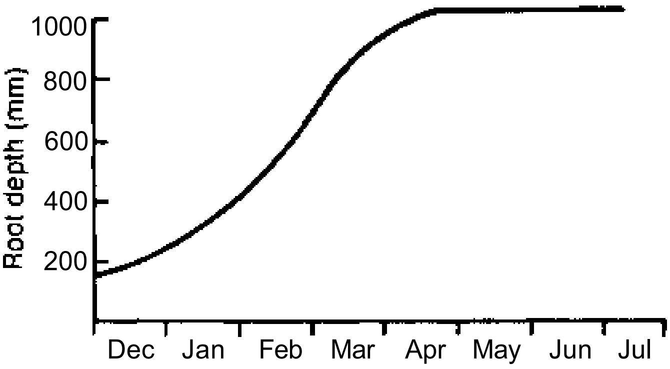


Figure 2. Root depth as a function of time for spring wheat at Aleppo, Syria.

Root Zone Moisture at Field Capacity. RZM (mm) is the percent available water that a soil will hold, and is estimated by the difference between the percent field capacity and the percent permanent wilting point on a dry mass basis (% Available Water = % Field Capacity -% Wilting Point). For the Aleppo clay soil (70% clay, 15% silt, and 15% sand), the difference between field capacity, 44.6%, and wilting point, 25.7%, is 18.9%, the available water. When the soil profile is at field capacity, the total available moisture, TA (mm m^{-1}) in 1 m of soil depth, is found by multiplying the percent available moisture by apparent specific gravity, BD (soil bulk density, BD, in units of g cm^{-3} divided by density of water, 1.0 g cm^{-3}, gives the dimensionless apparent specific gravity for soil). For convenience TA is written as:

$$TA = BD \times \% \text{ Available Moisture} \times 1000 \text{ mm m}^{-1}.$$

The 1000 mm m^{-1} value is to correct the values to millimeters, and percentage values are divided by 100. For the Aleppo clay soil:

$$\begin{aligned} TA &= 1.01 \times 18.9/100 \times 1000 \text{ mm m}^{-1} \\ &= 190.9 \text{ mm m}^{-1}. \end{aligned}$$

If the water balance is to be calculated before germination or if the soil profile is not at field capacity at planting time, then TA must be determined by direct measurement of soil moisture to the depth of the soil profile or expected root depth.

The total available moisture in the root zone, RZM, is TA multiplied by the root depth, RD:

$$\text{RZM mm} = \text{RD mm}/1000 \text{ mm m}^{-1} \times \text{TA mm m}^{-1}.$$

For spring wheat in Aleppo, Syria, the total available water in the root zone of the soil profile at planting time (root depth equal to seeding depth) which must be available for optimal crop growth is:

$$\text{RZM} = 150.0 \text{ mm}/1000 \text{ mm m}^{-1} \times 190.9 \text{ mm m}^{-1} = 28.64 \text{ mm}.$$

Water Balance. WB (mm) is the estimate of the daily amount of available moisture in the root zone, which can be an indication of drought stress. At the start of water balance computations, WB = RZM; but thereafter WB is equal to the previous daily value for net gain. Table 1 shows the initial calculations at the time of germination. As calculations continue, net gain may exceed RZM if rainfall is high, the difference between the two values, net gain - RZM, is surface runoff or deep percolation, then WB becomes the previous value of RZM. For the Aleppo example, the first value of WB = 28.64 mm at planting time.

Net Gain (mm) is computed from the daily value of water balance plus rainfall minus ET_{cr}. Net gain is computed as:

$$\text{Net Gain} = \text{WB} + \text{Rain} + I_{Appl} - ET_{cr}.$$

For Aleppo, the net gain at planting time was computed as:

$$\text{Net Gain} = 28.63 \text{ mm} - 0.34 \text{ mm} = 28.29 \text{ mm}.$$

Deep Percolation or Surface Runoff. Perc/Runoff (mm) is the daily amount of water lost to the plant growth system computed from the difference between the net gain and RZM:

$$\text{Perc/Runoff} = \text{Net gain} - \text{RZM}.$$

For the Aleppo example on 12 Dec 1984:

$$\text{Perc/Runoff} = 26.89 \text{ mm} - 35.35 \text{ mm} = 6.71 \text{ mm}.$$

Water Requirement. W_{Req} (mm) is determined from the amount of available water permitting unrestricted evapotranspiration, i.e., the plant is not under drought stress. On most soils, when the moisture in the soil profile has been reduced to at least 50% of the available water (soil moisture suction is at or exceeds 0.1 MPa) plants begin to show stress and irrigation is recommended; therefore, RZM is multiplied by 0.5 to estimate the daily values of W_{Req} for the season or:

$$W_{Req} = 0.5 \times \text{RZM}.$$

For the Aleppo example, W_{Req} = 14.32 mm at germination.

Water Deficit. WD (mm) is the amount of water needed to replenish soil moisture used by evapotranspiration, or the difference between RZM and net gain for each day:

$$\text{WD} = \text{RZM} - \text{Net Gain}.$$

If net gain is greater than RZM, then WD = 0. When WD is equal to or greater than W_{Req}, the plants are experiencing stress and irrigation is indicated, i.e., irrigate when WD = W_{Req}. For the Aleppo example on 14 Dec 1984:

$$\text{WD} = 28.63 \text{ mm} - 28.34 \text{ mm} = 0.29 \text{ mm},$$

which is much less than 14.32 mm and no irrigation is required.

Irrigation To Be Applied. I_{Appl} (mm) is the amount of water to be applied before correcting for irrigation efficiency. For the Aleppo example, the soil profile was at field capacity at planting time and no irrigation was needed during the 11-day period (Table 1).

Table 1 shows the effect of light rains on the water balance as evident by computed percolation and runoff values. Although December does not have large ET_{cr} values, the process of calculating water balance and the potential water deficit in the soil profile can be easily followed. Verification of these calculations can be made by measuring moisture in the soil profile as a function of time to the estimated depth of root development. These values can be used to adjust the coefficients used in water balance calculations of rainfall and pan evaporation data.

Table 1. Example worksheet for calculation of supplemental irrigation scheduling and water quantities from rainfall and pan evaporation data starting at planting time, 6 Dec 1984, Aleppo, Syria.

	Day in December										
	6	7	8	9	10	11	12	13	14	15	16
Rain[1]							8.7	4.6			8.8
E_{pan}	1.4	1.0	0.7	1.5	1.4	1.1	1.0	0.6	1.2	0.7	0.2
ET_o	0.98	0.70	0.49	1.05	0.98	0.77	0.70	0.42	0.84	0.49	0.14
K_c	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35
ET_{cr}	0.34	0.24	0.17	0.36	0.34	0.26	0.24	0.14	0.29	0.17	0.04
RD	150	150	150	150	150	150	150	150	150	150	150
RZM	28.64	28.64	28.64	28.64	28.64	28.64	28.64	28.64	28.64	28.64	28.64
WB	28.64	28.29	28.04	27.87	27.50	27.16	26.89	28.63	28.63	28.34	28.16
Net gain	28.29	28.04	27.87	27.50	27.16	26.89	35.35	33.08	28.34	28.16	36.92
Perc/ Runoff							6.71	4.45		8.28	
W_{Req}	14.32	14.32	14.32	14.32	14.32	14.32	14.32	14.32	14.32	14.32	14.32
WD	0.34	0.58	0.75	1.12	1.47	1.73			0.29	0.46	
I_{Appl}											

1. See text for explanation of variable codes.

Irrigation Application. IA (mm) is calculated by:

$$IA = (2-I_{cr}/100)xI_{Appl}.$$

The irrigation efficiency, I_{off}, is the percentage ratio of the crop evapotranspiration to the irrigation application, 100 X ET_{cr}/IA. For the furrow method, to attain a uniform distribution, the irrigation application, IA, would be adjusted for the water application efficiency, I_{off}, which is usually 60-70% for medium to heavy-textured soils and for the Aleppo example, I_{off} = 70%.

Infiltration Rate. IR (mm h^{-1}) determines the length of time required to wet a soil and the time required, IT (h), to apply a given irrigation. For the Aleppo heavy clay soil the infiltration rate was measured at 8.5 mm h^{-1}.

The above variables can be computerized so that several years of water balance data can be calculated to estimate the recurrence values for the number of irrigations required (Table 2) for supplemental irrigation, and total runoff. In the Aleppo example for 23 years of rainfall and pan evaporation data, the soil profile is at field capacity at sowing time, sowing date is assumed fixed at 6 Dec, K_c and RD (Figs. 1 and 2) are the average values for spring wheat in the area, and all percola-

Table 2. Date of occurrence for the required number of supplemental irrigations, seasonal rainfall, evapotranspiration, water quantity required for irrigation, and total percolation/runoff for 23 years of data, Aleppo, Syria.

Growing season	Supplemental irrigation number					Seasonal rainfall (mm)	Evapo- transpiration (mm)	Quantity of irrigation of water (mm)	Total perc/ runoff (mm)
	1	2	3	4	5				
1963	5/4					373.5	211.5	93.5	128.5
1964	5/1	1/4	2/5			238.4	274.5	215.3	55.0
1965	12/3	3/5				310.5	267.9	180.2	104.6
1966	22/2	11/3	6/4	1/5		136.7	362.3	335.8	14.1
1967	16/4					437.7	196.4	97.2	174.3
1968	20/3	8/4	1/5			324.7	297.6	278.9	150.3
1969	1/3	14/4				399.3	230.2	166.3	211.7
1970	9/2	27/3	16/4	10/5		135.6	332.6	337.2	14.8
1971	6/1	16/2	26/3			234.2	281.1	170.4	42.0
1972	25/2					326.9	223.8	66.3	56.9
1973	28/12	9/2	16/3	15/4	11/5	136.4	341.4	348.7	2.3
1974	21/2	1/5				364.0	233.5	162.3	179.7
1975	16/3	10/4				271.0	283.0	177.5	64.5
1976						366.3	184.2		67.2
1977	24/2	5/4				262.5	254.9	158.8	25.6
1978	26/3	27/4				266.1	260.6	187.8	108.0
1979	6/2	11/3	9/4	9/5		182.2	269.0	322.1	82.7
1980	25/2	24/5				279.1	185.6	167.0	89.9
1981	2/4					322.0	204.9	92.2	67.6
1982	12/3	19/4				267.1	225.0	177.6	72.3
1983	1/2	29/4				245.5	214.7	143.3	38.3
1984	3/1	25/2	4/4	22/5		134.6	240.7	282.0	10.1
1985	10/3	16/4				247.7	253.7	175.4	89.1

tion/runoff values are not partitioned because the internal drainage of the soil or hydraulic conductivity is not known.

The stochasticity (real time variability) of the climatic system is easily recognizable by observing the variability of dates for supplemental irrigation. The years 1973 and 1976 show that extremes can be close together, and to stabilize food yield, management must plan for this variation to avoid chaos. The coefficient of correlation, r, for rainfall to the number of irrigations is $r = 0.83$ (Rainfall = 413.8 - 61.4 X No. of Irr.) and $r = 0.72$ for the correlation of rainfall to the evapotranspiration of the climatic system of Aleppo (Rainfall = 575.0 - 1.17 x ET_{cr}). These data suggest that some of the stochasticity can be managed as deterministic elements of the farming system.

The values for runoff show that water storage for supplemental irrigation is feasible regardless of the storage method or application means. The data show that, with systematic conservation, surplus water from wet years could be made available for dry periods or drought years. Water for agricultural development has become the major constraint in semi-arid farming systems. Whether this is a consequence of energy costs or an inadequate supply of water is immaterial; whatever the reason, this runoff should be the primary element to conserve for agricultural production.

Perrier et al. (1986) have shown that the Sham I variety of spring wheat, with one-third of the water requirement (120 mm versus 360 mm) and with a moderate amount of nitrogen (70 kg ha^{-1}), will produce as much as 8 t ha^{-1} if irrigations are scheduled on a crop water requirement basis. This yield is a 400% production increase over rainfed farming. Their data showed that scheduling supplemental irrigation is more important than the quantity of water applied, when the quantity is at least 30 mm. Therefore, the total water requirement for crop production may be somewhat lower (one-third the volume computed) than indicated by the calculated value of water deficit, WD. Although irrigation quantities calculated for the nonstressed plant condition can be reduced by two-thirds, scheduling (timing) of irrigation application should be for a nonstressed plant condition.

The 10-year recurrence rainfall is the standard used for design of supplemental irrigation and water harvesting systems. Storms of higher recurrence values could demand storage facilities beyond economic feasibility. Table 3 shows the relation of the four moments of the data along with the probability of recurrence in years for the 23-year data set (Hjelmfelt and Cassidy 1975). These data show that, on the average, seasonal rainfall is greater than evapotranspiration by a margin of 13.2 mm, which implies that agronomic production for this rainfall level should not be restricted.

However, data from Table 2 showed that, for 1966, the recurrence values for ET_{cr} were greater than 25 years (ET_{cr} = 362.3 mm), and the recurrence values for the minimum rainfall were greater than 10 years (rainfall = 136.7 mm). The rainfall data showed that only once (rainfall = 437.7 mm for 1967) for the 23-year data set was the rainfall recurrence greater than the 25-year event. Also, it should be noted that this high rainfall of 1967 followed a minimum rainfall with a 20-year recurrence in 1966. The analysis shows that the data are only slightly skewed and kurtotic,which suggests that the mean may be a good estimate of the central tendency. Nonetheless, the high values for the standard deviation and percentage coefficient of variation show the trend of a nonnormal data set.

These data can also be used to estimate the

Table 3. Relation of seasonal rainfall, evapotranspiration (ET_{cr}), percolation and runoff, irrigation amount, and number of irrigations to the mean, standard deviation, coefficient of skewness, coefficient of kurtosis, coefficient of variation, median, and the maximum and minimum 5, 10, 25, and 50 year recurrence for Aleppo, Syria.

							Recurrence			
Variable	Mean (mm)	Std. dev. (mm)	Coef. skew.	Coef. kurtosis	CV (%)	Median (mm)	5	10	25	50
Rainfall	272.3	85.3	-0.09	2.25	31.3	267.1	215	169	128	102
							354	394	435	462
ET_{cr}	259.1	52.3	0.59	2.51	20.2	254.9	305	330	356	373
							212	186	163	145
Perc/Run	80.4	56.1	0.69	2.70	69.8	67.6	123	147	174	190
							55	6	0	0
Irr. amt.	188.5	90.3	0.20	2.49	47.9	175.4	271	316	363	394
							100	57	20	0
No. irr.	2.3	1.2	0.40	2.86	50.3	2.0	3.6	4.2	4.9	5.3
							1.2	0.6	0	0

size of a collection check dam, pond, catchment basin, recharge well, etc., needed for supplemental irrigation to sustain a stable yield. The average irrigation amount needed on a yearly basis, suggests that a storage facility could be constructed to collect the runoff from a catchment basin design of 3:1 or 240.2 mm on the average. But nearly once in 5 years, according to the probability data, there would not be an adequate supply of water for supplemental irrigation. Of course, an alternative water source could alleviate this condition.

Various measures of the moisture status in the soil profile can effectively estimate the water balance without the measurement of climatic parameters. Tensiometers that measure the soil moisture suction (tension) between 0 and 0.1 MPa in the soil can be used to estimate the water requirements of plants (Perrier and Evans 1961). Neutron scattering devices (Perrier and Johnston 1962) can also be used to measure the volume moisture content of water in the soil profile. With the use of the soil bulk density and the soil moisture desorption curve, the same soil moisture desorption value of 0.1 MPa can be estimated for the crop water requirement of when and how much to irrigate.

Water Harvesting Farming

Water harvesting is a process of collecting rainwater from a modified or treated area to either maximize or minimize runoff, whichever technology is to be implemented at a specific site. Water harvesting farming has four common elements: catchment basin, conveyance device, storage facility, and cultivated field. While supplemental irrigation encompasses time in union with limited space through deterministic management of natural resources, water harvesting farming diminishes space and amplifies time to concentrate natural resources for agricultural production. With water harvesting farming, an area or region can be conceptualized as expanding infinitely into the arid regions of the world. There is no semi-arid region so large that implementation of some form of managed water harvesting design cannot be envisioned. For example, areas of Iran, Pakistan, the Sahel of Africa, and the Near East are regions which should adopt the technology of water harvesting farming for agricultural production.

Farmers in the semi-arid regions have little, if any, risk-bearing capacity. It becomes crucial for them to choose a crop and management system that can make the best use of rainfall collection and storage. The success of farming under rainfed conditions depends not only on the effective collection of runoff, but also upon efficient use of water by agricultural crops. In addition to techniques for direct application by intercepting runoff from sloping or drainage terraces and contour furrows, water harvesting catchment basins collect rainfall for storage in tanks, cisterns, or dams for deferred application by supplemental irrigation. The type and scale selected of water harvesting farming depends upon the economic evaluation of the soil and the rainfall quantity, distribution, and intensity, as well as the intended water use, site topography, construction materials availability, and skilled labor supply.

Collected runoff water can be stored in soils, behind dams, in wadis, or stored in-place on terraced or tied-ridged agricultural plots. By these methods, a rainfall of a few millimeters collected on a catchment area can be equivalent to several hundred millimeters of rainfall when supplied to a restricted cultivated area. A well-designed water harvesting system can help in the establishment of agriculture in most arid climates. Nonetheless, when mean annual rainfall is less than 50 mm it is extremely doubtful that this technology would be economically feasible (Cooley et al. 1975). Even during drought years, water-harvesting systems can fail unless they have adequate storage facilities.

The basic criteria for designing small-scale, water-harvesting systems are essentially the same irrespective of the eventual use of the water. The same criteria are required to design for water harvesting farming as for supplemental irrigation. The design has to incorporate the constraints of the local environment, equipment availability, and socioeconomic conditions. In addition, separate factors that may be interrelated must be considered: precipitation, catchment basins, water requirements, storage facilities, topography, labor and materials, and farmer acceptance of water management systems. Each site may have unique characteristics which can alter the eventual design of the optimal system.

Precipitation includes rainfall, as well as dew and snowfall. In the semi-arid regions where ICARDA has principal responsibility, rainfall is the element of major concern for plant growth. Because precipitation is a stochastic variable, its timing, distribution, and quantity are difficult to predict; therefore, probability techniques must be used to help the farmer evaluate the amount of risk involved before construction of a water harvesting farming system. The probability of the amount of rainfall and timing to meet agricultural production can be estimated from analysis of daily rainfall values, the most common climatic data available.

To illustrate computations needed to design a water harvesting system, some probability calculations are presented from 28 years of daily rainfall data in the semi-arid El Haseke Province, in northeastern Syria. For the example, the catchment basin would have a compacted soil surface which requires a threshold of minimum rainfall of 6 mm before runoff occurs, i. e., 6 mm of rainfall is lost to the processes of wetting, infiltration, and evaporation. If the runoff surface chosen for the example had been ridged and paved with asphalt (a more efficient but costlier catchment surface) then the threshold value could be as low as 3 mm. For water requirement computations, wheat is the field crop chosen for the cultivated area.

Table 4 shows the analysis of the rainfall data from El Haseke Province, Syria, for the example catchment basin with mean rainfall, mean number of runoff storms, and mean catchment runoff (above 6 mm), each with the standard deviation, percent coefficient of variation, and the coefficient of skewness. The mean annual rainfall for the region is 278 mm. For the 28-year example, there was an annual average of 15 runoff storms yielding 108 mm of runoff.

The seasonal events (Oct-May) show that January has the maximum rainfall, the highest number of runoff storms, and the largest amount of runoff. However, the months of greatest water need for wheat are in the fall at planting time (Dec), during the vegetative stage when fertilizer top dressing is applied (Mar), and during the grain-filling stage (May). If these average values were repeated each year, production risks could be minimized with a catchment basin of 2:1 (Table 4). The percent coefficient of variation and the skewness coefficient show the stochastic nature of the 28-year data set: in particular, a maximum monthly rainfall of 223 mm (1969) and a minimum monthly rainfall of 13 mm (1970) occurred during January in consecutive years. The percentage difference between the mean monthly rainfall and the mean monthly runoff for January is about 60%; therefore, 40% of the rainfall on the catchment basin would not be collected. If the runoff surface were ridged and sealed as for some "roaded catchments", then a much larger percentage of the rain-

Table 4. Mean rainfall, number of runoff storms, and catchment runoff, each with standard deviation, coefficient of variation, and skewness coefficient by month for 28 years of daily rainfall data for El Haseke, Syria.

Mean values	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May
Rainfall (mm)	12	22	43	52	39	42	46	20
Standard deviation (mm)	14	17	28	40	26	28	32	31
Coef. of variation (%)	124	77	64	78	66	66	69	156
Skewness coefficient	1.71	0.52	1.18	2.68	0.32	1.15	0.60	2.41
No. of runoff storms	1	1	3	3	2	2	2	1
Standard deviation	1	1	2	2	2	2	2	2
Coef. of variation (%)	147	116	60	69	75	82	73	160
Skewness coefficient	1.15	1.29	0.37	1.14	0.50	0.83	0.15	1.82
Catchment runoff (mm)	4	7	17	21	14	15	18	8
Standard deviation (mm)	10	8	20	29	13	16	18	19
Coef. of variation (%)	234	122	116	136	98	109	104	242
Skewness coefficient	2.91	1.08	1.95	2.98	0.70	1.47	0.94	3.34

Table 5. Probability (%) and recurrence values (years) for the means of monthly rainfall, number of runoff storms, and runoff by month, for 28 years of daily data for El Haseke, Syria.

Months	Mean value	Probability (%)/Recurrence (years)				
		50/2	33/3	10/10	2.5/40	1/100
October	Rainfall (mm)	12	19	30	40	45
	Number of storms	1	1	1	2	2
	Runoff (mm)	4	9	16	23	26
November	Rainfall (mm)	22	30	43	54	60
	Number of storms	1	2	3	4	4
	Runoff (mm)	7	11	18	23	27
December	Rainfall (mm)	43	58	79	98	108
	Number of storms	3	3	4	5	6
	Runoff (mm)	17	27	42	55	62
January	Rainfall (mm)	52	73	104	131	146
	Number of storms	3	4	6	7	8
	Runoff (mm)	21	37	59	79	89
February	Rainfall (mm)	39	52	71	89	98
	Number of storms	2	3	4	6	6
	Runoff (mm)	14	21	31	40	45
March	Rainfall (mm)	42	56	77	96	106
	Number of storms	2	3	5	6	7
	Runoff (mm)	15	24	36	47	53
April	Rainfall (mm)	46	62	87	108	120
	Number of storms	2	3	4	6	6
	Runoff (mm)	18	27	41	53	60
May	Rainfall (mm)	20	37	60	82	93
	Number of storms	1	2	3	4	5
	Runoff (mm)	8	18	32	45	52

fall could be collected. October, November, and May are in general the most unstable rainfall months; therefore, to design a storage facility using these data requires evaluation of probability analysis.

Table 5 shows the percent probability and recurrence values (years) for the example data set. The minimum storm included in the analysis of runoff is a daily rainfall of 6 mm or more. For a probability of 2.5% or a recurrence of 40 years, the number of runoff storms for January would be seven storms per year; whereas, for 10% probability or a recurrence of 10 years, there would be six storms per year. At 50% probability or a recurrence of 2 years, there would be three storms per year or the mean number of runoff storms (Table 4).

The probability analysis demonstrates that at El Haseke a design storm based on runoff at the 10% probability value is the most feasible to calculate volume flows and storage for the design of a water harvesting farming system. The 10-year recurrence rainfall is usually adequate for the design of a storage facility. In the El Haseke example, the design storm at 10-year recurrence is double the mean monthly runoff and therefore justifies selection of a catchment basin large enough to manage this volume of water. Even though storm damage to the basin could be expected, design criteria for larger storms at smaller probabilities are not considered economical. The data show that for October and November there is only one low volume storm per year, which is not enough for basin design. Statistics for October and November do not indicate construction of a direct application of runoff; however, if a tank or pond storage were available, then water could be diverted to a storage facility for supplemental irrigation during the growing season.

Catchment basins for runoff collection are of three types, which can be modified to increase the quantity of runoff: topographical, soil, and impermeable coverings. A specific catchment basin should have a surface treatment designed for maximum runoff and minimum maintenance.

The simplest catchments involve some form of topographical alteration. Catchment basin designs using topographical techniques may be characterized by lower costs initially, but could have low runoff efficiencies. Hollick (1982) notes that slope angles and overland flow distances must be designed to avoid water erosion damage to the catchment surface. Soil types and topographic features must be properly matched if these catchments are to be effective.

When using soil for catchment basins, the soil can be sterilized to prevent plant growth. In general, soils are compacted by hand or machinery and protected from human, livestock, or mechanical traffic to ensure high runoff. In the El Haseke example, this type of catchment basin had a threshold runoff of 6 mm of rainfall; however with proper management, catchment basins with compacted soil surfaces can have a lower threshold value and produce higher runoff volumes. Soils unsuitable for constructing surface catchments are loose sands and gravels or expanding lattice clays (self-mulching).

Conventional construction materials such as concrete, latex rubber, black polyethylene, sheet metal, etc., have been used as impermeable coverings for catchment basins for water harvesting (Cooley et al. 1975). These materials, although expensive, may last a long time, and when properly installed and maintained, may be well-suited to some locations. These types of impermeable catchment basin coverings arranged in ridges could have a rainfall threshold value of 3 mm or less. Most thin film coverings are susceptible to mechanical damage, wind damage, and sunlight deterioration (Cluff 1975).

Water requirements for designing a water harvesting system include several factors such as crop and livestock production, domestic uses, and supplemental irrigation. For agronomic applications of water harvesting, the growing season is that period during which water will be needed, and the supply should be adequate to support the water requirements of a crop. Water balance calculations estimate the water requirements and aid in system design to determine the magnitude and distribution of expected runoff collection. Selected crops of the Near East are presented in Table 6. These values are guidelines for estimating design requirements for a water harvesting system.

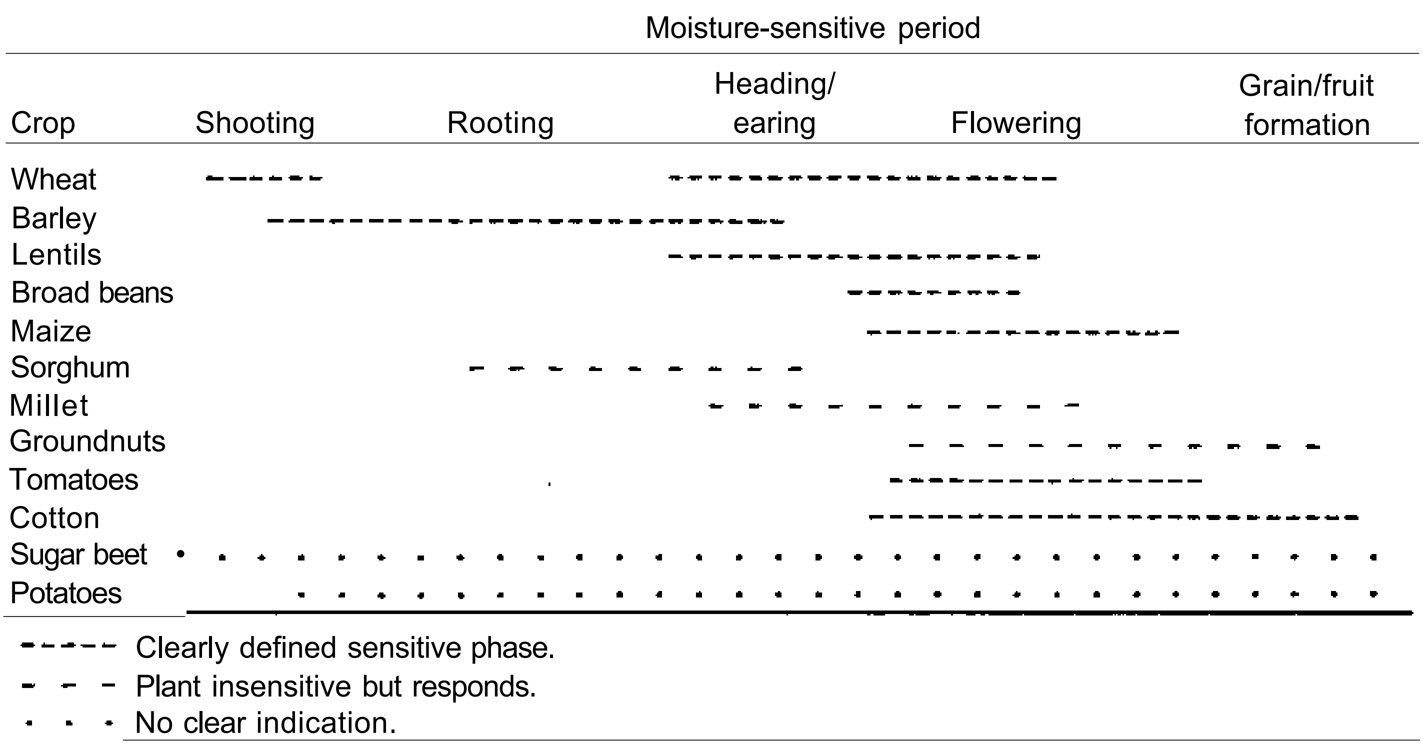
Plants respond positively when soil water is available during a sensitive growth stage. Table 7 shows the best potential use of limited water supplies for selected crops where water application can be scheduled at the moisture-sensitive stages of plant growth. For these data, it is assumed that the soil profile is at field capacity at planting time.

Estimated water requirements for household use and stock water for various animals in the Near East are shown in Table 8. In general, the water re-

Table 6. Range of seasonal evapotranspiration for selected crops at minimum and maximum yields in the Near East.

Crop	Growth period	Seasonal evapotranspiration (mm)
Wheat	Nov-May	300-555
Barley	Dec-Apr	200-450
Faba beans	Jan-May	300-495
Cotton	Apr-Nov	550-1130
Sugar beets	Oct-Jul	450-1090
Maize	Mar-Jun	400-750
Potatoes	Feb-Jun	350-620

Table 7. Moisture-sensitive growth stages for selected crops.



quirement per farm unit falls into four classes of use with relative percentages:

domestic purposes	10%
farm and animals	5%
irrigation	80%
waste	5%.

Waste is loss from the water conveyance system, such as open ditches, pipe joints, general leaks, and defective equipment. Seepage and evaporative water losses from storage must also be included as part of the water requirement during the design phase of the program.

Table 8. Range of daily water requirements for domestic use and animals in the Near East.

Use	Water requirements (L day^{-1})
Domestic	
Per person (includes cooking, drinking, and washing)	10-60
Animals	
Beef cattle	35
Dairy cattle	45
Mature sheep	4-10
Horses	45
Chickens (per 100 head)	8-15

To ensure that no critical periods of water shortage will exist, the size of the catchment basin and storage facility should be determined by computing an incremental water budget of collected water versus requirement (Frasier and Myers 1983). The water budget or water balance for the design of a water harvesting system for field crop use is determined by estimating or measuring the major input and output components of water movement on a catchment basin and cultivated area.

A simple calculation, but without the aid of probability analysis, can be made to determine the feasibility of water harvesting farming showing the size of catchment basin to cultivated area that could be expected for the El Haseke region with an average annual rainfall of 278 mm. At this rainfall level, the ratio of catchment basin to cultivated area ranges from 2:1 to 4:1 with a runoff efficiency (100 x runoff/rainfall) varying from 20 to 90%.

The ratio of catchment basin to cultivated area and runoff efficiency is dependent upon the system design. Small-scale watersheds designed for row crops and small grains usually have catchment basin to cultivated area ratios of 3:1 to 5:1 when the average annual rainfall is as low as 100 mm. For the El Haseke example, if a catchment area were designed with a watershed ratio of 2:1 and the total annual runoff from the catchment basin was 38.8% efficient, then the volume of water collected for 1 ha (10000 m^2) of cultivated land would be:

2 x 10000 m^2 x 278/1000 m X 38.8/100 = 2157 m^3.

(Catchment basin threshold = 6 mm; therefore, 100 X mean runoff quantity/mean annual rainfall = catchment basin efficiency or 100 x 108/278 = 38.8%). For each hectare of cultivated land receiving the same mean annual precipitation of 278 mm, the volume of water collected would be:

10 000 m^2 X 278/1000 m = 2780 m^3.

The total volume of rainfall plus the catchment basin runoff reaching the cultivated area of the water harvesting system would be:

2157 m^3 + 2780 m^3 = 4937 m^3,

or for each hectare of cultivated area the rainfall equivalent would be: 4937 m^3/10 000 m^2 = 0.494 m or 494 mm. Table 6 shows that, for seasonal evapotranspiration, 494 mm would be an adequate supply of water for most of the crops grown in the El Haseke region.

Topography, such as slope, gradients of channels, extent of depressions, etc., affects both the rate and volume of surface runoff. Long narrow catchment basins will have lower runoff rates than more compact basins of the same areal extent. The geologic or soil materials will determine the degree of compaction, infiltration rate, and the effective runoff. Detailed designs and maps should be made of the terrain with reliable input and output figures to establish costs and returns for each design activity separately.

A topographic survey is needed at each proposed site to evaluate the potential design of a specific water-harvesting system. These surveys should be sufficiently accurate for calculation of surface area and of a scale to allow easy orientation within the site. They should include the location of the catchment basin and storage facility as well as the conveyance devices needed for storm water control at the cultivated field. Wherever possible, the maps should be prepared from aerial photographs with on-site verification (ground truth). The degree of accuracy of the survey is matched to the topographic requirement of the particular location. Topographic maps are used as a foundation for canal and drainage layouts as well as water harvesting farming plans.

Storage facilities are generally required for most water harvesting systems whether it is the soil, tied-ridges or microcatchment basins, a tank, or a check dam, i.e., small dams constructed across wadis (gullies) to create storage behind the dam walls. Efficient water storage is the primary objective and is associated with various water uses, e.g., livestock, commercial, domestic, and supplemental irrigation for agricultural crops. Normally, the intended use of the water will influence the design. Final recommendations for the selection of system design will be dependent on cost and local conditions (Dedrick 1975) such as:

- chemical and physical properties of soils;
- accessibility of personnel, equipment, and materials;
- availability of surface sealing materials;
- current costs; and,
- maintenance requirement for effective life of system.

In direct-runoff farming systems the cultivated soil is the water storage container. The collected water is diverted or directed onto the cultivated area during rainfall. Generally, the runoff quantity exceeds the infiltration rate of the soil and ridges are placed around the cultivated area to retain the water. Overflow from fields can be diverted by canals for storage or use on other fields. The effectiveness of this system depends on the water demands of the crop, the amount and distribution of rainfall, the soil infiltration rate, and the water storage capacity. Specific designs of this type of runoff collection can have a high risk as crops could fail in dry years or could be badly damaged by flooding during heavy rains (UNEP 1983).

A water storage facility can be any container capable of holding water (Frasier and Myers 1983). In many designs of water harvesting systems, the storage facility is the most expensive single item, and may. represent 50% of the total system cost. There are many types, shapes, and sizes of wooden, metal, clay, and reinforced plastic water storage facilities.

Materials and labor are of primary concern when selecting a water harvesting farming plan. The economic factors of alternative water sources or materials to be used for catchment and storage must be considered in determining the costs of construction and maintenance. Not all catchment basin designs require the same labor skills or type of maintenance (Frasier 1975). Maintenance on small-scale water harvesting areas can require 1-2 work days about 4 times each year. The storage facility and conveyance device must be included in any maintenance program. For the compacted soil treatments on the catchment basin, weed growth should be eliminated and soil erosion prevented.

Some materials and installation techniques have higher capital costs and require skilled labor especially for the impermeable catchment basin or storage facility. However, in many installation designs, there are several combinations of catchment and storage sizes which provide the required water quantity without high capital costs, but are labor-intensive, including tied-ridges, microcatchment basins, and berms.

Farmer acceptance of water-harvesting farming is an important factor in the success of any technology transfer. Farming with water harvesting always requires more physical effort than rainfed farming under comparable conditions. Farming based on small-scale water harvesting increases the food supply and does not involve the patterns of organization and social control that characterize large-scale irrigated agriculture. If the design of the water-harvesting system presents the farmer with too big a burden and too little profit, the system will likely fail. In areas where water harvesting is not fully understood or accepted because of various socioeconomic factors, system design is extremely critical. The system must be designed to conform with the local labor supply and implemented with materials that have a minimum maintenance requirement and maximum effectiveness. The selected water harvesting system must support a positive economic alternative to existing conditions if farmer acceptance can be expected.

Summary and Conclusions

The use of supplemental irrigation and water-harvesting farming can alleviate the climatic risk factors by increasing choices for soil and crop management, which can stabilize crop-water requirements and, therefore, yields. Farming based on supplemental irrigation and water-harvesting farming increases the food supply and management responsibilities, but does not involve the patterns of organization and social control that characterize large-scale irrigated agriculture. The water balance technique using climatic data and information on soils and crop physiological characteristics provides a method to evaluate design criteria to effectively and efficiently apply all precipitation that falls on a farmer's field.

Data collection is an important step in the early phases of designing small-scale water harvesting and supplemental irrigation projects. The need for extensive records of daily rainfall and pan evaporation or equivalent data at each location cannot be overstressed. General soils data on the physical and chemical properties gives the researchers a view of the potential for agriculture within the region. The analysis of rainfall and evapotranspiration data shows that variability is a constraint, but the potential for system design to control drought is within measurable limits.

The water balance method is calculated to determine the crop water requirement under local conditions to ensure the efficient use of water with supplemental irrigation and water harvesting. When applying the water balance method in a predictive mode (before actual measurements have been made) there are three coefficients that must be estimated to predict soil moisture deficits: k_p, K_c, and RD. In general, climatic methods for predicting the water balance are used because of the time required to obtain and analyze data from field measurements using soil-moisture samplers, tensiometers, lysimeters, and calibration of equipment such as gypsum blocks, neutron probe apparatus, etc.

The values for runoff show that water storage for supplemental irrigation is feasible regardless of the storage method or means of application. The data show that with systematic conservation surplus water from wet years could be made available during dry periods or drought years. Probability analysis shows that the size of storage facility can be estimated to ensure an adequate supply of water for supplemental irrigation.

Water harvesting farming can economically reduce risk of crop failure and increase crop production. Water harvesting to maximize or minimize runoff is a stabilizing factor for farming systems which depend on natural precipitation. Runoff can be used directly on cultivated fields or stored in soil, or used with supplemental irrigation when stored in excavated ponds or small check dams. Calculation of statistical parameters and probability analysis on the 10-year recurrence rainfall can provide design criteria to construct and optimize the catchment basin, conveyance device, storage facility, and cultivated field.

The performance of small-scale water Harvesting depends upon the effectiveness of the catchment basin to manage soil surface conditions, e.g., inhibit infiltration, produce runoff, or increase soil-water storage. Effectiveness depends on several factors including soil depth and type, surface cover, surface roughness and slope, climatic factors, labor and material costs, and water balance computations.

Infrastructural parameters or the permanent facilities (social institutions) required in the support environment must be evaluated if changes that occur through implementation of water harvesting and supplemental irrigation are to succeed. This implies a reassessment of markets and road networks as well as transportation. The availability of agricultural extension services for technology transfer of water harvesting and supplemental irrigation information must support farmers in new risk decisions incurred by agronomic change. Reorientation of cooperative societies and realignment of services must be supportive of farmers whose farming practices are being radically transformed.

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Development of Management Strategies for Minimizing the Impact of Seasonal Rainfall Variation

J. I. Stewart[1]

Abstract

A new management approach, response farming, is explained as rainfall prediction followed by appropriate agronomic responses. Research findings include: (a) usable levels of rainfall predictability in the Nepal terai and at Hyderabad, India, as of May 1, prior to the monsoon; (b) effects of leaf area index on crop water requirements, and of crop type and water adequacy on maximum soil water extraction, and how these affect water balance modeling; and (c) yield versus evapotranspiration functions of millets, sorghums, and beans suited to variable rainfall zones, and impacts of plant population, fertility level, and weed control on crop water production functions and crop-management models.

An example of the strategy suggested to minimize the impacts of rainfall variation is given, based on rainfall at Hyderabad. Briefly, the strategy is to predict a narrowed band of rainfall possibilities, aim seeding rates high and fertilizer rates low in the spectrum, then either sidedress with additional N or thin the plant population at 30 days, depending on actual early season rainfall. Specialized research needs, equipment and techniques are discussed.

Résumé

Mise au point des stratégies pour la réduction de l'impact des variations saisonnières de la pluviométrie : Une nouvelle approche "response farming" en tant que prévision de la pluviométrie suivie de réponses agronomiques appropriées est expliquée. Les résultats de la recherche comprennent : (a) niveaux utilisables de prévision de la pluviométrie dans le téraï au Népal et à Hyderabad, en Inde avant la saison des pluies; (b) effets de l'indice de surface foliaire sur les besoins en eau de la culture, ceux du type de la culture et de la suffisance de l'eau sur l'extraction maximum de l'eau du sol, et la manière dont ces facteurs affectent la modélisation du bilan hydrique; et (c) fonctions rendement/évapotranspiration des mils, des sorghos et des haricots adaptés à la pluviométrie variable dans certaines zones et impacts de la densité, du niveau de fertilité et du désherbage sur les fonctions des besoins en eau des cultures et des modèles de la gestion de la culture.

Basé sur la pluviométrie de Hyderabad en Inde, un exemple d'une stratégie pour réduire l'impact de la variation de la pluviométrie est donné. La stratégie consiste en prévision d'une gamme étroite de possibilités pluviométriques, pratiques culturales telles que les taux élevés de semis et faibles d'engrais et ensuite l'épandage entre les rangs de N supplémentaire ou le démariage des populations après 30 jours, dépendant de la pluviométrie réelle au début de la saison des pluies. Des besoins de recherche spécialisée, de l'équipment et des techniques sont discutés.

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Introduction to Response Farming

The strategy under development to minimize the impacts of variable rainfall has two principle facets:

- Reduction of the effective variability as it relates to the rainfall season at hand. This may be accomplished through improved rainfall prediction, or physically, using water harvesting and/or supplemental irrigation.
- Sowing-time decisions aimed initially at the upper half of the reduced spectrum of rainfall possibilities, but which may, at the appropriate growth stage, be shifted downward, by thinning the plant population and withholding further fertilization, should actual early-season rainfall be less than normal.

The system outlined is termed response farming, meaning the farmer is provided an assessment of his rainfall prospects prior to or at the start of each rainfall season, together with detailed recommendations about how best to respond to the assessment in terms of land preparation, crops/cultivars to plant, soil selection for critical food crops, intercropping versus monocropping, seeding and initial fertilization rates, row spacing, and dry sowing versus waiting for the rains.

There are a number of planning site factors other than rainfall which affect the actual recommendations. These include economic and social realities (markets for proposed crops; cost and availability of inputs/supplies, especially fertilizers; or simply the desires and traditions of the farming community), and physical factors (evaporation rates, topography, and soil depth).

Five types of studies provide the information required to make response farming operative:

1. Rainfall analyses in and around planning sites to determine degree of predictability.
2. Water production function studies of selected crops and cultivars to compare crop yield potential, water use, and responses to water deficits, with each of these parameters related to appropriate climate and soil characteristics.
3. Crop management studies conducted under continuously variable water supply conditions to determine optimum plant populations, fertilizer levels, intercropping/monocropping practices, etc., for each crop/cultivar of interest under each level of (simulated) rainfall.
4. Modeling crop water utilization and yield expectations in varying soil/climate circumstances, and development of crop-management models that simulate the effects of changes in plant population, soil fertility level, etc., on crop water utilization and yield.
5. Water balance analyses for the planning site that incorporate findings from the previous four studies, together with localized records of rainfall and evaporative conditions, measurements of soil depth and water-holding capacity, and specifics of crops presently grown, inputs utilized, and practices followed.

The final steps are to:

- utilize the above findings to formulate rainfall prediction criteria and detailed response-farming recommendations for each crop/cropping system to be grown at the planning site, and
- transmit these to the farmers prior to each season.

Note that the farmer will be instructed from the beginning of the program on the full range of crops to be planted, inputs that might be used, practices to be followed, etc., so he will be prepared to execute Plan A versus Plan B on short notice. Economically and logistically, the most difficult variations to execute will be to shift crops, which means that seeds will have to be available, and, if fertilizing, to shift amounts of fertilizer applied from one season to the next.

History and Present Situation

The conceptualization and research underlying the response farming development was begun by the author and collegues at the University of California, Davis, in 1967 (Stewart 1972); was broadened to a four-state effort in 1974 (Stewart et al. 1977); was then packaged and farm-tested in Kenya from late 1977 through 1983 (Stewart and Hash 1982, Stewart and Faught 1984, Stewart and Kashasha 1984). During 1984-86, the research has been largely focused on the rainfall prediction aspect, with studies conducted in the Mediterranean (Stewart 1986a and 1986b), and in Rwanda, Virgin Islands, Yemen Arab Republic, Nepal, and India. Only the Mediterranean studies are published, but the work in Nepal and India will be discussed.

The response farming concept, however, has been practiced by farmers for centuries in Jordan and India. The Indians term it "contingency planning", marked by the date of the monsoon onset or "sowing rains" (Virmani 1975, Rao et al. 1979, Ramakrishna et al. 1984-85). Basically, if the monsoon is late farmers switch from sowing their longer-season, higher water requirement crops, to medium- or short-maturity crops. With late drought (August onward), they may reduce plant populations by thinning (Mann et al. 1981). These are not just farmer practices, but have also been encouraged and improved by considerable research (Sastry 1978, Victor and Sastry 1979, Krishnan and Rao 1980, Sastri et al. 1982, Mondal et al. 1983, Vijayalakshmi et al. 1983, Chakravarty and Sastry 1984, Ramakrishna et al. 1984, Appa Rao 1985, Ray and Nathan 1985, Sinha et al. 1985).

Despite all the excellent research, there remains room for further improvement. Rainfall prediction for purposes of localized crop production has great strides to make. This is equally true for development of transferable equations describing crop behavior in terms of water use and yield ability when water is adequate, and soil water extraction and yield responses when water is limiting. Similarly, there remains much to learn about effects of plant population, soil fertility level, and intercropping on these behavior patterns.

Our present water-balance models and crop-management models are not really very advanced. Transforming our information into simply understood and practical farm-level recommendations also has far to go.

From the beginning, a fundamental principle of the author's research approach has been simplification. Efforts are made to include only the most important variables in experiments. Experimental designs and equipment are selected to provide the greatest amount of data with the least expenditure of money, labor, land, and other resources. Data measurements are minimized both in kind and in number or rapidity. Findings are mostly empirical, often unaccompanied by a deep understanding of occurrences. The focus is on a working system as quickly as it can be produced. Refinements can be added in later.

Research Needs to Guide Response Farming

In the author's experience, certain aspects of experimental design, environmental requirements, and techniques are essential for response farming research:

- deep soil at the experimental site if findings are to be transferred widely;
- low rainfall in the experimental period if findings are to be transferred widely;
- line source design experiments, featuring a continuously variable water supply (Hanks et al. 1974, Stewart et al. 1977);
- neutron meter measurements of soil water;
- lysimeter experiments;
- meteorological observations at the experimental site; and
- computerized data storage, analysis, and modeling.

A deep experimental soil permits total quantification of the particular cultivar's root growth pattern and maximum soil water extraction when under drought stress. Estimates of soil water extraction from shallower soils at planning sites can easily ,be made, whereas experimental findings from shallow soils are transferable only to other shallow soil sites. Examples of this will be shown later.

Low rainfall in the experimental period permits simulation of the entire range of possible rainfall conditions when using the line source design. Higher rainfall reduces the experimental treatment range, and thus does not clarify the entire water production function for the study crop(s).

The line source experimental design is the only design known by the author capable of simulating the entire range of rainfall conditions with a relatively modest input of land, labor, equipment, and money. Usable data production per unit of required input (of any type) is considerably greater than with more conventional designs. In addition, its demonstration value for teaching agricultural extensionists and farmers is equal to its experimental value.

The many uses of the line source design are illustrated by the author's experiences from 1974 to 1982. By the nature of the experiment, water quantity was a variable in all cases. Other variables interacting with water (not in all experiments) were intraseason timing of water deficits and effects of salinity in both the irrigation water and the soil, crop cultivars (maize, three species of beans, cotton, grain sorghum, and two species of millet), intercropping versus monocropping, plant populations, and nitrogen fertilizer rates. Two water/plant population experiments with maize were negated by high rainfall and required repeating. All other experiments produced the information sought.

Neutron probes are the only way to measure volumetric soil water content repeatedly in situ. Gravimetric sampling or any method requiring transformation of water content from a weight to volume basis simply cannot produce the same accuracy.

However, there are three cautions in the use of neutron meters:

- Neutron meters require careful calibration, a laborious task. Errors in this determination can cause serious continuing errors.
- Neutron meter readings from moderately wet to wet treatments can be very confusing, even uninterpretable, unless there are readings from drier treatments to provide a baseline.
- Neutron meters suffer breakdowns from various causes during heavy use, just when they are most needed. It is not wise to begin serious research without a backup instrument.

Like neutron meters, lysimcters are the only way known to perform certain studies with acceptable accuracy. The first of these is daily determination of crop water use with adequate water. Field studies that assume insignificant losses to deep percolation, or in which measurements are not sufficiently deep, do not produce the same results.

In rainfed agriculture, crops seldom attain full canopy conditions (leaf area index >3). Yet all published crop coefficients used to estimate crop water requirements are predicated on full canopy conditions. It is important in rainfed agriculture to adjust plant populations in accordance with actual rainfall conditions because reduced leaf cover reduces the water requirement, which in turn reduces the stress when water is limiting.

If in the future we are to successfully guide farmers in adjusting to actual rainfall, we must have more quantitative information on effects of leaf cover on water requirement. Although several attempts have been made to develop such information (Ritchie 1972; Mugah and Stewart 1984), there is a clear need for good lysimeter experiments to improve our estimation capabilities.

A third important need from lysimeter data (it is possible these data already exist and simply need synthesis) is to model base soil evaporation losses from different soil types in different rainfall regimes (sequences). Improved evaporation models are required to permit better assessments of crop suitabilities for different areas by more accurate water balance calculations. They will also permit development of more effective farm recommendations concerning when, how, and how quickly different crops should be sown in different rainfall seasons.

An additional research need is for meteorological measurements to be made at (or in certain cases near) the experimental site. Certainly this includes the critical factors of rainfall and evaporation—the latter because it is negatively correlated with rainfall/cloudiness—and radiation, while temperature, humidity, etc., are often satisfactorily obtained from the nearest government meteorological station.

Little needs to be explained about the requirement for computerization. The masses of meteorological, soils, crop, economic, experimental and other data required for the modeling tasks ahead can be accomodated only with computers. We live in exciting times for agrometeorological research. It is only now that the experimental tools and long data records have all become available.

New Response Farming Research Findings

There are a number of new and mostly unpublished research developments concerning rainfall prediction to reduce the effective variability, leaf area index effects on water requirements and crop coefficients, soil water extraction under limiting water conditions, cultivar differences in soil water extraction behavior, crop water production functions, and the merging of all of these into a guidance system for farmers, farm advisors, plant breeders, economic and food planners, and others concerned with agricultural production in semi-arid, rainfed agriculture.

The author views this symposium as a particularly fitting forum through which to introduce new findings. This is because ICRISAT has a major interest in the same research aspects, and has linkages with research institutions throughout the world's semi-arid tropical regions. In the case of India, there is at present a great surge of interest in agrometeorological research. It is hoped this presentation may provide some new thoughts for that effort.

Rainfall Prediction: Recent Findings

Present day rainfall probability analyses tend to quantify the probabilities of different rainfall amounts in selected time periods. This also reveals the probabilities of dry (or wet) spells in specific time periods, and of dates when the rainy period may begin and end.

The major weakness of this type of analysis is that it provides no specific information about the upcoming season with which the farmer must deal. It may fall anywhere at all within the total range of possibilities revealed by the rainfall record. All one has learned is that certain events and patterns are more or less probable than others.

It would be useful if, prior to the start of each season, a significant portion of the range of rainfall possibilities could be excluded altogether, and new probabilities assigned to the remainder. The first principle of response farming was mentioned in the introduction: reduction of the effective variability through improved rainfall predictability. In other words, "rainfall prediction" in the response farming context does not mean pinpointing what is to occur, but, rather, identifying a portion of the range of recorded happenings that should not need to be considered as possibilities in the current season.

This concept is based on previously cited findings in Africa and the Middle East that there is a relationship between the time the rainfall season begins (date of onset) and the rainfall amount and duration thereafter. In short, the earlier the date of onset, the better the rainfall expectations (both amount and duration). A typical coefficient of variation (R^2) for rainfall amount regressed on onset date is of the order of 0.33.

In practical terms, this means that in the past very early starting seasons never fell in the lower one-third of the range of recorded happenings. Similarly, very late seasons were never in the upper one-third. A season with an "average" onset date never was in the extreme upper or lower one-sixth portions of the range. This information is of particular value because it is precisely the extremes of dryness (always) and wetness (sometimes) that cause the greatest problems in decision-making for rainfed crop production.

However, the author believes the present level of predictability can be markedly improved, and the time of prediction possibly advanced, to before the date of onset. The basis for earlier predictability for South Asia is simply the amount of off-season (Dec-Apr) rainfall prior to the monsoon. Table 1 provides an example of the nature and degree of early predictability from preliminary studies of rainfall at Kusum, Nepal, in the terai, just north of the Uttar Pradesh (India) border during 1957-84.

Rainfall amounts were divided into six categories, and probabilities calculated. Kusum rainfall is extremely variable, falling to the (assumed) crop failure level in 7% of all years, to the subsistence crop level in another 7%, and on the wet extreme, rising to the probable flooding level in 18% of all years.

In all the 4 years that had little or no rain (0-14 mm) preceding the monsoon, there was a late monsoon onset, 8 Jun or later. The following probabilities for monsoon rainfall show a strong shift to the dry side compared with the 28-year probabilities. Both of the "crop failure" years are included in this group, with obvious impacts on management decisions. Similarly, at the wet end of the scale, the probabilities of flooding conditions or excellent crop conditions have fallen to 0.

Moving to the other extreme, in the 8 years with the greatest rainfall (156-334 mm) preceding the monsoon, the monsoon always started before 8 Jun. In these years we see no "crop failure" or "subsistence" levels of monsoon rainfall. However, the chance of "flooding" conditions has increased to 50%, again with clear implications for changed management conditions.

The 16 years of intermediate rainfall (34-148 mm) were followed by both early and late onsets of the monsoon, thus extremely light or heavy off-season rains at Kusum appear to be predictors of the:

- date of onset,
- amount of monsoon rainfall, and
- duration of the rainy period.

Intermediate off-season rainfall also predicts rainfall amount, but only weakly predicts whether onset will be early or late. In these years (16 of 28, or 57% of all years), predictability is distinctly improved at the time when onset actually occurs (if early) or on 8 Jun (if late).

The ranges of three predicted characteristics (date of onset, rainfall amount, and duration) can be shown in terms of percentages of the overall range (100%) (Table 2). For example, following

Table 1. Probabilities of monsoon rainfall amounts following extreme low or high amounts of off-season (Dec-Apr) rainfall at Kusum, Nepal (median 1200 mm), and probabilities associated with late versus early onset following intermediate off-season rainfall (1957-84 data).

Off-season rainfall		Monsoon season rainfall (percent of median)					
(mm)	years	<50	50-75	75-100	100-125	125-150	>150
0-334 (Early & late)	28 (All yrs)	.07 (Crop failure)	.07 (Subsistence)	.36 (Low normal)	.21 (High normal)	.11 (Excellent)	.18 (Excess water)
0-14 (Late onset)	4	.50	-[1]	.25	.25	0	0
35-148 (Late onset)	10	0	.20	.40	.20	.20	0
34-97 (Early onset)	6	0	0	.50	.33	-[1]	.17
156-334 (Early onset)	8	0	0	.25	.12	.13	.50

1. A longer data record would be expected to show probabilities in these spaces with a value between the two flanking values.

very high rainfall (156-334 mm), onset is early, within the first 38% of the overall range of onset dates. The predicted range of rainfall amounts is reduced to 71% of the overall range, and the predicted range of rainy season duration is only 40% of the overall range.

If the two middle categories (intermediate off-season rainfall with early or late onset) are combined the overall ranges are reduced: possible onset dates, 77%; rainfall amounts, 50%; and durations, 64%. On the actual onset date, if prior to 8 Jun, the predictions of ranges of rainfall amounts and durations may be refined to only 40% and 22% respectively of overall ranges. On 8 Jun the remaining predictions may be refined to 34% and 62% respectively.

Monsoon rainfall in Hyderabad, India, also exhibits linkage with prior off-season rainfall (Table 3). Greater off-season rainfall indicates earlier onset of the monsoon, more rainfall, and a longer duration. The predictions may be made on 1 May, based on total Dec-Apr rainfall amount.

The monsoon rainfall at Hyderabad exhibits less overall variability than at Kusum. There were no years at Hyderabad with rainfall less than half of the median value (crop failure category), whereas there were 2 such years (0.07 probability) in the 28 year period at Kusum. At the other extreme (excess water), Hyderabad experienced only 2 years with rainfall greater than 1.5 times the median, while Kusum had 5 such years.

The 4 years with least off-season rainfall all produced monsoon rains less than the median, while at the other end of the scale, all 8 years with highest prior rains produced above-median monsoon rains. As the extremes suggest, the intermediate years also "lean" in the expected directions: for example in 8 of 12 years with lower pre-rains (10-41 mm), monsoon rains were below median and none were in the excess water category.

Table 2. Using off-season (Dec-Apr) rainfall amount to predict characteristics of the following monsoon at Kusum, Nepal.

				Monsoon			Ranges of monsoon rainfall (relative values)		
No. of years	Onset period	Off-season rainfall (mm)	Prediction date	Onset dates	Rainfall (mm)	Duration (days)	Onset	Amount	Duration
		Ranges of values							
28	All	0-334	NA	16 May-14 Jul	398-3032	73-159	100	100	100
	Four categories of seasons								
4	Late	0-14	01 May	15 Jun-14 Jul	398-1270	73-130	67	33	67
10	Late	35-148	08 Jun	08 Jun-30 Jun	775-1671	83-136	NA	34	62
6	Early	34-97	Onset	16 May-07 Jun	1025-2088	120-138	NA	40	22
(16)	(Early or late)	(34-148)	(01 May)	(16 May - 30 Jun)	(775-2088)	(83-138)	(77)	(50)	(64)
8	Early	156-334	01 May	16 May-07 Jun	1154-3032	125-159	38	71	40

Table 3. Probabilities of monsoon rainfall amounts following four levels of off-season (Dec-Apr) rainfall (median 624 mm) at Hyderabad, India (1957-84 data).

Off-season rainfall		Monsoon season rainfall (percent of median)					
(mm)	years	<50	50-75	75-100	100-125	125-150	>150
5-163	28 (All yrs)	.0 (Crop failure)	.18 (Subsistence)	.32 (Low normal)	.32 (High normal)	.11 (Excellent)	.07 (Excess water)
5-8	4	0	.25	.75	0	0	0
10-41	12	0	.33	.33	.25	.09	0
43-47	4	0	0	.50	.25	-[1]	.25
59-163	8	0	0	0	.62	.25	.13

1. A longer data record would be expected to show a probability in this space with a value between the two flanking values.

Table 4 quantifies how much a 1 May prediction can reduce the expected ranges of Hyderabad monsoon onset dates, rainfall amounts, and durations. For example when off-season rains are low, these ranges are reduced to 68, 61, and 65% respectively, of the total ranges of record for these three monsoon rainfall variables.

Figure 1 uses Hyderabad rainfall records to illustrate a few of the basic aspects of the strategy set forth in the introduction. It provides examples of:

- two ways to reduce the range of rainfall occurrences which must be considered for the coming season, and
- what it means to aim sowing-time decisions initially at the upper half of the remaining range, while being prepared to reduce plant numbers and withhold fertilizer if early rains are on the low side, or add additional fertilizer if on the high side.

The reader is cautioned that this example is neither complete nor definitive, but is simply intended to describe an approach to the problems posed by variable rainfall.

Figure 1 shows three ranges of monsoon rainfall amounts. The greatest range on the left includes the entire 28 years used in the present analysis, with the data points indicating the actual occurrences. The middle, lower range shows occurrences in the 16 years when off-season rains were low, not exceeding 41 mm (rows 2 and 3 of Table 4 combined). The right-hand range in the figure shows rainfall amounts in the 12 years when premonsoon rains were high (rows 4 and 5 of Table 4 combined).

The upper horizontal line is at an arbitrary monsoon rainfall amount of 850 mm to suggest that rainfall amounts above a certain level can be of no further use to crop production, but must be considered harmful in terms of waterlogging, crop washing, soil erosion, etc. Figure 1 shows these considerations are not relevant when off-season rains are low, but are very relevant when they are high. For other sowing-time decisions such as row

Table 4. Using off-season (Dec-Apr) rainfall amount to predict characteristics of the following monsoon at Hyderabad, India.

				Monsoon			Ranges of monsoon rainfall (relative values)		
No. of years	Onset period	Offseason rainfall (mm)	Prediction date	Onset dates	Rainfall (mm)	Duration (days)	Onset	Amt.	Duration
		Ranges of values							
28	All	5-163	NA	26 May- 09 Aug	314-1127	77-174	100	100	100
		Four categories of seasons							
4	Early/ Late	5-8	01 May	04 Jun 09 Aug	314-605	77-161	88	36	87
12	Early/ Late	10-41	01 May	04 Jun- 25 Jul	314-807	98-161	68	61	65
4	Early/ Late	43-47	01 May	02 Jun- 11 Jul	576-1127	101-174	53	68	76
8	Early/ Late	59-163	01 May	26 May- 11 Jul	643-1127	101-174	62	60	76

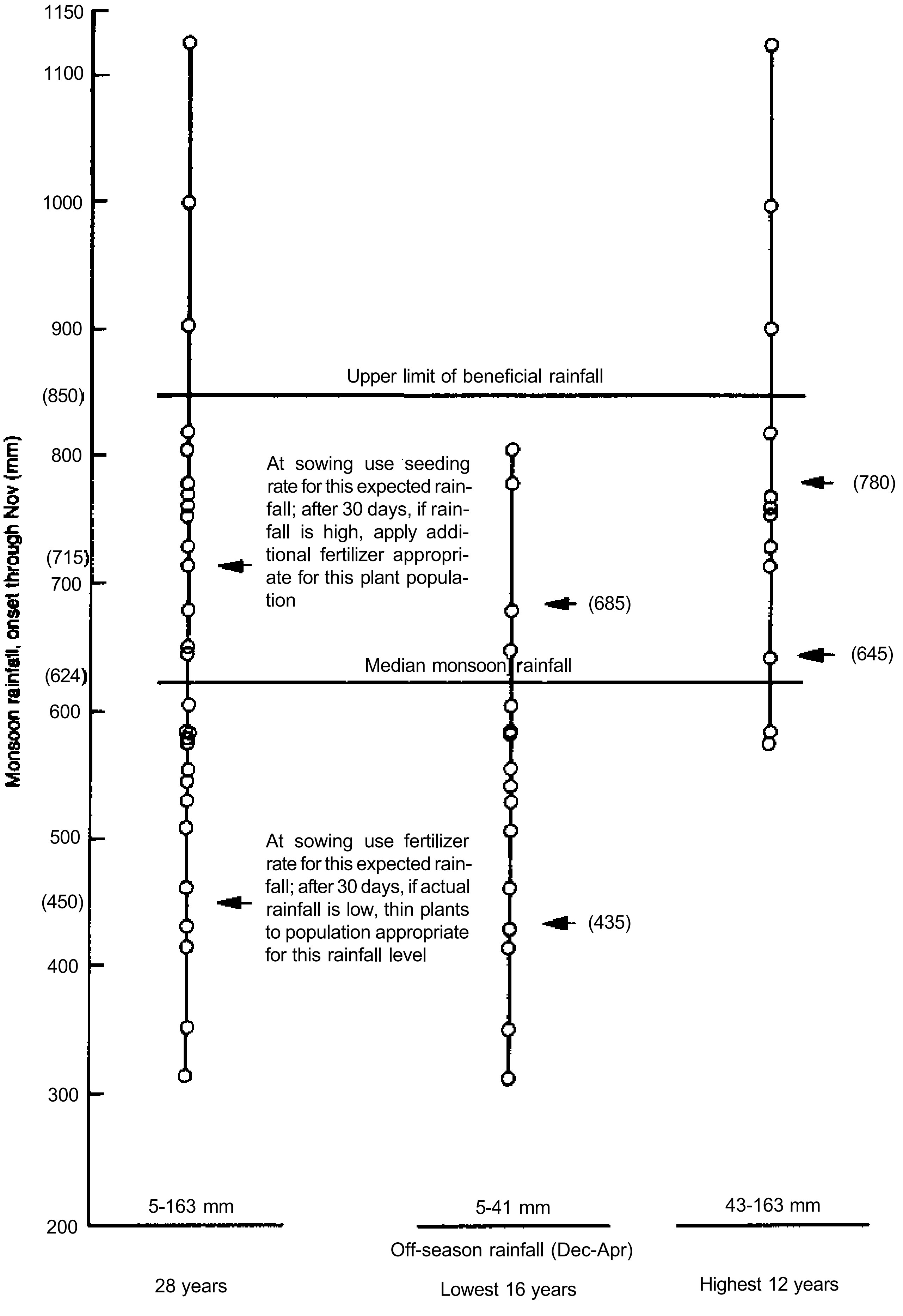

Figure 1. Monsoon rainfall associated with different amounts of off-season (Dec-Apr) rainfall. Hyderabad, India, 1957-84.

spacings, seed rates, fertilizer rates, etc., we may now proceed as if 850 mm were the top of all ranges.

The lower horizontal line is drawn at 624 mm, which is the median monsoon rainfall amount for the 28 years analyzed. When off-season rains were low (16 years), 75% of the following monsoons were below the median, and none reached the top of the designated useful range (850 mm). When premonsoon rains were high (12 years), 83% of the following monsoons were above the median and the remaining 17% (2 years) were not far below the median. Thus, all years of expected subsistence-level crops were preceded by low off-season rainfall. The two arrows next to each rainfall range show how the author proposes targeting sowing-time decisions.

When faced with the Hyderabad rainfall pattern as on the left side of Figure 1, the question is how should one plan for crop production? Generally in such rainfall zones, researchers have most commonly suggested making decisions as if rainfall were always normal, i.e., at Hyderabad mean rainfall of 650 mm, or median rainfall of 624 mm. Smallholders the world over have often selected a target water supply level below the median for two reasons: it is the best way to assure survival, and they have not had extra resources with which to gamble by purchasing fertilizers and chemicals, in the hope rainfall would be better. And for those willing to gamble, there are usually no lenders willing to take the risks involved.

The author's suggestion for this dilemma, assuming for the moment there is no known predictability, is indicated by the two arrows on the left side of Figure 1. Seeding rates should be as if rainfall were expected at the upper arrow level (715 mm) but initial fertilization should be for rain at the lower arrow level (450 mm). At the growth stage when further operations must be completed, perhaps 30 days into the season, rainfall to date is compared to normal standards. If higher than normal, additional fertilizers are side-dressed accordingly. But if rainfall is below normal, no more fertilizer is added and the plant stand is thinned accordingly, so that each remaining plant will receive enough water and nutrients.

Figure 1 illustrates how a seemingly minor prediction can ease the farmer's decision-making, using the two separate ranges of monsoon rainfall possibilities, based on prior rainfall in the Dec-Apr period. The more dramatic range is on the right, and includes the 12 years (of 28) that followed above-normal off-season rainfall. This range includes no dry years and all of the excessively wet years in the record. There is a radical shift in the placement of the arrows designating high and low rainfall expectations. It is certain that substantial amounts of fertilizers will be required, although the precise amount remains in doubt. Nevertheless, both the farmer and the lender could proceed with considerable confidence to invest their resources.

The lower range of rainfall possibilities represents the 16 years (of 28) following below-normal off-season rainfall. The principal changes from the overall record are that excess water is excluded as a problem, and that 75% of years will fall below the median, but not necessarily far below. The farmer should prepare his land to retain all rainfall, then make sowing decisions similar to those without predictability. However, when decisions on thinning or additional fertilization are made following early-season rainfall, the "normal" rainfall is based on the 16-year history, not the 28 years.

Crop Factors in Water Balance: Recent Findings

Figure 1 presented only preliminary steps in the process of formulating detailed recommendations for farmers in variable rainfall zones. Further guidance is gained by analyzing the rainfall record using water balance techniques and the actual planning site climate and soil characteristics.

Such analyses must be for specific crops. The purposes of these analyses are many, but primarily the result is a quantitative estimate of actual evapotranspiration (ETa) that should have occurred, had the study crop been planted in each rainy season in the rainfall record. The next step is to employ water production functions to turn the ETa estimates into quantitative yield estimates—at least possible yield estimates provided needed inputs were used, weeds were controlled, etc.

Water balance/water production function analyses, when performed for a number of crops, serve to identify those crops and cultivars that are best suited (physically) to the rainfall regime. They further pinpoint precisely what crops and cultivars should be selected for different seasonal rainfall expectations. And when the effects of management decisions (such as plant populations and fertilizer application levels) on crop water utilization and yield behavior are simulated in the analyses, optimal management practices for different types of rainfall seasons are identified. They can thus provide the basis for economic evaluations and for better estimates of food production capabilities.

Readers may be concerned that we are discussing the application of a complex approach by uneducated farmers. This is true, but not relevant; the complexity is handled at the research level. The guidance provided to both extension officers and farmers is simplicity itself. Generally it is Plan A versus Plan B, and, since the same two plans apply every season, the farmer knows them well and remains prepared. Farmers already make the same types of last minute changes in their operations as are suggested here. The difference is that they benefit from improved background information.

One of the most important aspects of crop factors on water balance calculations is the effect of leaf area index on crop water requirements. An experiment addressed to this question was carried out by the author's Kenyan collegue Mr. J. O. Mugah, who grew Katumani Composite B maize (a Kenyan white maize well known for adaptability to variable rainfall conditions) in 1980 at the University of California at Davis. His findings confirmed (Table 5) the widely accepted belief that water requirement rates are maximized at approximately LAI 3, and do not increase thereafter. However, the sowings that eventually achieved LAI values above 3 required substantially more water in the period from germination to full canopy.

Reducing the canopy to LAI 1.9 did reduce the maximum rate of water requirement as expected, however once again the greater reduction took place before leaf area reached a maximum. Water balance calculations are not very accurate if a single figure is cited as the water requirement. Studies to relate water requirements to leaf area indices are needed if crop water management is to improve.

Even greater weaknesses exist in our knowledge of the capabilities of different crops to extract soil water when water is limiting growth. The classical belief is that water extraction proceeds to permanent wilting percentage (PWP), which is said to be a characteristic of soil alone. The author's research shows maximum extraction by different crops grown side by side under drought stress is very different. But when the same crop is again

Table 5. Effects of leaf area index (LAI) on maximum evapotranspiration (ETm) by Katumani Composite B maize grown with adequate water. Experiment terminated 80 days after germination (Mugah and Stewart 1984).

	Plant population (plants ha^{-1})							
	16700		33 300		50000		66700	
Time after germination (days)	Avg LAI	ETm (mm)	Avg LAI	ETm (mm)	Avg LAI	ETm (mm)	Avg LAI	ETm (mm)
0-38	0.2	34	0.3	68	0.6	72	0.7	103
39-52	1.1	48	2.1	87	2.8	112	3.8	118
53-66	1.8	70	2.8	106	3.8	126	6.1	113
67-80	1.9	110	3.0	126	4.5	126	6.2	126
0-80	0.9	262	1.5	387	2.2	436	31.1	460

stressed in another season, it repeats its past performance; thus the result is predictable once it is determined and properly related to other factors (besides crop type) affecting it.

Principal factors are soil temperature, depth, and water-holding capacity, and one not known by the author to have been previously identified, water adequacy. When transferring results within a region, soil temperature may often be dismissed from consideration. If soil depth is limited, that is also easily dealt with by assigning zero values in the model for extraction from nonexistent layers. However, it is essential to understand expectations when the soil is deep.

The more complicated factors are soil water-holding capacity and crop water adequacy. Soil water-holding capacity is the well-drained field capacity as measured in situ. The author and collegues have defined a "soil water unit" (SWU) as 1% of the field capacity of a 30-cm soil layer (Stewart et al. 1976). The suggestion is that as a first approximation, a given crop will extract the same number of SWUs from different soils of the same depth.

Crop water adequacy is the seasonal degree of satisfaction of the crop water requirement, i.e., ETa/ETm. Water adequacy affects shoot growth and yield, but less is known about its effect on root growth and capabilities for water extraction.

To test the effects of these two factors, the author carried out a line source design experiment in 1981-82 at Kiboko National Range Research Station in Machakos District of Eastern Kenya, comparing water use and yield behavior of several crops grown simultaneously under six levels of (simulated) rainfall, ranging from the natural rainfall of 138 mm up to sufficient water supply to provide full water adequacy of (estimated) 362 mm for grain sorghum.

Crops compared were Katumani maize, six cultivars of grain sorghum, pearl and proso millets, pinto and mwezi moja bean, and tepary bean, a drought-hardy type from the Sonoran desert of Mexico. The soil was more than 2 m deep, with a loamy-sand to sandy-loam texture and a water-holding capacity of 57-91 mm of water per 30-cm layer of soil (1 SWU = 0.57-0.91 mm of water). Wild boars ate much of the maize, so data for that crop in Table 6 were supplemented with findings from another experiment.

Rather startling differences were found in the capabilities of different crops to extract soil water when under stress and also when nearing the little-stressed or near water adequate condition (Table 6). Each figure in this table shows the maximum

Table 6. Maximum soil water extraction by crops under water-limiting conditions: effects of soil profile depth and seasonal water adequacy. Water extracted expressed in soil water units (SWU). Kiboko and Katumani Research Stations, Kenya, 1981-82.

Total soil depth (m)	Crop water adequacy (ETa/ETm)				
	0.2	0.4	0.6	0.8	0.9
Katumani Composite B maize					
0.5	46	60	69	69	64
1.0	49	80	109	109	94
1.5	53	95	130	130	114
2.0	55	107	140	140	124
CSH 6 hybrid grain sorghum					
0.5	69	76	76	76	77
1.0	85	96	97	102	107
1.5	94	107	108	119	127
2.0	101	114	117	127	135
Pearl millet					
0.5	50	57	59	66	69
1.0	54	61	64	79	89
1.5	55	62	66	83	95
2.0	55	62	66	83	95
Pinto bean					
0.5	43	52	57	61	63
1.0	43	59	72	83	89
1.5	43	59	75	90	97
2.0	43	59	75	90	97
Tepary bean					
0.5	46	57	60	61	62
1.0	48	62	67	72	75
1.5	48	62	68	75	78
2.0	48	62	68	75	78

difference between actual water content and field capacity of the soil profile, when the crop growth was limited by water. The three factors affecting this maximum soil water extraction are crop type, soil depth, and season-total water adequacy.

For example, to compare maximum water extraction by Katumani maize and CSH 6 grain sorghum from a soil 1-m deep under severe drought conditions (40% water adequacy), and under mild drought conditions (80% water adequacy), grain sorghum would extract 96 SWU compared with only 80 SWU by maize—one more reason why grain sorghum is superior under severe drought conditions. On the other hand, at 80% adequacy maize extracts somewhat more water (109 SWU) than does sorghum (102 SWU). At 90% adequacy this has again reversed in favor of sorghum (Table 6).

Table 6 clarifies the great differences in the amounts of soil water different crops extract, and shows that water adequacy is very influential. A water-balance calculation that assumes "extractable" water is "available" water in the classical definition of the latter, can result in serious errors. Much more research of this type is needed.

The concept of soil water units implies that the same crop will extract the same number of SWU from a given soil depth when the overall water adequacy is about the same, regardless of the soil water holding capacity (related to texture). Four years of experiments with two maize hybrids (2 years each) at U.C., Davis, yielded some interesting data on this point. In the warm summer growing season and deep soil conditions at Davis, maize under limiting water conditions extracts soil water to a depth of 3 m; essentially completely to 2 m, then in diminishing amounts below that (Stewart 1972, Stewart et al. 1977).

Research at Davis on plant-soil-water relations is sometimes criticized because of the excellent soil characteristics—uniform, very deep, well drained, and of high water-holding capacity. Compared to most soils, this is true, but high uniform water-holding capacity is far from true in the subsoil. Two 30-cm layers are of particular interest because sandy lenses occur erratically through them, sometimes not at all, sometimes in both, and other times in one or the other. These layers are at the 165-195-cm (complete extraction) and 195-225-cm (near complete extraction) levels.

The actual variation in field capacity encountered in these layers was surprisingly great, ranging from a maximum of 130 mm/30 cm soil (silty clay loam) to as low as 57 mm/30cm soil (sand), with all values between represented in the same experiments. Figures 2 and 3 respectively show the

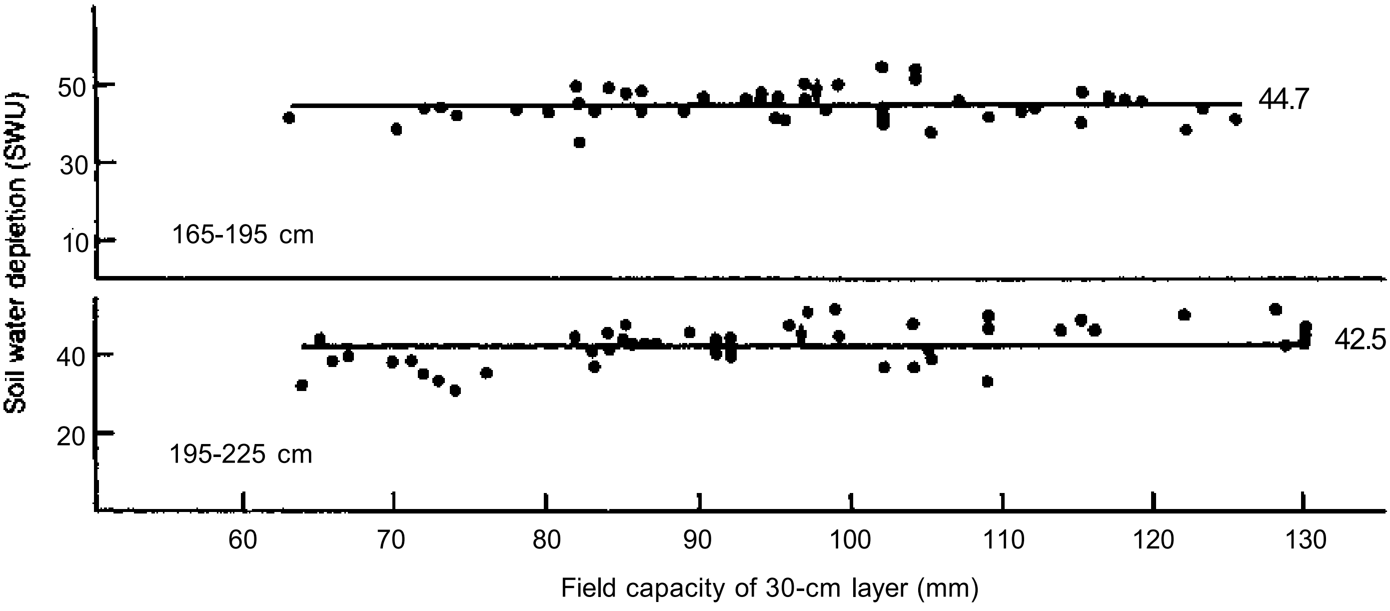

Figure 2. Maximum soil water extraction from soil depths of 165-195 and 195-225 cm by Funk's G 4444 hybrid maize under water-limiting conditions, as affected by soil field capacity (measured in situ). U.C., Davis, California, 1974-75. SWU = Soil Water Units = percent of field capacity of 30-cm layer.

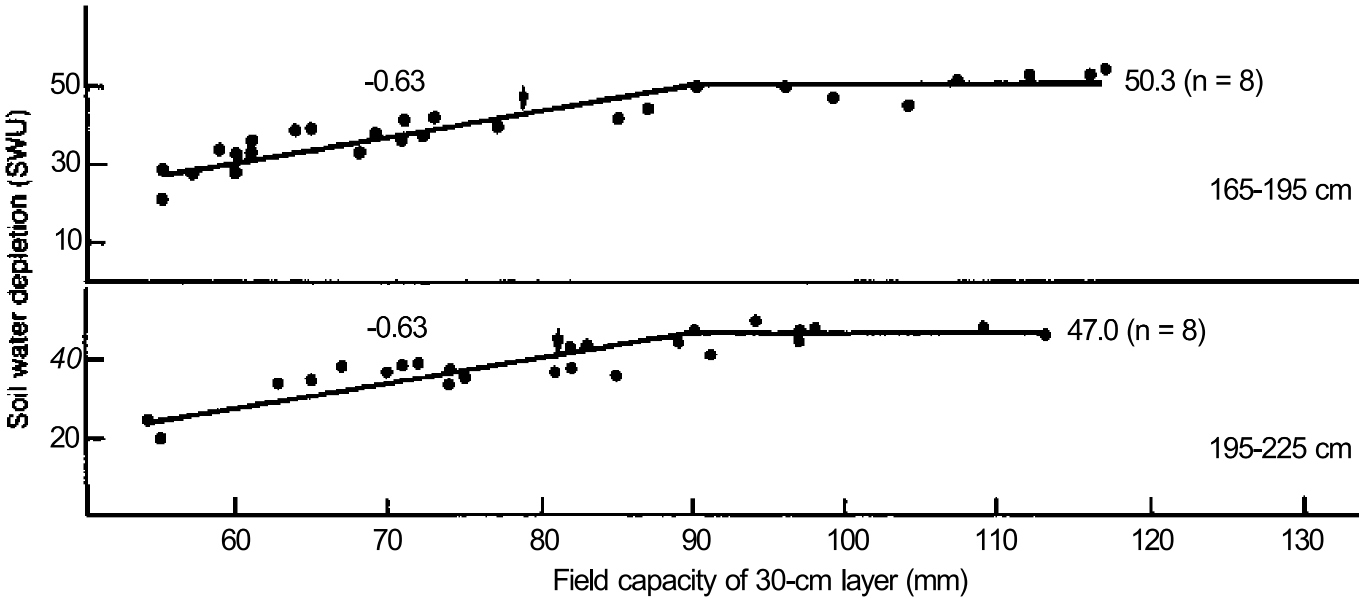

Figure 3. Maximum soil water extraction from soil depths of 165-195 and 195-225 cm by Pioneer 3775 hybrid maize under water-limiting conditions, as affected by soil field capacity (measured in situ). U.C., Davis, California, 1970-71. SWU = Soil Water Units = percent of field capacity of 30-cm layer.

current capabilities of Funk's G 4444 and Pioneer 3775 hybrid maize to extract water from these layers under identical stress conditions.

A given cultivar will extract equal numbers of SWU from soils of different water-holding capacities when the water adequacy levels are comparable; from silty clay loam to sand, the percent of field capacity (SWU) extracted by the G4444 hybrid remains constant in both soil layers (Fig. 2).

Soil water extraction by the P3775 hybrid was different (Fig. 3). Throughout the higher range of field capacities (above 90 mm), SWU extracted are uniform, but at a distinctly higher level than for the G4444 hybrid. However, with soils of lower field capacity (below 90 mm), the SWU extraction falls at a rate of 0.63 SWU per mm of field capacity. Exactly the same pattern is seen in the 195-225 cm soil layer. Thus, it appears extraction by a given cultivar is repeatable in different soils, but may differ between cultivars, and the same cultivar may alter its pattern (as in the case of P3775) in sandy-textured soils.

There are practical lessons to be learned from this information. First, in water-limiting conditions, G4444 always extracted more water overall than did P3775 and always yielded significantly higher—this in the Davis soil where sandy lenses did not predominate, but were common. Second, it would appear that in a light soil, such as a loamy sand with field capacity of 70 mm, G4444 would greatly outperform P3775, provided water were limiting as it frequently is in rainfed agriculture.

Information based on Figures 2 and 3 has at least three immediate applications:

- Those selecting new cultivars for introduction to variable rainfall zones could make better choices based on soil types at the planning sites.
- When selecting genetic lines to breed new cultivars, plant breeders should consider specific soil conditions.
- Those using water balance techniques to estimate crop suitabilities for planning sites could do so more realistically with this information built into their models.

Crop Water Production Functions: Recent Findings

Early research at UC Davis demonstrated that the relationship between yield and evapotranspiration (Y vs ET) is linear and that each cultivar has its own ratio of yield decline to ET deficit provided water is the limiting factor. These findings and the model developed from them (Stewart 1972), are presently in wide usage (Doorenbos and Kassam 1979).

But the model developed at Davis fits only water-limiting conditions, which, paradoxically, is only occasionally the case in the semi-arid, variable rainfall zones. Yields in these areas are usually limited in better rainfall seasons by soil fertility, because the high risk of water shortage discourages the purchase of adequate fertilizers. In drier seasons excessive plant populations often limit yield because there is insufficient water per plant to generate a normal harvest index. In eastern Kenya the excess plant population is often due to intercropping, which is a highly desirable practice when water is in the upper part of the range.

Y vs ET relationships in variable rainfall zones require modification to account for actual fertility and plant population levels. The modified functions serve two purposes. One is to simulate present management/yield relationships in order to estimate crop yields on the basis of rainfall (water balance studies). The other is for direct illustration of optimal management decisions at different water supply levels. Figures 4-6 further clarify these points.

Figure 4 compares Y vs ET functions for six crops grown side by side in a line source experiment. All of the functions are linear with high coefficients of determination (0.83-0.96) (Table 7).

However, in the reduced water supply/lower yield range, the tepary bean and CSH 6 hybrid grain sorghum exhibit an interesting and practical characteristic. Both crops go through a process one might term self-thinning, so surviving plants or stems have a near-normal harvest index. In effect, this establishes new production functions with the field impact of providing subsistence yields at very low water supply levels (see lower portion of Figure 4).

Ignoring this behavior, the order of water use efficiency of the experimental crops is panicum millet > tepary bean > pearl millet > P 898012 grain sorghum > CSH 6 grain sorghum (Fig. 4).

Not all crops will "thin themselves*', but the same result is possible if the farmer controls plant numbers in accordance with actual water supply. For example, Figure 5 shows two Y vs ET functions for Katumani maize grown in a line source experiment at two population levels. Note that the highest level of simulated rainfall, while adequate for the lower population, was inadequate for the higher population. Thus (ETm,Ym) for the latter is estimated. The estimate is in keeping with actual findings in other experiments.

The purpose of making the above estimate is to illustrate that higher plant populations use more water, but also yield more. However, when water is quite limiting, the reduced population is distinctly superior. For example, when ET is 160 mm, 20 000

Table 7. Grain yield compared with evapotranspiration (Y vs ET) functions for millet species, bean, and grain sorghum cultivars adapted to semi-arid, variable rainfall zones, Kiboko, Kenya, 1981-82.

Crop or cultivar	Maturity (days)	Yield ($kg\ ha^{-1}$) vs evapotranspiration (mm)		
		Regression equation	R^2	n
Panicum millet	65	Y = -1998 + 17.43 ET	0.93	5
Pearl millet	75	Y = - 3439 + 18.55 ET	0.83	6
Tepary bean	70	Y = -1922+15.18 ET	0.96	8
Grain sorghum P 898012	95	Y = -4629+ 21.46 ET	0.94	7
Grain sorghum CSH 6	95	Y = - 3387 + 15.34 ET	0.91	6

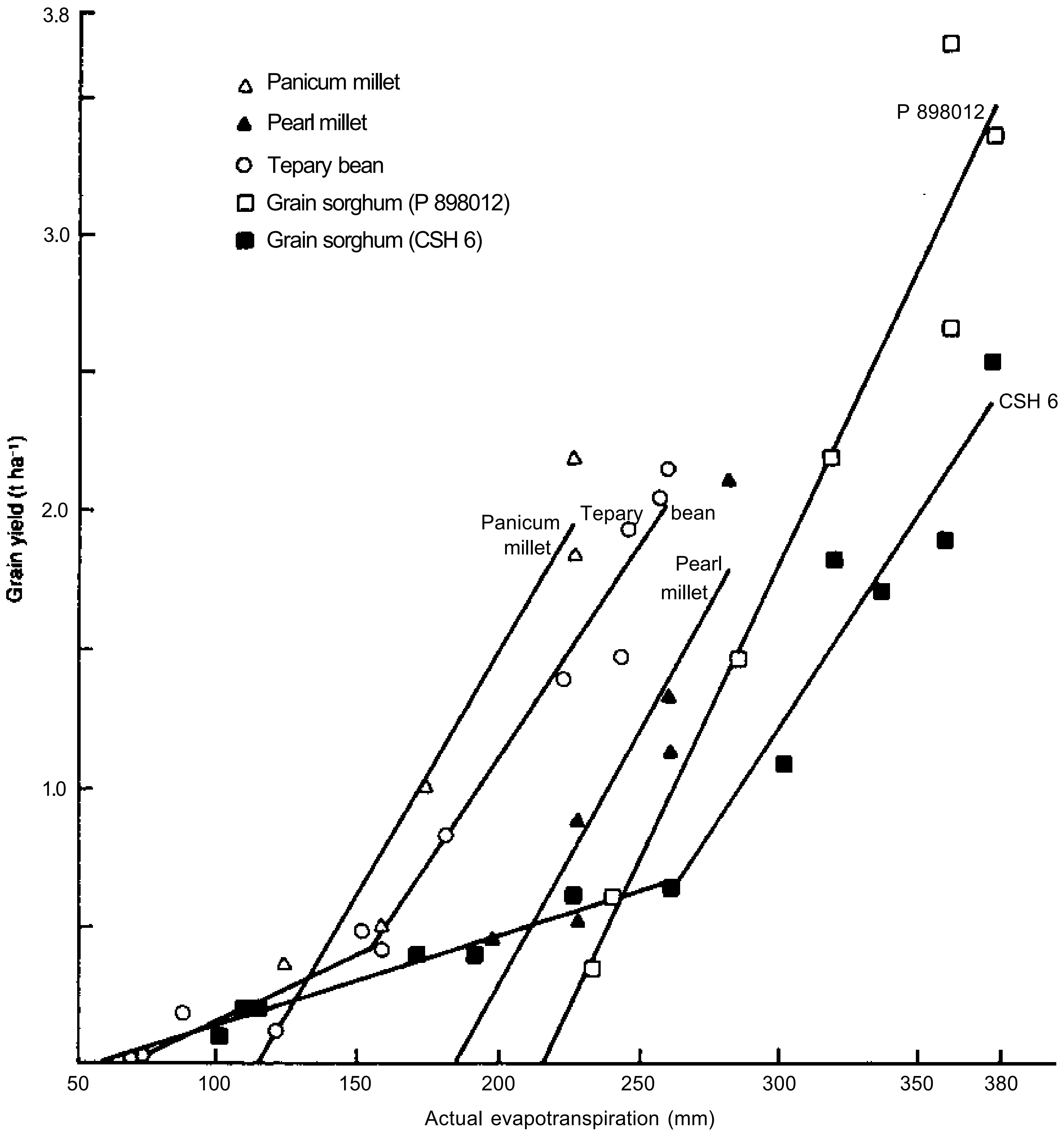

Figure 4. Yield responses to water: selected food crops for semi-arid variable rainfall regions. Kiboko National Range Research Station, Kenya, short rainy season, 1981-82.

plants ha^{-1} still yield 1.0 t ha^{-1} maize, while 60 000 plants ha^{-1} yield only 0.4 t ha^{-1}. This is due to less stress on each plant in the reduced population (Fig. 5).

Figure 6 provides three examples of maize Y vs ET functions for semi-arid, variable rainfall zones, each reflecting a different management level of soil fertility and weed control, but all reflecting optimal plant populations at any given ET level. The three functions may appear to be curvilinear, but in fact are each composed of several straight-line segments representing optimal por-

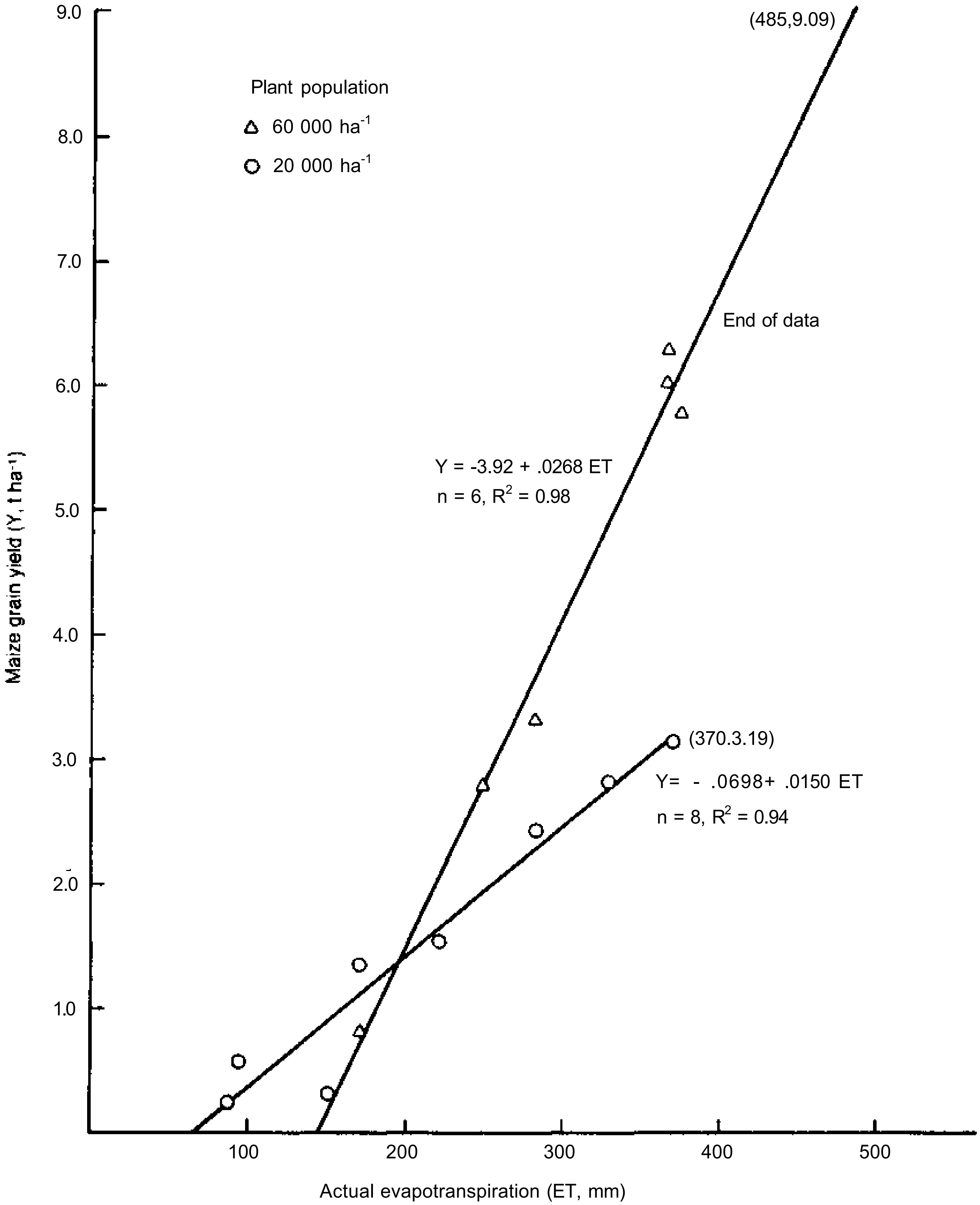

Figure 5. Water production functions for Katumani maize at two plant population levels. High-level management with only water limiting. Katumani National Dryland Farming Research Station, Kenya, short rainy season, 1981-82. Figures in parentheses are the regression estimated maximum evapotranspiration (ETm) and maximum yield (Ym).

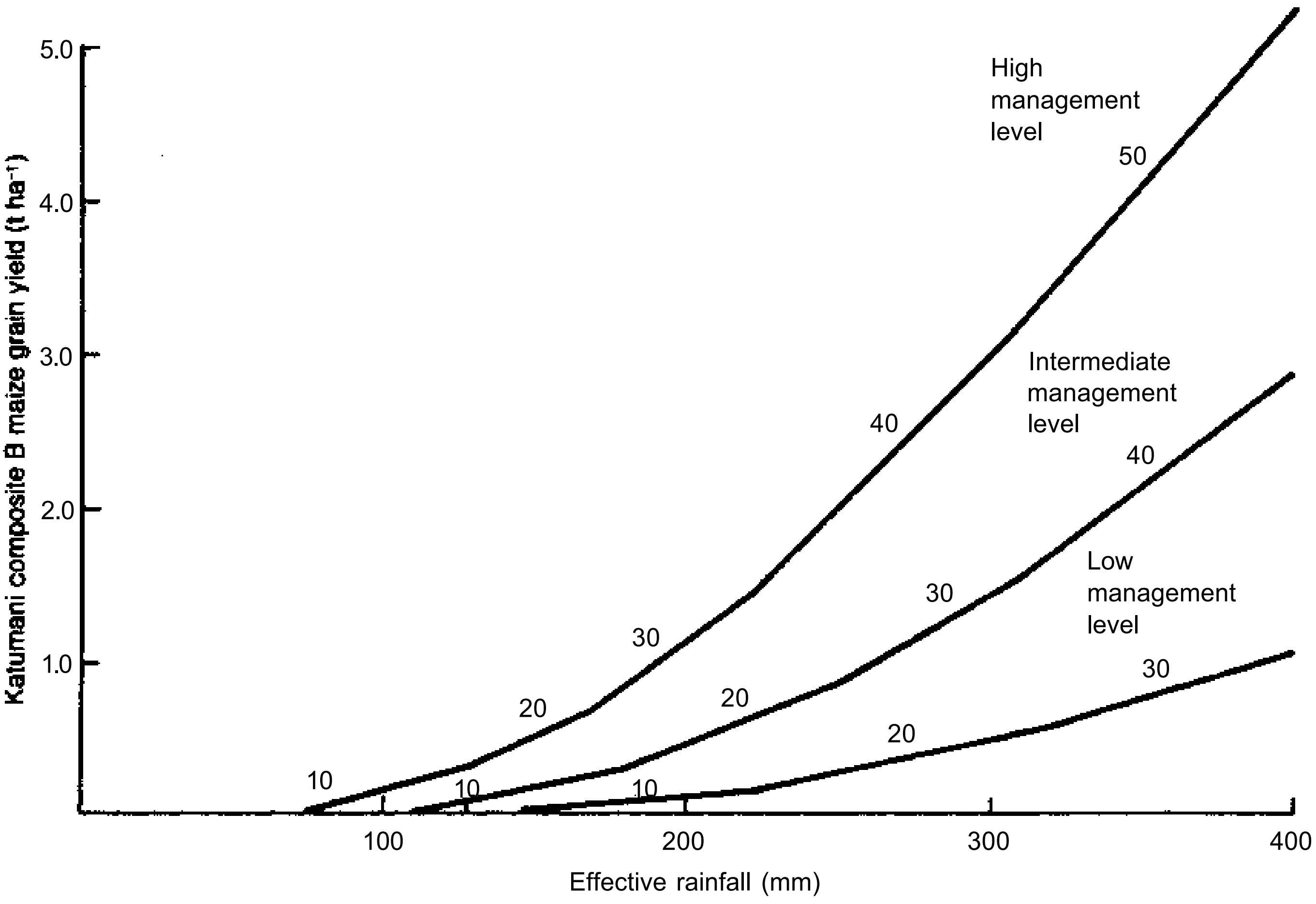

Figure 6. Research-based maize water production functions reflecting three management levels of fertility, weeds, etc., but always optimal plant populations. Machakos District, Kenya, 1977-82. Numbers adjacent to functions are optimal plant populations for rainfall and management levels (1000 ha^{-1}).

tions of different functions such as were seen in Figure 5.

The uppermost function in Figure 6 represents findings from experiment station level management, where, presumably, only water is limiting. However, it should be noted that the best farmers equal these results. The middle function represents the best management, but lacking commercial fertilizers. Soil fertility in this case is maintained by legume/cereal rotations. The lowest function represents optimal plant population, but no particular fertility management of any kind, and a low level of weed control.

The functions in Figure 6 are not the findings of a single massive experiment, but are synthesized from the findings of many experiment station trials and on-farm verification trials of the types described in this paper. Such synthetic functions constitute, in effect, a model useful to estimate yields at different water/management levels, and to illustrate practices that will improve output, and the degree of improvement possible.

Summary

A strategy is presented for coping at the farm level with seasonal rainfall variation. The aims of the strategy are to first reduce, then manage the risks involved to assure basic food production in low rainfall seasons, and to obtain high yields and break the poverty cycle in higher rainfall seasons, all on a least cost, maximum return basis. Major components are:

- Use newly defined, agriculturally relevant rainfall predictors before each season to quantify the actual variation faced, by excluding irrelevant portions of the historical range of variability.

- Use improved water balance/water production function analyses of the rainfall record to improve selection of crops and cultivars to be grown in different rainfall circumstances, and to provide guidance to plant breeders.
- Use improved findings on crop yield responses to interactions between plant population, fertilizer levels, and water to guide farmers in a flexible planting strategy, which permits final decisions on plant numbers and fertilizer rates to be based on actual rainfall in the first 30 days of the season.

Examples of research findings are presented to support the proposed program:

- 1 May prediction of the approaching monsoon, based on Dec-Apr rainfall, is demonstrated for Kusum, Nepal, and for Hyderabad, India. The flexible planting strategy is shown as it might apply in Hyderabad.
- Research findings from Kenya and from Davis, California, are presented to show effects of crop type, cultivar, leaf area index (plant population), and seasonal water adequacy on crop water balance. Effects of crop type, cultivar, plant population, fertility level, and degree of weed control on crop water production functions are also discussed.
- Future research, including environmental requirements, experimental designs, equipment and techniques is suggested.

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Interpretive Summary of Part 3:

Possibilities for Modifying Crop and Soil Management Practices to Maximize Production per Unit Rainfall

J. R. Anderson[1]

Introduction

This session featured three wide-ranging invited papers, ICRISAT contributions that ranged just as widely, and diverse, often controversial, discussion. My approach to pursuing "justice" in overviewing the controversies is to broach the topic from the viewpoint of a production economist, prior to examining the opportunities and exploring the implications.

Perspective from Production Economics

The complexities of farm life in the semi-arid tropics are not easily represented in formal models that are both insightful and analytically tractable. Farm households strive to survive and advance economically in the face of sparse resources and an uncertain environment. They can be thought of as attempting to maximize the expectation of E[ ] of a utility or welfare function U( ) with respect to production factors represented by a vector X, i.e., $\max_x E[U(\ )]$. The argument of U is arguable but probably features some economic measure of performance such as overall net financial return, F, which in turn depends on the costs incurred p_xX, and generated revenues. Simplifying to a single composite measure of physical output, Q, for what is inevitably a multi-enterprise and multicrop output vector, with unit returns of p_Q.

$$F = p_QQ - p_xX \qquad (1)$$

and the household's optimization problem is

$$\max_x E[U(F)]. \qquad (2)$$

The production possibilities for a representative household are governed by a technological relationship or production function:

$$Q = f(X), \qquad (3a)$$

which for the present purpose might be elaborated as:

$$Q = f(A,L,K,Z,R,u), \qquad (3b)$$

where A = land area,
L = labor,
K = capital services,
Z = management practices,
R = rainfall, and
u = a random variable.

In the spirit of Mihram's (1972, p. 15) Uncertainy Principle of Modeling ("Refinement in modeling eventuates a requirement for stochasticity"), it is important to represent in such a relationship,

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through the random variable, u, uncertainties in the natural and economic environment beyond those embodied in the production factors mentioned (especially in R, in amount, timing, and intensity).

The first-order conditions for (2) can be written (Pope and Just 1977) as:

$$E[U_p(F)(p_Q Q_i - p_i)]_r = 0 \qquad i = 1, 2, \ldots \qquad (4)$$

where

$U_p(\ )$ is the marginal utility of returns,

Q_i is the partial derivative (marginal product) of Q with respect to the i-th element of X, X_i, and

p_i is the i-th element of p_x.

Farmers' attitudes towards risk enter (4) through the marginal utility term. Decisions on risk-efficient resource use also clearly depend on the random marginal products of Q_i of the factors under the control of the household such as for land acquisition (Q_A), labor application (Q_L), capital investment (Q_k), and choice of management practices (Q_z). Rainfall itself is not controllable so its marginal product is irrelevant, except, to the extent that rainfall is without cost, it is driven to around zero through the other input choices. There are, needless to say, considerable research challenges in empirical estimation of relationships such as (3b), which span virtually all of ICRISAT's mandate, as well as econometric problems as those treated by Just and Pope (1978) and Anderson and Griffiths (1981).

The title of this part refers to "maximizing production per unit rainfall" and, to address this issue, some new variables must be introduced. These are, in the jargon of production economics, average products such as "yield", $Y_A = Q/A$; and its counterparts: labor productivity, $Y_L = Q/L$; capital productivity, $Y_K = Q/K$; managerial/"non-factor" productivity, $Y_z = Q/Z$; and rainfall productivity (i.e., output per unit rainfall), $Y_R = Q/R$. These productivity measures are not inherently useful in a world of optimization, but do have some intuitive appeal in various contexts. In an economic sense, it is never rational to seek to maximize any of them with respect to a variable factor of production (Dillon 1977), rather it is the marginal products that are important. Their intuitive appeal rests in the scarcity of the factor in the denominator.

Thus it is useful to reflect on average productivity with respect to the most limiting factor to understand the potential profitability and adoptability of research-based innovations. Land is scarce in most of Asia so that Y_A is a useful indicator in research assessment. In much of Africa, labor rather than land is often the key constraint, so that Y_L is a potentially more informative indicator of "yield", although it is very seldom used as such. When capital is highly constrained, as it is increasingly in Australia for instance, Y_K becomes an informative index. Very little attention has been addressed to Y_z, perhaps reflecting the relatively minor resources devoted to Z vis-a-vis A, L, and K. In some of the literature, (e.g., Lipton with Longhurst 1985) there is a concern that technological innovation should be directed to minimizing cash inputs of the Z type, while pursuing low-cost biological innovations that enhance such productivity changes, which typically work across area, labor, and capital productivity also.

This digression was pursued in order to address the session topic pointedly. In the jargon of production economics, it does not make sense to seek to maximize Y_R per se, as is implied in the title. Given the uncontrollability of R, it is also unrealistic to maximize anything important such as U or, more simplistically, Q, conditional on R, since it is a random variable. A crude approach would be to maximize U (or crudely Q) given E[R] presuming average rainfall experience, but this still misses the inherent stochasticity of the task and the risk effects connected to R. To recap, maximizing (2) is a task demanding much information and skill.

The preceding discussion brings this observer to a suggested cryptic reinterpretation of the title of this part: "How to improve, and attempt to maximize, farmers' welfare through research and development on the effects of L, K, and Z on Q and U." There are many opportunities and some are explained in the following sections.

The preceding paragraphs are an economist's interpretation of the key interrelationships. This particular perspective was not shared by all participants and, to be fair to those working in a somewhat different paradigm, my sympathy extends to the rather pragmatic but surely sensible guidelines suggested in the session. Consideration was given to technology that would:

- assure that a "maximum" possible fraction of the rainfall was used for crop growth (parts of the Unger et al. paper and the Perrier paper), and

- consider strategies to reduce the effects of other limitations to crop production which result in yields being less than the theoretical "maximum" for the amount of moisture available (parts of the Unger et al. paper and the Stewart paper).

Biological scientists may find the above concentration on variables under human control somewhat strange. It may be, of course, that maximizing (2) with respect to such variables may (and probably will) also lead to relatively high values of Y_R or other measures of the rainfall (or soil moisture) productivity. Whether this is the case or not depends on the nature of function (3b) and, unfortunately, cogent data that would help to resolve this empirical question are still very sparse.

Before leaving this rather abstract perspective, it should be noted that the focus on rainfall or R above reflects the title of this part. Other nonlinear transformations of R, such as effective rainfall or available soil moisture, may prove to be more useful as production variables, and may in some cases be more predictable than rainfall. The symbol R can thus be interpreted as any appropriate measure of the moisture regime faced by crops and pastures.

Opportunities That Are Virtually Costless

The most obvious approach to improving productivity, which contains the costs of adjustment to very low levels, is through plant breeding and germplasm enhancement. Farmers themselves have been doing this for millennia but, in recent decades, the ability to make rapid progress has been greatly increased. This has been particularly true for crops that grow in relatively favorable agronomic environments. Progress has, however, been understandably rather slower in the semi-arid tropics and other difficult environments. It must still be potentially the most cost-effective approach to adopt. This explains the enthusiasm for international research centers such as ICRISAT and ICARDA, for example, to devote extensive resources to improve crops that have hitherto been greatly neglected but, given the constraints of the environment, necessarily offer only restricted opportunities for significant improvement. Nevertheless, substantial progress has been made in all the mandate crops of these centers and in other crops that have received substantial recent attention from other agencies whose mandates include large areas of arid and semi-arid crop environments.

Apart from plant breeding, the other major opportunity to improve productivity without investing too many resources in inputs, especially the modern expensive ones, is by modifying the timing of cultural practices. There are potentials for making utility-enhancing progress in almost every input that is applied to crop production in the semi-arid tropics. Perhaps the most straightforward is the use of mineral fertilizers. Nitrogen is a classic case, because plants demand nitrogen throughout their life, whereas with a nutrient such as phosphorus, major demands are very early in the life of the plant.

Applying nitrogenous fertilizer to a crop which has an uncertain growth path is a risky business. The most simplistic approach is to apply all the anticipated nitrogen needs at the beginning of the growth cycle. This is not sensible if the nitrogen demands of the plant are likely to vary with the environmental circumstances during crop growth. A better approach is to split the applications and provide only minimal starter amounts at the beginning of crop growth and adjust subsequent applications to the physiological performance of the crop and to updated environmental prospects, as well as to any new information concerning the economic environment in which the crop will be harvested. Such a problem can be represented as a dynamic programming problem (Kennedy et al. 1973, Kennedy 1981), but is typically even more cumbersome because of the uncertainty of the response processes themselves, as well as the prices to be received for the crops the farmer hopes to harvest. This problem is a classic one in terms of exploiting emerging information on the processes involved, and is yet a rather underresearched issue in agricultural research generally.

Yet another opportunity that received such attention during the discussion is the effective utilization of crop residues. Some authorities express considerable enthusiasm for mulching to improve such ratios as effective evapotranspiration. The difficulty with such practices is that the direction of crop residues towards such activities is not without considerable cost. In agricultural situations where there are many livestock that depend on eat-ing crop residues, the residues that might otherwise go towards effective soil management with whatever efficiency gains can be conjured up, in fact have very high opportunity costs in their alternative utilization through animal feeding programs. The Indian national research system has also demonstrated the technical feasibility but economic impracticability of mulching. Thus it is necessary to take a whole-farm view of residue utilization before any conclusions can be reached about what would otherwise seem to be low-cost ameliorations of soil conditions and sponsorship of plant growth.

The other opportunity that could conceivably fit into this category, if it is done with low-cost labor, is soil surface modification such as creating ridges and furrows. Some discussants reported extensive areas of these that had been hand made. The idea is consistent with ICRISAT's continuing endeavors to conserve as much rainfall per unit of land as possible, while at the same time avoiding waterlogging during the wet season. Some of this work has, however, been approached through mechanical innovations that are too expensive for resource-poor farmers in densely populated areas of the semi-arid tropics.

In summary, there has been considerable investment in research and development towards technologies that are potentially very low cost for farm adopters. The greatest successes have been in plant breeding, and there have been some worthwhile achievements in agronomy and engineering. It does seem, however, that this is not a field for substantial further productivity, but it will continue to be very important because the gains that are achievable are very low cost, and will be significant in many disadvantaged agricultural systems.

Opportunities Involving Input Expenses

The opportunities for progress through investment in working capital items are really very significant. They have already been the subject of much research, which will continue. A classic case is fertilizer. Fertilizer has a somewhat tainted reputation in terms of the risk that is sometimes feared to be introduced through relatively intensive application. The matter is empirical, however, and there is still too little evidence on which way the effects tend to work. It seems plausible that, in general, high rates of nitrogen tend to make crop production relatively risky. Indian data on this were discussed by Rego. On the other hand, phosphorus is often a risk-reducing input, particularly at the low levels that crops need to make any decent growth. The empirical situation concerning these nutrients in the Sahelian Zone, as contributed by Renard, requires further clarification through research.

The risk-changing situation of several other agricultural chemical inputs is much less ambiguous. Pesticides, for instance, if sensibly used, make the life of the farmer rather safer. Cost of production per unit area may rise, but typically the productivity of all the resources is boosted through efficient and timely use of pesticides. Discussants, however, generally felt that antitranspirants were not effectve.

Demands for cash can be very awkward for small-scale farmers to meet in a timely manner, particularly for agricultural chemicals that might otherwise be applied profitably. Many governments in developing countries have recognized this problem and have instituted distribution and rural credit programs designed to facilitate the acquisition of inputs that mat prove to be profitable in farm business. Sometimes such schemes have heavily subsidized interest rates and repayment schedules. At other times the access to credit is merely facilitated, without the extensive subsidization such as is involved in the cheap-water schemes that have often been so critically appraised.

Yet another important category in this list of opportunities is the provision of *information* about the uncertain quantities involved in production, which make the whole process-management task so difficult. There are many elements of uncertainty in the life of a small-scale producer in the semi-arid tropics but nearly every aspect that affects rural households is amenable to some sort of prediction. A key question is the precision of supposedly skilled forecasters.

Information is typically not costless and, in general, farm household decision-makers have to share some of their resources to acquire useful information. Some of the information may be forecasting endeavors in either the economic or the biological attributes of production, although at this stage, very rarely the meteorological. In spite of the enthusiasm expressed by some discussants for the predictability of the monsoon, exploiting the expanding knowledge of the ENSO (El Nino/ Southern Oscillation) phenomenon, etc., this observer remains pessimistic about the likely value of seasonal meteorological forecasting (Byerlee and Anderson 1969 and 1982, Paltridge 1985, Weiss 1985).

Apart from forecasting uncertain futures, there may also be a considerable reward in more effective monitoring of crop growth, of the dynamics of insect populations, etc. Monitoring is also not costless, and given the increasingly expensive inputs from modern science, is actually becoming quite expensive, although it is probably still a very cost-effective approach. Methods of monitoring have been worked out most comprehensively for fungal diseases and insect pests of major crops, particularly cotton. There is surely much more work to do here, particularly in the semi-arid tropics of countries such as India, where there is little reliable empirical information.

Opportunities Involving Investment in Structures

There is a vague line that divides expenditures on consumable versus more durable productive factors. In this section, the sorts of structures considered are those that most people would regard as capital investments in the sense that they are long-lived physical assets that have a potential impact over many production periods.

The discussions in the morning and afternoon sessions highlighted many opportunities for effective investment, both public and private, to enhance agricultural productivity in this region. The cheapest opportunities to explore relate to tillage practices. Many options were discussed including such high-tech innovations as the use of lasers to facilitate field leveling, particularly in areas to be flood-irrigated.

The major investment under this heading is irrigation, where water that is harvested conveniently from some source is used to boost the productivity of other resources—with good management and some luck avoiding salination problems. There are, however, many other techniques that can boost the effective rainfall use for crop production. These include various forms of water trapping such as contour cultivation that reduces run-off both within a plowed furrow and across a field in general. More elaborate versions of this idea trap water in larger storages such as tanks of various designs. There was considerable discussion on the applicability of mechanized approaches from industrial countries to developing countries in this regard. The important point was that, especially in semi-arid areas where rainfall is very intensive, drainage can also be very useful. In the same vein, more work is surely needed to evaluate groundwater resources and their management. A systems approach to such research work is clearly needed.

Notwithstanding the long experience in some areas, such as Roman-farmed areas of north Africa, water harvesting is something of a Cinderella among the panoply of subdisciplies in agricultural science and research and development work. Opportunities have often been evangelized, occasionally been realized, but far too often have been illusory through the failure of the structues and other implementation problems. The problems range into engineering and soil science as well as economics.

Implications for Intervention through Research, Development, and Extension

There are not many unambiguous results in the theory of investment in risky enterprises, but one which stands out for its applicability is that diversification usually pays—often handsomely. Given the range of opportunities reviewed here, it is evident that a research and development program must work on most or all opportunities to facilitate eventual high-impact levels. Research is generally rather risky, especially in the semi-arid tropics. Accordingly, expected returns from research investment for these difficult environments will be small but probably positive. There was considerable discussion of how ICRISAT was endeavoring to determine priorities for its own research, and for collaboration with national programs, in order to maximize these returns.

Beyond such economic efficiency arguments, it is imperative that rapid technological progress be made to foster the economic advancement, and in many cases even the very survival, of the millions of resource-poor farmers and those who depend on them in the arid and semi-arid tropics. Vigorous attention to the research and development possibilities addressed in this session will do much to make such progress a reality.

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Part 4.

Possibilities for modifying crop varieties to increase production per unit rainfall

Adaptation Mechanisms of Noncultivated Arid-zone Plants: Useful Lessons for Agriculture?

E. D. Schulze[1]

Abstract

It should be possible to exploit a knowledge of the evolutionary solutions to problems of growth and survival in arid and semi-arid conditions in improving the performance of agricultural plants faced with drought stress. The various habits of noncultivated plants are compared in terms of adaptation to resource-scarce environments. These habits include annual vs. perennial, woody vs. herbacious, and evergreen vs. deciduous. The basic relationships between parameters indicative of plant water relations and potential for growth, survival, and reproduction are presented. The nexus between increased drought tolerance and lower biomass production potential is demonstrated. A summary of the multitude of adaptations to drought stress evolved in the plant kingdom is also given. Highly specialized plant forms have evolved but drought tolerance is generally determined by many traits acting simultaneously. Further, several thousands of plant species have evolved differing whole-plant organizations to cope with drought stress and species behave in a successional pattern depending on the type and severity of the stress.

The implications of this knowledge in improving adaptation to drought of agriculturally important plants are then discussed. The major contrast between crop and noncrop species is that noncrop species have a much wider spectrum of response mechanisms to adverse environmental changes. This implies that agriculturalists should be trying to utilize a much wider range of crop species in semi-arid and arid regions. However, there appears to be some scope for incorporating drought resistance traits in traditionally cultivated species without excessive penalties to yield potential. Screening for more appropriate root systems is an example.

Résumé

Mécanismes de l'adaptation des plantes non-cultivées de zone aride—expérience utile pour l'agriculture : Une bonne compréhension des solutions évolutives pour les problèmes de la croissance et de la survie dans des conditions arides et semi-arides devrait favoriser l'amélioration de la performance des plantes agricoles sous stress hydrique. Les divers comportements des plantes non-cultivées sont comparés concernant l'adaptation aux milieux à ressources insuffisantes. L'article fait la comparaison entre les plantes annuelles et vivaces, ligneuses et herbacées, semper virens et feuillues. Les relations de base entre les paramètres des rapports plante/eau et le potentiel pour la croissance, la survie et la reproduction sont présentées. Est expliqué aussi le lien entre la tolérance accrue à la sécheresse et le potentiel plus faible de la production de la biomasse. La multiplicité des adaptations produites dans le domaine de la plante au stress hydrique est brièvement présentée. Des formes spécialisées de la plante ont développé, mais la tolérance à la sécheresse est généralement déterminée par

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ICRISAT (International Crops Research Institute for the Semi-Arid Tropics). 1988. Drought research priorities for the dryland tropics (Bidinger, F.R., and Johansen, C., eds.). Patancheru, A.P. 502 324, India: ICRISAT.

plusieurs facteurs qui agissent à la fois. Plusieurs milliers d'espèces végétales ont produit divers moyens pour le contrôle du stress hydrique et se comportent selon des schémas successifs dépendant du type et de la gravité du stress.

La portée de cette connaissance pour l'amélioration de l'adaptation à la sécheresse des plantes importantes pour l'agriculture est ensuite discutée. La plus grande différence entre les espèces cultivées et les espèces non-cultivées est que ces dernières ont un très large spectre de mécànismes de réponse aux changements défavorables de l'environnement. Donc les agriculteurs devraient essayer l'utilisation d'un nombre élevé d'espèces dans les régions semi-arides et arides. Cependant, des possibilités semblent être présentes pour l'incorporation des facteurs de la résistance à la sécheresse dans des espèces traditionnelles sans une réduction majeure dans le potentiel du rendement. Le criblage pour les systèmes radiculaires plus appropriés est cité comme exemple.

Introduction

Plants inhabit the different climatic regions of the world in a variety of growth forms and structures. In the course of evolution they have developed so that life cycle, growth habit, and physiology are adapted to specific environmental conditions. During 450 million years of evolution, plants have occupied all environmental regions—from the ocean to the alpine zone, from the humid tropics to the cold and dry deserts.

Studying functional properties of plants in different climatic areas is one way to understand plant adaptations on a broad scale, since adaptations are often more obvious under extreme environmental conditions. In addition, about 30-40% of the earth's terrestrial surface is arid or semi-arid (Fischer and Turner 1978). Thus it may be tempting to regard steppes and savannahs, tropical grasslands, semi-deserts, and deserts as potential reserves for future agricultural use as world population increases. To cope with this challenge, it is necessary to continually improve crop hardiness. In order to do this, we should know more about the evolutionary solutions to the problems of survival and performance under arid and semi-arid conditions, an aspect which has stimulated research on nonagricultural as much as on agricultural plants in arid regions.

This paper analyzes the manifold features that enable plants to cope with extreme environmental situations in tropical semi-arid and arid regions. Those adaptations that may be important for agriculture in these areas are discussed, but, because a very broad range of botanical ecophysiology is necessary, only certain new aspects will be summarized here, and the reader is referred to earlier books and reviews which have been written on plant adaptations to arid regions, e.g., Turner and Passioura (1986), Turner and Kramer (1980), Hall et al. (1979), Penning de Vries and Djiteye (1982), Lange et al. (1982; 1986).

Plant Organization and Performance

Plant growth is linearly related to the assimilation of carbon, its partitioning into different plant structures, and to its loss, all of which must be accompanied by nutrient and water uptake (Schulze and Chapin III 1986). The assimilated carbon enters a pool of carbohydrates, and from there it is used either in respiration, or in growth of assimilatory and supportive structures. Partitioning into leaves has a positive feedback on plant productivity because of its effects on total leaf area, but it inevitably increases the demand for nutrients and water under conditions where too few carbohydrates are available for growth of supporting structures. Plants have to balance these simultaneous, parallel requirements, e.g., by changing the uptake efficiency of limiting resources by roots or by abscission of plant parts. Although this process is qualitatively understood, it is very difficult to describe it on a quantitative basis. To do so, aging, abscission, and retranslocation have to be considered, and the analysis varies depending on growth habit:

- leaves may be shed continuously (many crop plants) or seasonally (deciduous trees),

- supporting structures may be nonliving but functional components of the plant (wood),
- resources may be reallocated to other plant parts before abscission (nitrogen), or
- abscission can be a process of excretion (salt).

During their evolution, plants have responded to the variation in resource availability in many different ways (Schulze 1982). It is important for the following analysis to briefly introduce the major different characteristics.

Annuals allocate a very large proportion of their dry mass increase to the growth of new leaves. When compared with other plant life forms, they have the highest relative growth rates in the vegetative phase (Grime and Hunt 1975). In order to meet the increasing demand by the shoot for water and nutrients, annuals must have high rates of nutrient and water uptake. Their survival is secured by a high plasticity of phenological development, and by forming large numbers of seeds.

Perennial herbaceous plants store nutrients and carbohydrates (Schulze 1982), which results in a lower relative growth rate in the seedling year as compared with annuals (Grime and Hunt 1975). Nevertheless, perennials may have an advantage over annuals in the following season when stored resources allow them a faster and earlier leaf and fine root development. Thus at a time when annuals are just germinating, the perennial root system is ready for nutrient and water uptake without an additional major investment of carbon. It is not only the storage of carbohydrates that needs to be considered; nitrogen and other nutrients may be much more important storage compounds. For example, in a biennial thistle (Heilmeier et al. 1986), stored carbohydrates supported the growth of only new rosette leaves, which are less than 1% of the peak biomass in the second year. In contrast, 40% of the nitrogen requirement in the second season was accumulated in the first season. Obviously all factors interfering with the storage pool have an effect on the species performance in its second season.

Wood species differ from herbaceous plants by having smaller nitrogen requirements and lower maintenance respiration in their supporting, nonliving biomass (Matyssek 1985). The woody biomass is most important to compete for light (Kuppers 1985) and to explore a large volume of soil for water. For resource use, a distinction between deciduous and evergreen species is important. Evergreen species generally have a lower nutrient turnover and lower rates of photosynthesis. In addition, the investment of carbohydrates for new growth is smaller than in the deciduous woody species, but total biomass production may be greater because of the long-lasting investment in perennial foliage.

Also, a large proportion of the plant nutrient stock is in the evergreen foliage. In contrast, deciduous species depend to a large degree on nutrient uptake at the beginning of the growing season. In a drought situation, additional factors need to be considered. Evergreen species require some water at all times, whereas deciduous species can endure very long drought periods in a seasonal climate (acacia in Africa). But under extreme drought or in habitats with poor nutrient supplies in addition to insufficient and unpredictable moisture, evergreen species may be more predominant (acacia in Australia, Chenopodiaceae with green stems in the Sahara).

When investigating the different forms of plant organization, resources of carbon, water, and nutrients are of obvious importance. Photosynthesis is the primary carbon source for biomass increase. There is a linear correlation (Fig. 1) between the maximum relative growth rate of different ecological species groups (Grime and Hunt 1975) and their photosynthetic capacity (Larcher 1983). Photosynthetic differences between plant life forms are associated with differences in resource requirements. This implies that under conditions of restricted resource supply, a change in the prevalence of certain life forms is to be expected.

The capacity to open stomata (leaf conductance at maximum rate of photosynthesis) is linearly correlated with the photosynthetic capacity (Fig. 2), and the maximum rate of CO_2 assimilation is dependent on the nitrogen content of the leaf (Fig. 3). Nutrition, therefore, not only affects the photosynthetic capacity, but also leaf conductance (Fig. 4).

In contrast, transpiration is partially determined by stomatal conductance, but also by the vapor concentration difference between leaf and air. This meteorological component is a function of radiation and the boundary conditions of the. canopy. Plant life forms will differ in the aerodynamic roughness of their canopies and in the degree of dependence of transpiration on atmospheric conditions. Dependence is strongest at a high boundary layer conductance (trees and shrubs with open canopies), and is very weak at a low boundary layer conductance (in a uniform crop or in natural grasslands) (Jarvis 1986). In the latter case canopy transpiration is not affected very

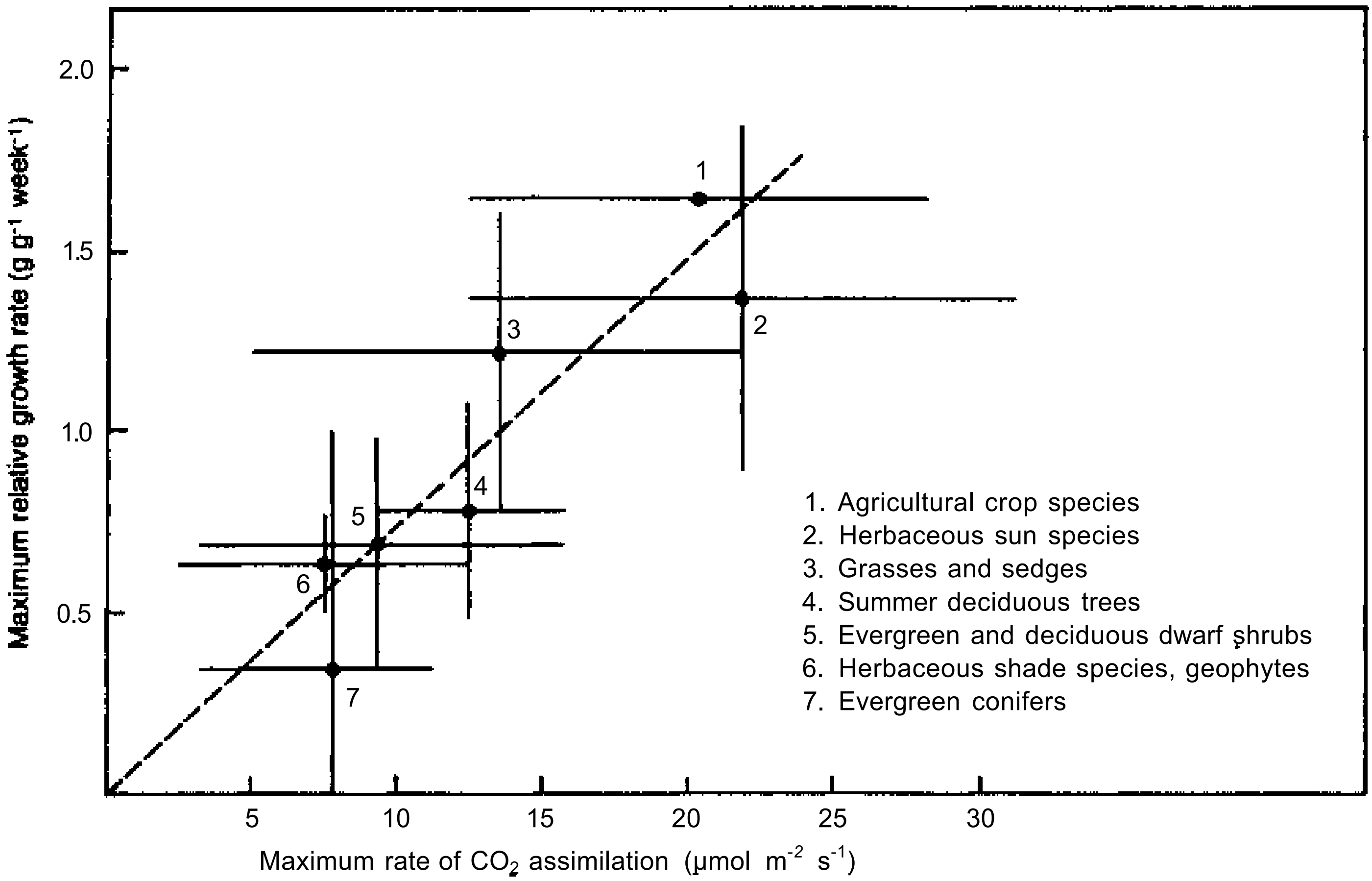


Figure 1. Maximum relative growth rate as related to maximum rate of CO, assimilation for different plants (from Schulze and Chapin III 1986).

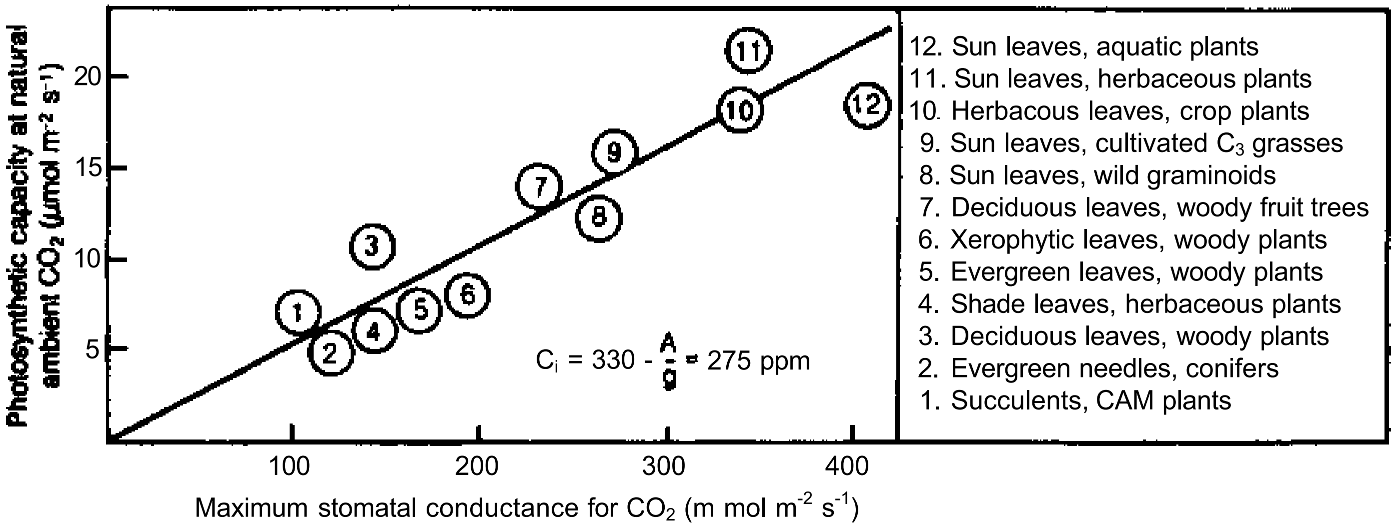


Figure 2. Photosynthetic capacity at natural ambient CO_2 as related to maximum stomatal conductance (after Korner et al. 1979).

much by changes in leaf conductance; however, conductance will affect the assimilation rate.

Whether plants interfere with their water loss by stomatal regulation or not, transpiration will influence plant performance in two ways: it will reduce the leaf water potential and available soil water. In Figure 5 the slope of the transpiration/water potential relationship represents the hydraulic conductance; various life forms are quite different in their hydraulic properties. In woody species the drop in water potential is much larger at a given change in transpiration than in herbaceous annuals. Changes in leaf water potential which are the result of changes in transpiration will not affect stomata (Schulze and Kuppers 1979, Gollan et al. 1985).

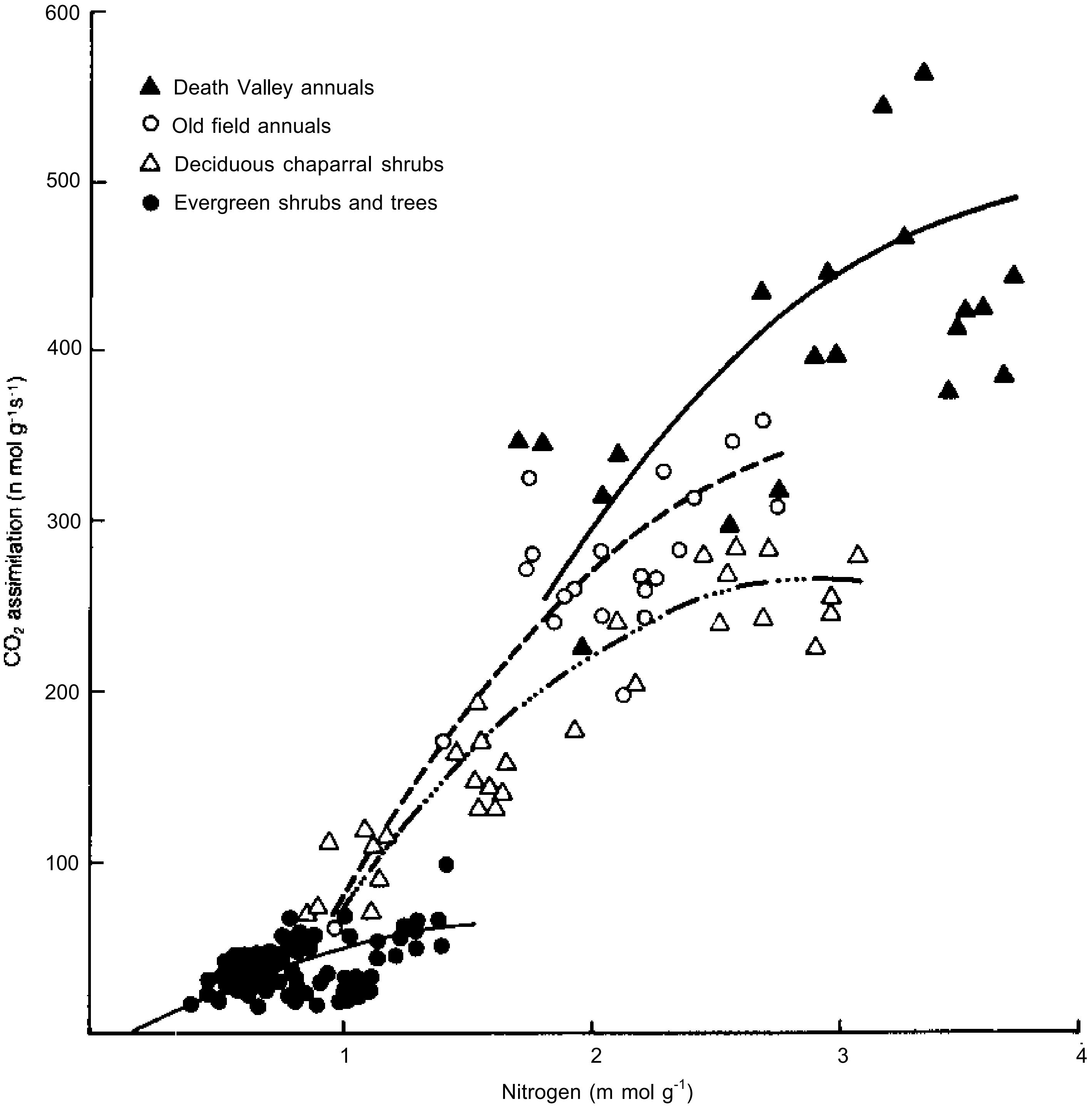


Figure 3. CO_2 assimilation as related to the nitrogen content of the leaf of various plant groups (after Schulze and Cahpin III 1986).

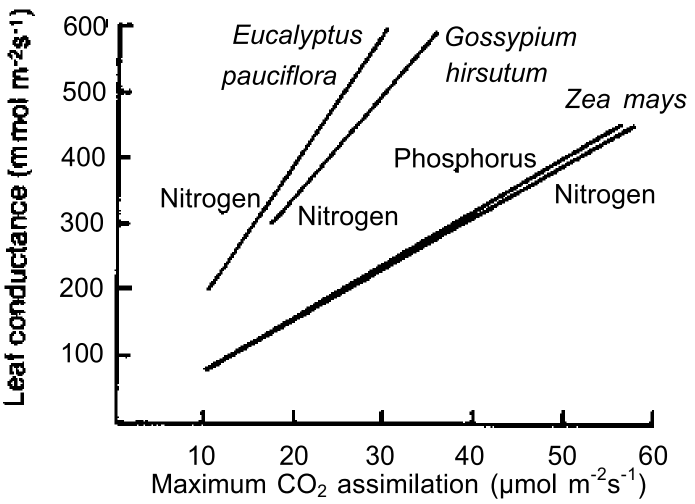


Figure 4. Leaf conductance as related to maximum CO_2 assimilation for variatipns in nitrogen and phosporous nutrition. Increasing rates represent increasing N-supply (from Schulze and Hall 1982).

Figure 6 shows an experiment in which the same species were grown at different transpiration rates, which causes differences in leaf water potential. When the soil was drying out, there was no unique relationship between leaf conductance and leaf water potential. The response curve could be shifted by about 1.0 MPa depending on the humidity in the atmosphere. But, transpiration will affect the soil water status, and in the same experiment a unique relation between leaf conductance and available soil water was observed that was independent of leaf water potential and transpiration. This observation can be interpreted to mean that soil water status regulates stomatal conductance.

It is difficult to predict the overall effects of boundary layer conductance on transpiration, de Wit (1958) proposed that plant growth is directly

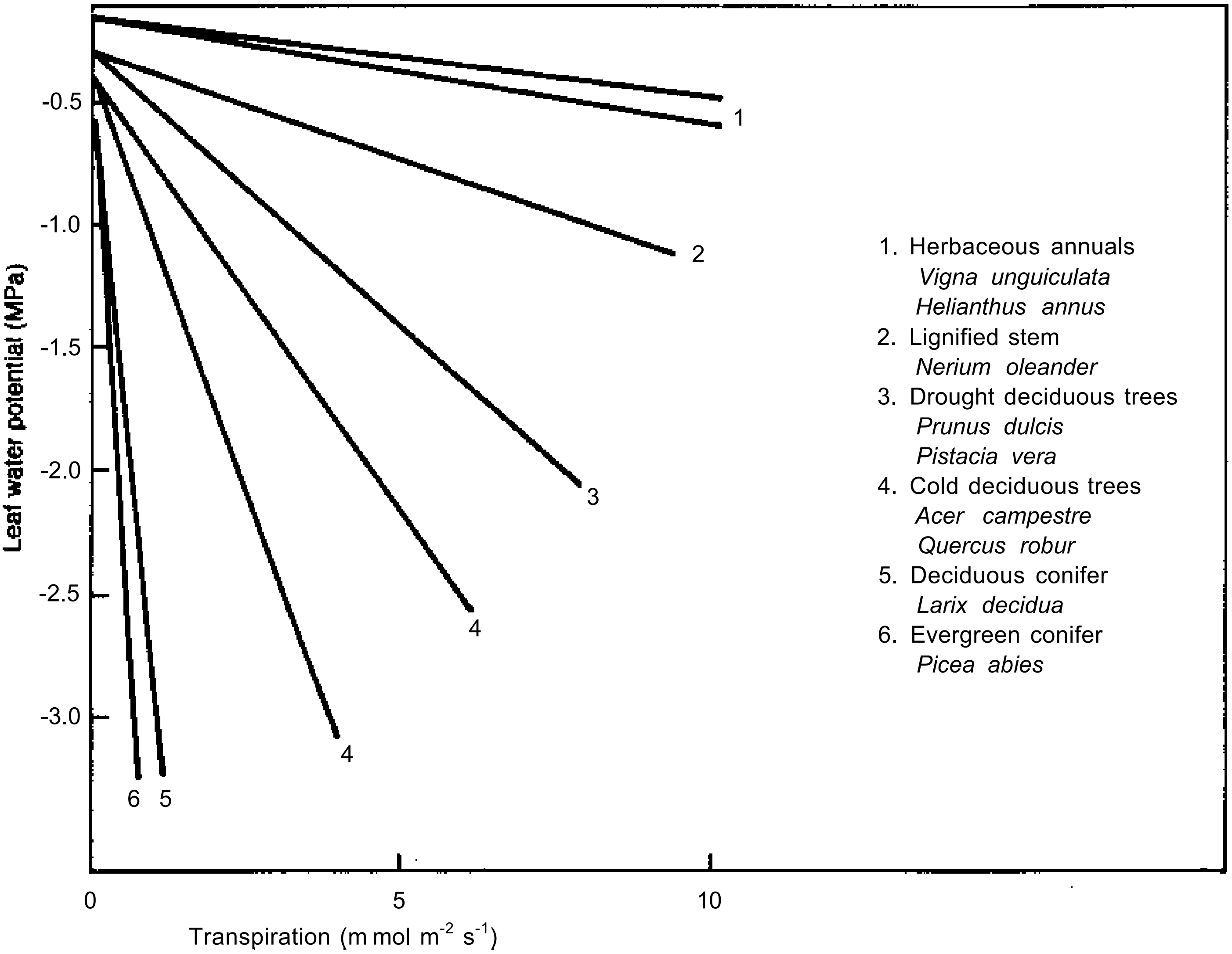


Figure 5. Relations between transpiration and leaf water potential for different life forms. The slopes of the lines represent the liquid flow resistance (from Schulze and Chapin III 1986).

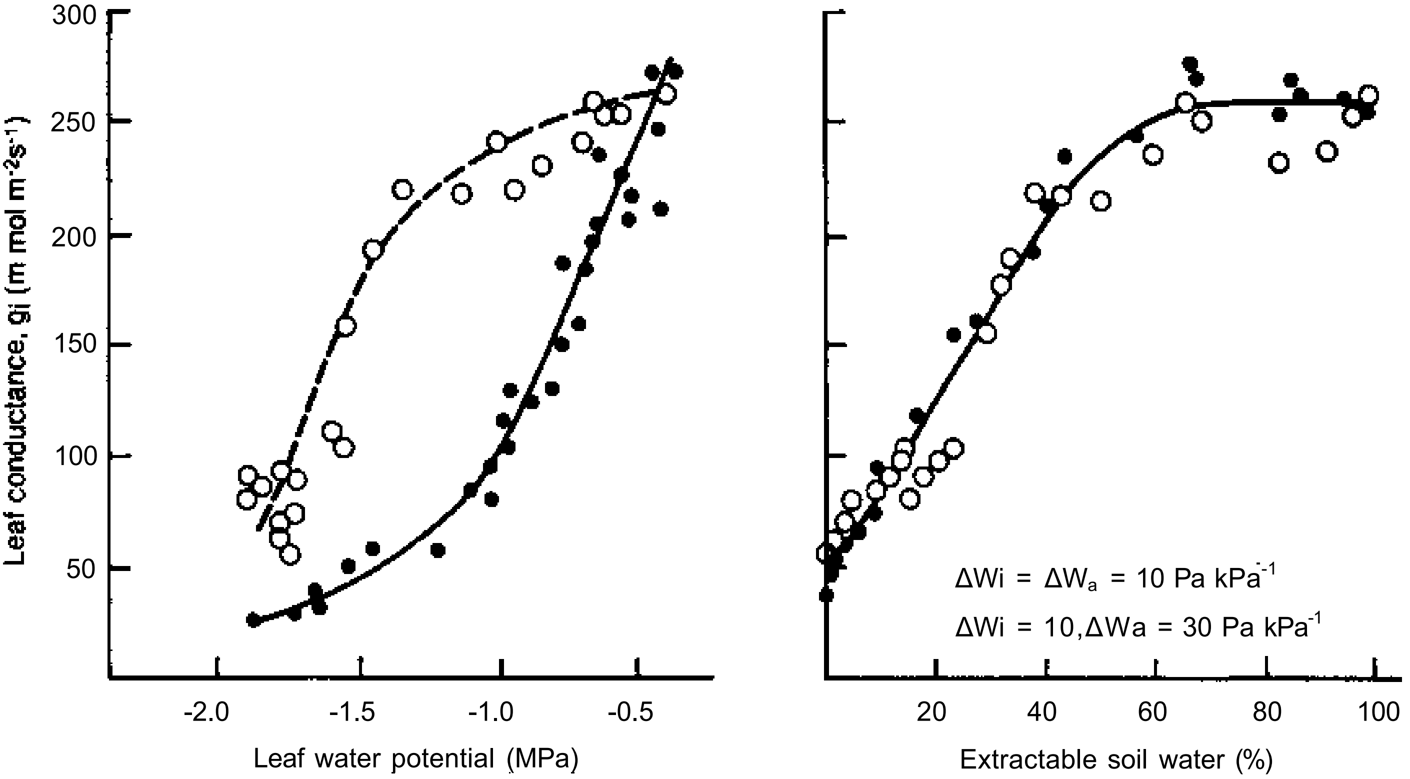


Figure 6. Leaf conductance as related to leaf water potential and extractable soil water for *Nerium oleander.* Leaf water potential was varied by changes of the air humidity over the entire plant between 10 and 30 Pa kPa. Soil water status was changed in a dry-out cycle (after Gollan et al. 1985).

related to the ratio of the cumulative transpiration divided by the average daily free water evaporation. The proportionality factor varied from 10 to 14 g m^{-2} d^{-1} in C_3- and from 21 to 23 g $m^{-2}d^{-1}$ in C_4-crops. These values represent differences in depletion of CO_2 in the mesophyll (Schulze 1982). Consequently, biomass production of herbaceous species in the broad range is linearly correlated with rainfall in arid areas (Fig. 7), but not just one species covers the full range of conditions.

In the Sahel a change in species composition is associated with variation in resource use (Fig. 8). Perennial C_4 grasses have twice the biomass production of C_3 annuals, but in contrast to annuals, which have a higher nitrogen content in their foliage, the perennial grasses operate at a much lower nitrogen status, which may even be below the limit necessary to feed livestock. In herbaceous legumes the nitrogen content increases, but this is only possible with a proportional cost, decreasing maximum biomass production.

The temporal and spatial variation of the available resources has led to a different distribution of plant life forms along environmental gradients (Fig. 9). The variable resource supply is complemented by a biological factor, the competitive ability for light. The evergreen woody "niche" requires a permanent resource supply over time, irrespective of whether the supply is rich (an oasis) or poor (lateritic soils of Australia). The highly competitive ability of woody species is known in semiarid regions, especially savannas, where thorn shrubs invade overgrazed areas. If the availability of the resource is seasonal, herbaceous perennial species replace the woody competitors. With predictable, although short, seasonal resource availability, perennial herbaceous vegetation becomes dominant (tropical grasslands), but with unpredictable pulses of resource availability, the annual vegetation becomes more competitive.

In summary, the plant kingdom has a large reservoir of life forms that are specialized for specific environments of resource availability. If conditions change, life forms will also change, and in addition, a change in the dominent life form affects resource availability (Schulze and Chapin III 1986). Natural systems appear to maximize consumption of available resources, thus interrupting

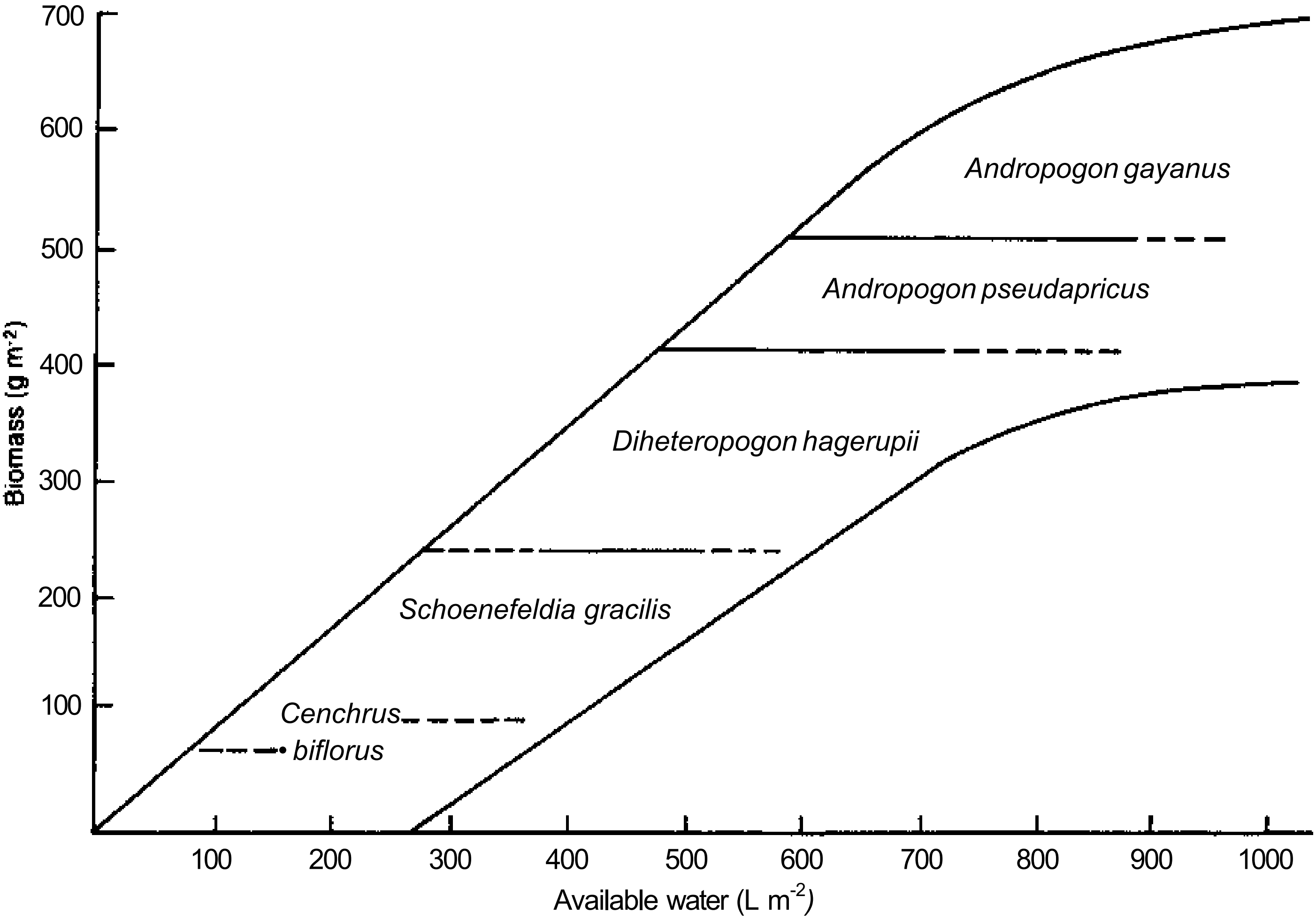


Figure 7. Biomass as related to available water and the associated change of dominant species of Sahelian perennial grasses (after Penning de Vries and Djiteye 1982).

the carbon and nutrient cycle will change species composition.

Mechanisms for Enduring Arid and Semi-arid Environments

In arid and semi-arid regions, conditions for plant life are extreme: the amount of available water is small, the drought period may be long, rainfall is often unpredictable, solar radiation and temperatures are high, and air humidity is low. All this causes a high potential evaporation, which in turn will lead to the accumulation of salt in the topsoil when the soil water balance is negative. Plant parts both above and below ground are subjected to seasonally severe stress.

Plants produce their highest biomass under adequate water and nutrients, except for some halophytic species, which need salt for maximum performance (Wyn Jones 1981). Species differ in the degree and time span for which they can endure drought; these are generally negatively correlated with biomass production, simply because costs and benefits of the investment for drought tolerance and carbon gain have to be balanced (Bloom et al. 1985). Figure 10 shows hypothetical lines of how carbon gain of a species will change if it has morphological or physiological features that allow it to endure increasing drought. With no investment in drought tolerance, the rate of biomass production will be very high, but, with various adaptive plant responses such as stomatal responsiveness, morphological changes in the leaf, osmoregulation, and alterations in the root/shoot ratio, plants gain drought tolerance while losing yield capacity. In nature, many examples of overlapping "niches" can be demonstrated (Schulze and Chapin III 1986) for factors such as drought, light, and available nitrogen. In all cases plants that are capable of tolerating a nonoptimal situ-

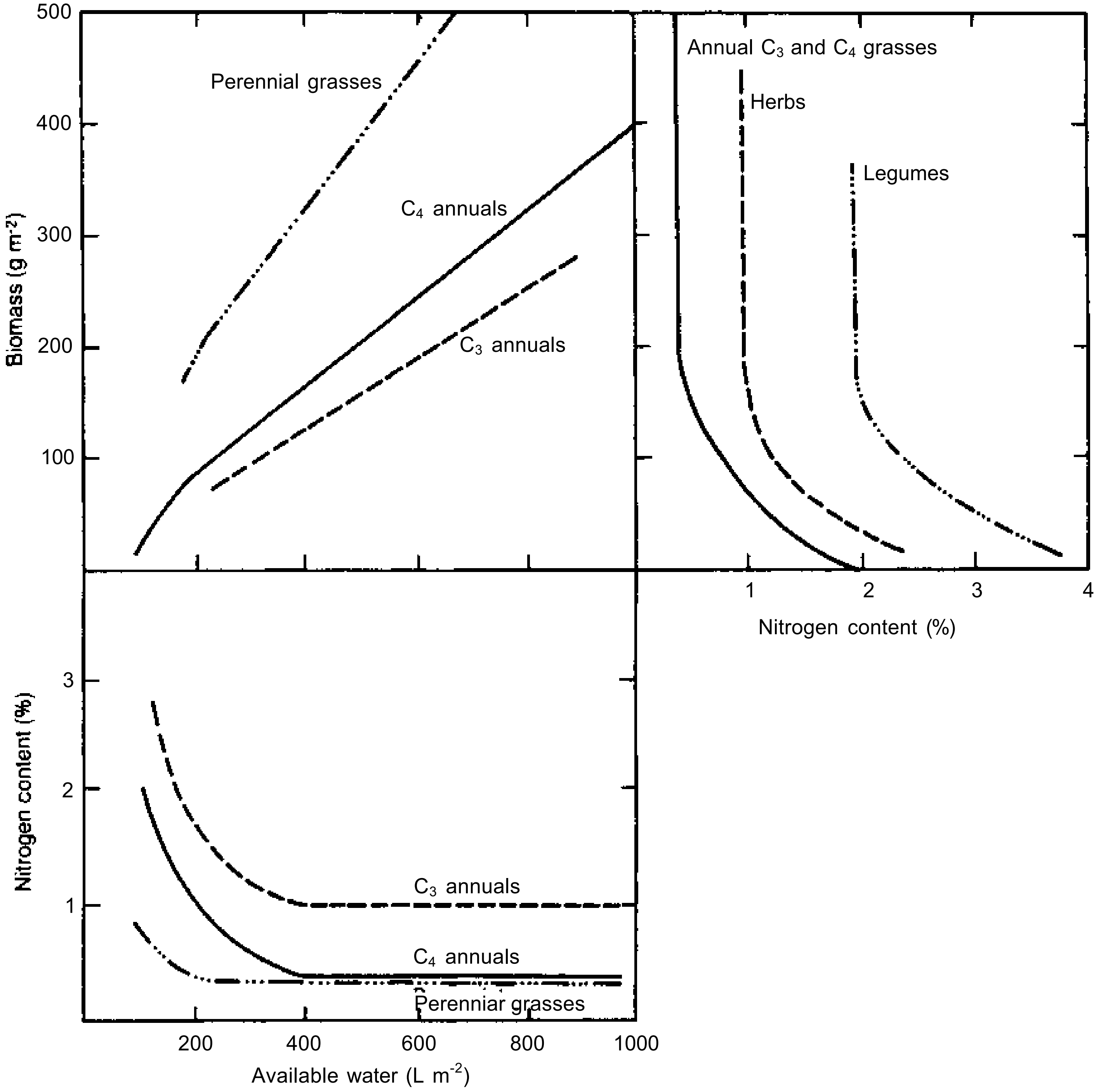


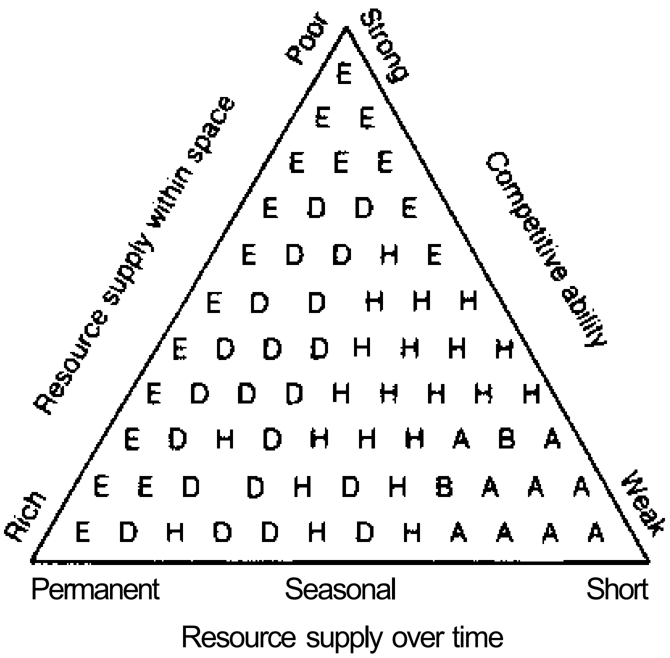
Figure 8. Relations between biomass, leaf nitrogen content, and available water for different herbaceous plant groups (after Penning de Vries and Djiteye 1982).

ation lose -yield capacity when compared with a nontolerant counterpart.

Besides changing features, plants have other ways of coping with aridity, as below.

Drought Escape

Drought escape is generally associated with annuals. In order to ensure survival during rapid cycling between an active and a dormant state, nonagricultural annuals show a large developmental plasticity, i.e., the ability to rapidly change phenological development and germination. For example, seeds show different germination requirements depending on the hierarchy under which they were formed on the flower stalk (Evenari 1984). Additionally, seed dimorphism is very common in arid regions. Plants may produce subterranean fruits to ensure the occupation of the habitat



A = Annual
B = Biennial
H = Herbaceous perennial
D = Deciduous woody
E = Evergreen woody

Figure 9. The distribution of plant life forms in relation to resource supply over time and space and to the competitive ability (from Schulze and Chapin III 1986).

that they already successfully occupy, but at the same time they may produce small seeds on aerial parts that can be distributed by animals or the wind to invade new habitats.

The seed bank is usually very large (10 000 to 100 000 m^{-2}) in arid habitats (Penning de Vries and Djiteye 1982). Following rain, a large number of seeds germinate (1500 to 15 000 m^{-2}), but only 10% may survive (Penning de Vries and Djiteye 1982). To compete with other seedlings, it may be important to be quicker than other species or individuals since water is limited; however, this risks germination after light rains followed by drought, which will kill many seedlings. Seeds of other species or other seeds of the same species may germinate only after considerable moisture becomes available, but these run the risk of germinating late in the rainy season and experiencing drought in the seed filling stage. Homogenous germination seems too risky under desert conditions.

Complementary to germination plasticity is the variability in the phenological development. If conditions become dry, flower and seed formation may be earlier than under moist conditions, for example, linaria species may complete the full life cycle within 2-3 weeks. Despite the development variability, the total number of seeds produced is very high, ranging between 8000 and 100 000 m^{-2} (Penning de Vries and Djiteye 1982).

In general, most species adapted to natural environments show great plasticity in the time of flowering and seed formation, but this plasticity is greatest in annuals. Differences in seed ripening on the same flower stalk are one major difficulty in domesticating amaranthus (Tucker 1986). The variability and plasticity of phenological development diminishes the risk of damage during sensitive stages such as filament formation. Thus in natural vegetation, only a minor proportion of the total flower population will be affected by adverse climatic events.

Drought Tolerance

All perennial species must find ways to stabilize their water balance during the dry season. Generally, it appears to be too risky to rely on one mechanism of drought tolerance only; due to internal feedback mechanisms, one characteristic is frequently associated with other supplementary or complementary ones. For example, measures to reduce transpiration may be supplemented with responses to increased water uptake.

Desiccation Tolerance

This feature is exhibited by the poikilohydric plants: algae, lichens, mosses, a few ferns, seeds, and some higher plants only in their vegetative phase (Gaff 1980). Most important and very widely distributed are the lichens. They use high air humidity and dew to activate their metabolism (Lange 1969). After overnight hydration, they may contain sufficient water for 1 or 2 hours of photosynthesis in the following morning before the sun dehydrates the thallus, and the metabolism falls into a latent stage for the rest of the day. Lichens are important for desert ecosystems as agents to weather rock surfaces (Krumbein and Jens 1981) and to fix nitrogen through symbiosis with blue-green algae (West and Gunn 1974). Most arid regions have a surprisingly high cover of lichens. They may be the only living plants and may completely cover the ground in areas that never re-

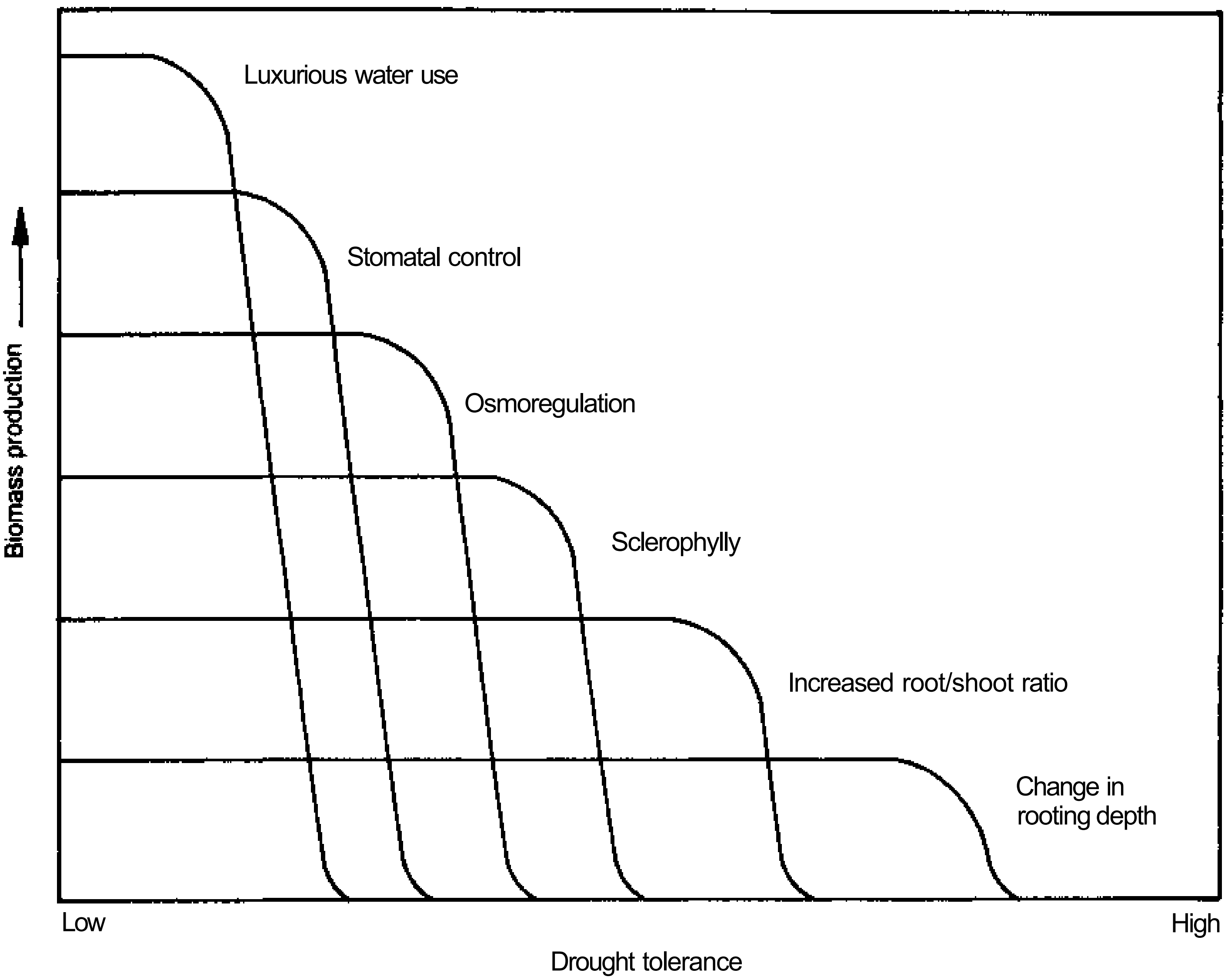


Figure 10. Cost/gain comparison of biomass production and drought tolerance. The lines represent potential production that can be achieved if various characteristics for drought tolerance are adapted in a cumulative manner.

ceive rainfall, but have extensive dew. such as the coast line of the Namibian desert.

Turgor Maintenance

At the tissue level, arid-region plants have developed turgor maintenance mechanisms. It is probably not just drought, but also leaf growth in high light environments that increases cell numbers and decreases cell size. These characteristics are essential for efficient changes in elasticity and turgor maintenance at low water potentials. Osmotic pressures increase passively with increasing dehydration; but. important active mechanisms of osmoregulation also exist, which allow the osmotic pressure to increase at full hydration in herbaceous plants by about 0.5 MPa (Turner 1986). However, in halophytes osmotic pressure can increase much further if salt is accumulated in the vacuole (Wyn Jones 1981). Most desert perennials are not only drought tolerant but also salt tolerant, and have developed special mechanisms for salt excretion, such as glands, bladders, and shedding salt-containing plant parts (Osmond et al. 1980). The range of osmotic pressures appears to vary in different life forms (Fig. 11).

Two groups have an exceptionally wide range of osmotic pressures in the vacuole: sclerophyllous shrubs and summer annuals. In the

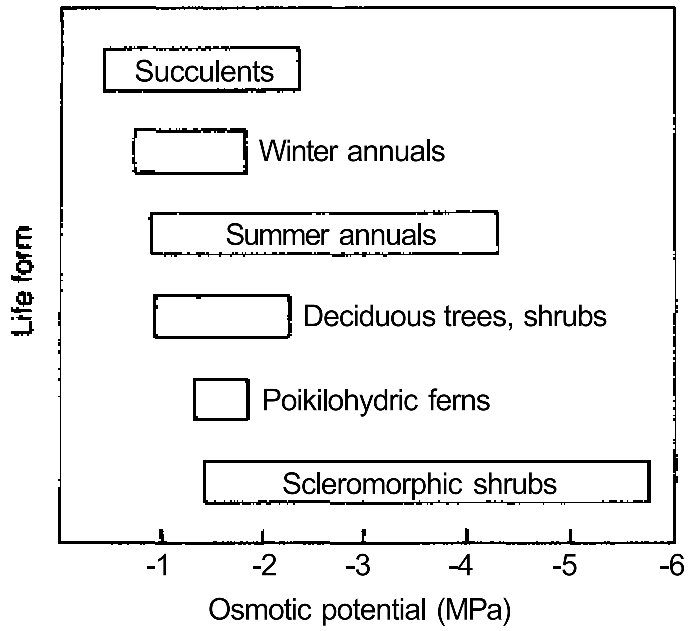


Figure 11. Potential ranges of osmotic potential in different life forms (after Osmond et al. 1980).

sclerophyllous *Hamadas scoparia* the overall seasonal change in osmotic potential (dehydration plus osmoregulation) was 4 MPa (Kappen et al. 1975). Probably desert species survive stress because they have the capacity to lower osmotic potential and maintain positive turgor at low total water potential (Hsiao 1973) or because they can tolerate high osmotic pressure, whichever is cause and effect (Walter and Stadelmann 1974). Successful species have the capacity of osmotic adjustment, although they may not grow under these conditions.

At the leaf level, drought affects extension growth and therefore changes leaf size. Generally leaf size decreases with aridity (Stocker 1976), which has a positive effect on the leaf energy balance (Nobel 1983). As usual, there are exceptions to this rule; welwitschia in the Namibian desert has leaves of 2 x 8 m (Giess 1969).

Water storage as a mechanism to stabilize the plant water status is found in some specialized plant groups, such as succulents and bottle trees. It seems to be the most obvious way to compete for water; it is therefore surprising that water storage is not a more predominant feature in arid vegetations. In order to be effective, the volume of stored water must be very large in relation to the transpiration. As a consequence, the organism may have to reduce transpiration and thereby sacrifice carbon gain. Also, stored water is a reservoir attractive to animals, unless the plant is protected against herbivors; e.g., *Adansonia digentata* is heavily browsed by elephants in Africa.

Reducing Water Loss

The most common way plants regulate water balance and maintain turgidity is to reduce water loss. Several mechanisms are possible, such as changes in specific leaf surface, stomatal regulation, and the ability to shed leaves or plant parts.

Numerous changes of the leaf surface have been associated with drought response, such as thickening of the epidermal cell wall and the cuticle (Walter 1973), and development of leaf hairs (Ehlcringer et al. 1976) and cuticular waxes (Turner 1986). These responses interact with plant nutrition under drought conditions (Schulze 1982). The carbon/nitrogen ratio increases with drought (Schulze and Chapin III 1986) and the formation of cell wall waxes and cuticles may be one way of depositing excess carbon. The efficiency of a cuticle to reduce water loss may not necessarily be determined by its thickness, but more by the chain length of the lipids forming it. For example, the cuticle of onion scales can more effectively withhold water than the thick cuticle of an orange fruit (Schbnherr 1982). The development of leaf hairs along with glaucescence improves the surface reflectivity and thus alters the energy balance of the leaf. This can very significantly increase the photosynthetic rate, especially if temperatures are above the metabolic optimum (Ehleringer 1980).

At high boundary layer conductance, stomatal closure may effectively reduce transpiration. Two responses appear to be important, one to air humidity and a second to soil moisture (Schulze 1986). Both responses, of course, also affect photosynthesis, thus there is a cost to saving water by stomatal closure.

Leaf orientation and leaf movement are the other morphological features that may reduce the heat load and maintain photosynthesis at a lower transpiration rate. Many arid-zone plants show vertical leaf arrangement. A special case of leaf orientation is active leaf movement as in Cucurbitaceae, Capparidaceae, Asteraceae, Leguminosae, and others. At adequate water supply leaves are oriented perpendicular to incoming solar radiation, photosynthetic rates are at maximum, and water loss is high. When the plant is stressed for water, leaves orient parallel to the incoming radiation, reducing heat load to a minimum and thus lowering transpiration. Indirect light is still sufficient for photosynthesis (Shackel and Hall 1979).

Leaf dimorphism, leaf abscission, and shedding of supporting biomass are more drastic modes of regulating plant water status. They strongly affect root/leaf ratios and the carbon balance of the plant. Leaf dimorphism is quite common in arid-zone plants (Orshan 1973). This was commonly interpreted as an adaptation to drought, but it may also be an expression of the changes in the nitrogen supply at different times of the season (Schulze 1982). Leaf abscission with drought is a common feature in all perennial species. Generally, nitrogen is recovered before abscission. Even evergreen leafless photosynthetic stems can adjust the photosynthetic stem surface (Evenari et al. 1983). If leaf loss is not sufficient to regulate the plant water balance, supporting biomass is abscised, a process that has been described by Evenari et al. (1983) as "survival by die-back". This process is common in shrubs and trees not only in arid environments, although desert species appear to have preadapted stem morphology so that a certain proportion of roots and shoots can die without endangering other parts, which still obtain sufficient water to live.

Maintenance of Water Uptake

In contrast to the diverse responses that have been studied for above-ground organs of desert species, very little is known about root responses. It is likely that osmoregulation occurs in root tips (Davies et al. 1986) which allows roots to penetrate soil layers of a different water status. But more commonly, root tips follow the gradient of water from the upper soil layers to various depths (Fernandez and Caldwell 1975). Plant life forms differ in the ability to exploit various soil depths and soil volumes. Annual species are generally rooted in the upper soil layers, although summer annuals (e.g., polygonum) may have tap roots that reach more than 3 m deep. Woody species, because of their extensive root systems, can reach much deeper by following seasonal waves of penetrating moisture after rain. By exploitation of large soil volumes, trees and shrubs maintain their water balance. Generally the hydraulic conductance decreases with drought, which promotes abscission of aerial parts rather than die-back of below-ground biomass (Schulze and Hall 1982, Evenari et al. 1983).

Improving CO_2 Uptake and Water-use Efficiency

Besides mechanisms to ensure adequate plant water status there are several processes that allow plants to improve their water-use efficiency and thus their carbon balance. Most prominent is the evolution of different modes of carbon fixation: C_4, C_3, and the crassulacean acid (CAM) metabolism. C_4 plants have a physiological advantage over C_3 plants at higher temperatures and at high light intensities (Ehleringer and Mooney 1983), and there are indications that C_4 plants will be more drought tolerant than C_3 species (Schulze and Hall 1982). Nevertheless, the large superiority of C_4 over C_3 plants at the cellular level disappears at the canopy level (Gifford 1974). CAM plants have the highest water-use efficiency, but grow very slowly since their carbon gain is dependent on the size of the vacuole for malate storage.

Besides the evolution of different metabolic pathways for carbon fixation, there are additional ways to improve the water-use efficiency. Specific leaf mass increases with increasing aridity, and in plants adapted to extreme drought (Stocker 1976). Since water loss is a function of the total leaf surface, but photosynthesis a function of mesophyll volume, an increased specific leaf mass, which reduces the surface/volume ratio, -will improve the water-use efficiency. Specific leaf mass is directly correlated with the rate of assimilation in some species (Orem et al. 1986). However, an increase in specific leaf mass will also increase the nitrogen demand per unit leaf area.

There has been much discussion on possible ways to "optimize" water use (Cowan 1982). The highest carbon gain for a given water loss would be achieved if plants operated in the regions of the "break-point" of the curve relating CO_2 uptake to mesophyll internal CO_2. It appears, however, that most species in arid conditions operate below this point, in the linear portion of the CO_2 response curve, which represents the region of most efficient water use (Schulze and Hall 1982).

Besides these mechanisms that directly influence water use, the protection against herbivores has not been studied adequately. Complicated mechanisms to protect against herbivores have been described for sclerophyllous vegetation in

Mediterranean climates (Mooney et al. 1983). Since herbivores will interfere with storage when the resource supply is unreliable, protection is of special importance in the arid and semi-arid climates.

Overall Plant Performance in Arid Regions

The distribution of various vegetation types is related to the resource supply over space and time (Fig. 12). Ephemeral vegetation covers only a small niche when resources are available only during very short time periods. At higher resource levels, annual species are succeeded by perennial woody species because of their higher competitive ability for light, their capacity to store nutrients, and the presence of roots whenever water becomes available. The major proportion of arid habitats is occupied by perennial plants. Figure 12 suggests a stable configuration of vegetation types. But since the rainfall variability is high (Ehleringer and Mooney 1983) this pattern also may change with rainfall. In the Negev, the above-ground production increases in wet years, but this is not due to an increase of leaf biomass in the dominant perennial vegetation, but almost totally due to a production increase of annuals and geophytes (Fig. 13).

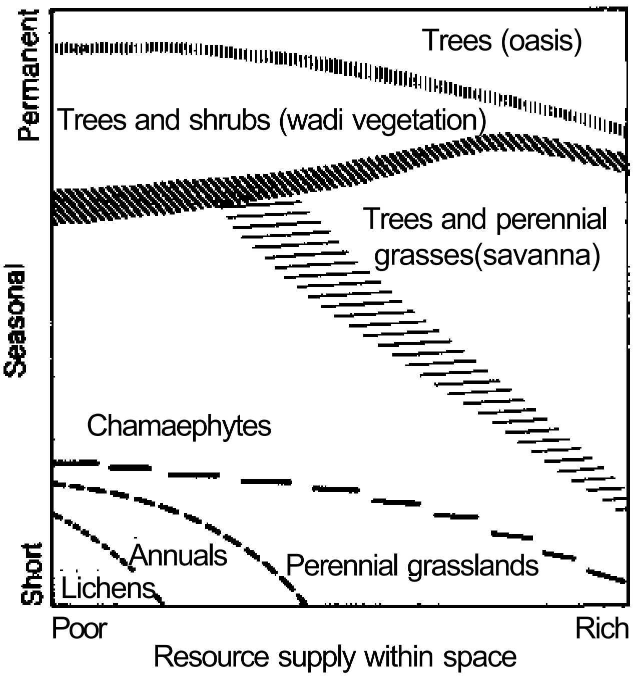


Figure 12. The arrangement of different vegetation types according to resource supply over time and space.

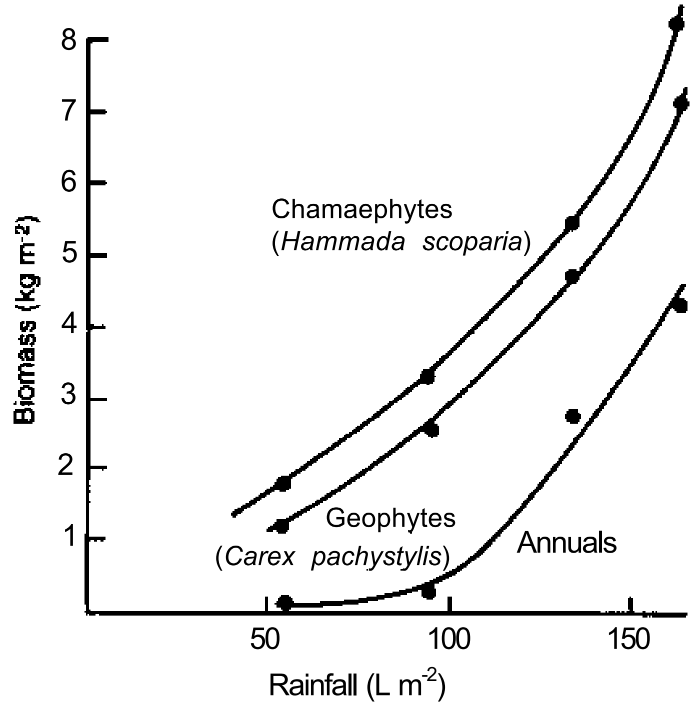


Figure 13. Biomass of chamaephytes, geophytes, and annuals as related to rainfall in the Negev desert (after Evenari et al. 1976).

Summary

Highly specialized plant forms exist that enable plants to grow in most deserts of the world; in fact, there are very few places where plants cannot live. However, this is not achieved through a few traits that permit drought tolerance, nor is it accomplished by a selected smaller number of species. Several thousand plant species have differentiated their organization and performance, and can replace each other gradually in a broad range of environments.

Some Implications for Agriculture

Boyer (1982) pointed out that the genetic potential for productivity in crops is very high, but improvements are necessary to bring actual productivity closer to the existing genetic potential. The major factor depressing yields is unfavorable physico-chemical environments, which depress potential yields by more than 70% compared with only a 2.6% loss attributed to insects. The dominating environmental factor is low water availability (45% of the 70%). The question remains, which characters may be of value to improve yields in environments with an inadequate water supply?

To answer this question, it is necessary to identify major differences between modern crop species for food production and noncultivated arid-zone plants?

- All major crop species are annuals, of which four species contributed about two-thirds of the world food production: wheat, potato, rice, and maize (Brucher 1977). This contrasts with nonagricultural plants, where a large variety of species and life forms occupy specialized niches.
- Crop species are bred to be uniform in major developmental stages; they are highly determinate. Floral initiation, flowering, and fruit set are fixed to certain dates after germination for a technical reason: the possibility of mechanization. In contrast, nonagricultural plants show a high degree of variability in the same environment. It is too risky for all individuals to undergo sensitive stages at one time. Only some flowers develop at any one time and flowering may be delayed or enhanced depending on the climatic conditions.
- Crop species are selected for a few important traits; often it is not clear if there are additional, hidden side effects to any one trait that may be disadvantageous if conditions change. For noncrop species it appears too risky to rely on one or a few characteristics only; generally there are numerous characteristics that perform to the same end, but which have slightly different effects. They behave such that many contingencies, even those that occur episodically, are met. For example, there are no species that have only an increase in specific leaf mass when compared with their counterparts in humid regions, but generally high specific leaf mass is associated with a change in leaf size, leaf surface, leaf orientation, and other properties.
- Crop species compete weakly with other plants as well as with insects, whereas noncrop species are very competitive and may be able to resist insect attacks, because long-term, overall performance is affected by insects. In this respect the nutritional status is important, since insect attack appears to be correlated with the species-specific change of the C/N ratio (Waring 1987).
- Crop species operate at a much higher nutritional status than many noncrop species, which may have a leaf nutrient content too low to sustain grazing (*Acacia aneura* in Australia).
- Crop species are selected in order to maximize the yield of certain plant parts, whereas noncrop species have evolved for the survival of the species or the individual, and not to maximize productivity.

Despite these differences, important crop species have, in principle, most drought-specific characters. Maize has C_4 metabolism, the ability to adjust leaf area and leaf angle surface properties, regulate stomatal and osmotic potentials, and adjust root/shoot ratios. There are no principal differences between crop and noncrop species in any one of these features, but there are gradual differences in scale. Noncrop species always have a wider spectrum of response mechanisms when the environment changes. In addition, nature does not rely on one species, but when conditions change, different groups of species respond or a succession takes place with the invasion of new species, life forms, or physiological adaptations.

A general relationship exists between relative growth rate and CO_2 assimilation (Fig. 1). Crop species operate at the upper end of this relationship. It seems unlikely that it will be possible to maintain growth rates and assimilation but also reduce leaf conductance and whole plant transpiration. Additionally, the plant must pay for its ability to tolerate drought, a factor which inevitably reduces growth. There are very few characters that appear to reduce transpiration more than they reduce photosynthesis, such as changes in radiation absorbtion in high light environments; but generally all changes have a negative effect on the high rates of carbon gain that are possible under nonlimiting conditions. Rapid plant development requires a partitioning towards leaf growth, whereas survival will require root development and leaf area adjustment according to the water available. The amount of water that can be used until a critical root water status is reached is mainly determined by the soil volume occupied by roots. The development of a large root system conflicts with rapid shoot growth, but root water status seems to have a dominant role in regulating assimilation and leaf conductance (Schulze 1986).

It is thus possible to adapt crop plants to arid regions, but the benefit will reduce the potential productivity. Jordan et al. (1983) have identified only three mechanisms of drought resistance that should not reduce yield. These are increases in cuticular waxes, in liquid phase conductance, and in cellular elasticity. Even for these traits, it is not yet proven that there are no detrimental effects on yield.

From the many mechanisms for tolerating drought in nonagricultural species, some seem to be of major importance for arid-land agriculture: for high specific leaf mass, deep-penetrating roots of low structural cost, and leaf movement and proper leaf orientation.

High specific leaf mass will improve the water-use efficiency through more carbon-fixing enzymes per leaf area; but, in order to achieve this, the nutritional status of arid environments needs to be improved. Penning de Vries and Dijteye (1982) found a very low nitrogen content in Sahelian grasses, far below what is generally required for crop species. Increasing specific leaf mass at low nutritional status will not increase productivity, but rather enlarge cell walls. The effect of fertilization in arid climates may be quite long-lasting, because there is little leaching and low rates of mineralization. However, species of high nutritional value will be more attractive to insects.

Screening for better rooting seems to be the most promising field of research. Roots should have the capability of osmoregulation in order to cope with low soil moisture horizons, and carbon and nitrogen investments to roots should be low. Nonagricultural plants appear to have the capability to grow very fine roots that penetrate aggregated soils. They also have the capability to maintain function in those horizons through which they transport water and nutrients, even in extreme drought.

Considering the numerous attempts to screen for drought-tolerant characteristics and to incorporate them into existing germplasm, the overall progress is not substantial. There is less need to improve drought tolerance of cash crops since they are normally grown with irrigation and fertilization. In addition, there are large areas of dryland farming where land is managed using machinery. In these areas, farmers are dependent on crop varieties that uniformly germinate, flower, and mature. This inevitably increases the risk during sensitive stages, such as drought during filament formation. There may be some risk estimate that will encourage the farmer to risk growing a high-yielding crop successfully once in several years, rather than lose the advantage of a good year with a crop variety that is drought-adapted but not high-yielding.

In arid and semi-arid regions a third type of farming needs support, one which operates with a minimum input of energy and technology and which meets three demands: food, fodder, and firewood. Existing crop species meet only one of these. Natural systems indicate it may be more promising not to rely on the paucity of existing crop species, but rather investigate other drought-tolerant species. Amaranthus may be one example, the rich flora of legumes has scarcely been exploited, the native millets need further attention, and woody species should also be considered. To use the range of existing adaptations to certain resource niches seems more promising than to try to rerun evolution and change one species so that it meets all demands.

In addition to the need for food, there is a large demand for fodder and firewood. The desertification of arid regions (e.g., the Sahel) is not a result of climatic changes, but of the pressure on the natural vegetation to meet fodder and firewood requirements. Additionally, there is the danger that the carrying capacity based on the biomass of ungrazed natural ecosystems may be considerably overestimated. Grazing in very arid regions causes an interruption of the carbon cycle and affects nitrogen mineralization. Grazing perennial grasses in semi-arid regions interferes with the storage of nitrogen and thus decreases the nutrient status of this vegetation. There is, however, a large potential to improve, select, and import new species for fodder and firewood. Woody species meet these requirements. It would be desirable to rely on a variety of species which are already adapted to certain resource-poor conditions. In concert with promoting cultivation for food, fodder, and firewood, agricultural practices in arid regions should probably change more towards agroforestry, which depends on mixed stands of different plants.

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Critical Evaluation of the Possibilities for Modifying Crops for High Production per Unit of Precipitation

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Abstract

The potential for putative traits to increase grain yield per unit of precipitation is critically assessed via their contribution to three components of yield (water transpired, water-use efficiency, and harvest index), and to three determinants of survival (drought escape, dehydration avoidance, and dehydration tolerance). Based on this assessment, benefits to yield potential and yield stability, and the scope for genetic improvement, traits are recommended in order of priority for grain sorghum and cowpea grown in intermittent and terminal stress environments in both modern (opportunistic) and subsistence (conservative) agriculture.

Matching the phenology of the crop to the expected water supply is the most important trait in all four situations. In all but terminal stress in subsistence agriculture, the next most important traits are osmotic adjustment and larger root systems to maximize transpired water. Traits that enhance leaf survival are more important in intermittent than in terminal stress, and more important in subsistence than in modern agriculture. Traits for sorghum and cowpea were similar except that developmental plasticity was an additional important trait in cowpea for intermittent stress environments. Other traits specific to one or more of the four situations are also given.

Finally, the need to develop techniques for demonstrating the value of putative traits and to apply them before traits are proposed as selection criteria is stressed.

Résumé

Evaluation critique des possibilités de modification des cultures pour une production plus élevée par unité de précipitation : Le potentiel pour les facteurs probables d'augmenter le rendement en grain par unité de précipitation est évalué selon leur contribution à trois facteurs du rendement (eau transpirée, efficacité de l'utilisation de l'eau et indice de récolte) et à trois facteurs de la survie (évitement de la sécheresse, et de la déshydratation et tolérance de la déshydratation). Des facteurs sont recommandés pour le sorgho grain et le niébé poussés dans l'environnement avec les stress intermittents et terminaux dans l'agriculture moderne (opportunistique) ainsi que dans l'agriculture de subsistance (conservatrice).

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Le facteur le plus important dans toutes les quatre situations est la correspondance de la phénologie de la culture avec l'alimentation en eau espérée. Dans tous les stress sauf le stress terminal en agriculture de subsistance, les autres facteurs importants sont l'ajustement osmotique et les systèmes radiculaires plus grands pour la transpiration maximum de l'eau. Les facteurs de la survie de la feuille sont plus importants pour les stress intermittents et dans l'agriculture de subsistance que dans l'agriculture moderne. Les facteurs pour le sorgho et le niébé sont semblables bien que la plasticité du développement soit un facteur supplémentaire important chez le niébé dans l'environnement avec le stress intermittent. D'autres facteurs spécifiques à une situation ou à plusieurs situations (4) sont également donnés.

Des techniques doivent être mises au point pour la démonstration de la valeur des facteurs probables et appliqués avant que des facteurs en tant que critères de la sélection soient proposés.

Introduction

Breeding improved genotypes for the arid and semiarid tropics by selecting solely for grain yield is difficult because the amount and temporal distribution of available moisture varies from year to year. The genotypic yield variance is low under these conditions because plant characters that influence performance have differing opportunities for expression in different years. Plant breeders (Blum 1983, Rosenow et al. 1983) and crop and plant physiologists (Bidinger et al. 1982, Garrity et al. 1982) believe better-adapted and higher-yielding genotypes could be bred more efficiently and effectively if attributes that confer drought resistance could be identified and used as selection criteria. However, there are few examples where this approach has been used, and even fewer where it was successful (Passioura 1981, Richards 1982).

This arises partly because it is difficult to understand what causes low grain yields, and how putative traits enhance drought resistance and contribute to grain yield in water-limited environments. For example, because final yield is an integral of the growth over the whole season, a trait that influences the ability of the plant to grow in or survive a period of drought stress may be relatively unimportant in the context of the total life of the crop.

Too often, traits are advocated based on theory, laboratory experimentation, or correlations (probably more casual than causal) between the presence of the trait and yield in drought-prone environments, without sufficient attempt to demonstrate that the particular trait does contribute to final yield. Proline accumulation is a good example of such a trait, which has not proved of value as a selection criterion. High proline accumulation was advocated as a drought resistance trait in barley because of its correlation with grain yield in water-limited environments (Stewart and Hanson 1980). However, subsequent research showed that most of the proline was in dead leaves, and hence made no contribution to survival, let alone to grain yield.

In addition, there are few attempts to establish if there is genetic variability for particular traits among genotypes of the crop, and even fewer attempts to study their inheritance. All these steps are necessary to ensure that a yield increase will occur in the target environment when a trait is introduced into otherwise well-adapted genotypes with good yield potential. With few exceptions this has rarely been done, and consequently it is not surprising that the success rate has been low.

Many traits have been proposed to improve the performance of drought-affected crops (see Seetharama et al. 1983 for references prior to 1983; Clarke and Townley-Smith 1984; Turner 1986a, b). We will restrict our coverage to critically assessing their demonstrated contribution to grain yield or the proposed benefits using a framework proposed by Passioura (1977) for analyzing the yield of crops in water-limited environments. Here grain yield is a function of water used (WU), water-use efficiency (WUE), and harvest index (HI); these are the components of grain yield considered in this paper.

In addition, because leaf or plant survival has an important influence on final grain yield in areas with intermittent drought stress, the proposed and demonstrated benefits of traits conferring survival will be assessed using a framework similar to the one proposed by Levitt (1980): Drought Escape and Drought Resistance (Dehydration Avoidance and Dehydration

Tolerance). There seems little point pursuing a trait unless it can be shown that it benefits one of the components of grain yield (Passioura 1986), or contributes to one of the determinants of survival.

With the exception of osmotic adjustment, which is a trait with many ramifications for both yield and survival, only the direct effects of particular traits are discussed. We have made no attempt to assess the antagonistic or synergistic effects arising from the simultaneous presence of two or more traits. While this needs to be done in deciding which traits to choose in a plant improvement program, we felt that it was outside the scope of this paper because these effects depend upon the crop, the moisture environment, and crop management.

In this paper, we describe yield components and the determinants of survival against which the proposed and demonstrated contributions by traits are critically assessed. The "cost" of the traits is also discussed and the impact upon both potential yield (i.e., yield in the absence of water deficits) and yield stability. Then we consider if there is genetic variability for the trait and whether the inheritance has been determined. Finally, we make a judgment whether a trait is desirable for crops growing in two different moisture environments (intermittent and terminal), typical of the semi-arid tropics in both modern (opportunistic) and subsistence (conservative) agriculture.

Intermittent stress is typical of the wet season in the monsoonal semi-arid tropics when stress can occur any time and with varying intensities between emergence and maturity, especially on lighter soils. Terminal stress is typical of the dry season in the semi-arid tropics, where crops are usually grown on heavy soils, primarily on stored moisture, and where the crop grows and matures on a progressively depleted soil moisture profile. We have differentiated between modern and subsistence agriculture mainly by the degree of risk that can be tolerated. While there are economic imperatives for farmers in modern agriculture to ensure some yield, there is a far greater imperative for the subsistence farmer in developing countries to ensure some yield to prevent starvation. Thus the farmer in the developed country can afford to be a greater risk-taker. To summarize and suggest possibilities for modifying crops to improve yield per unit of precipitation, we list in order of priority the traits for a tropical cereal (grain sorghum, *Sorghum bicolor)* and a food legume (cowpea, *Vigna unguiculata)* in the four target situations.

Frameworks for Assessing the Value of Traits

Grain Yield Components

Passioura (1977) proposed that grain yield of crops in water-limited environments could be analyzed in terms of three factors that are largely independent:

Grain Yield = Water Transpired X Efficiency of
Water Use X Harvest Index

Amount of Transpired Water

In the absence of weeds, the potential amount of water transpired by a crop is the sum of the precipitation during the growing season and the available water stored in the soil at sowing. Depending on seasonal and soil conditions, deductions can be made for direct evaporation from the soil surface, available soil water left at maturity, deep drainage, and runoff (Fig. 1). As genetic manipulation cannot influence runoff, it is not considered further here.

After extensive analyses, many workers (e.g., de Wit 1958, Fischer and Turner 1978, Tanner and Sinclair 1983) have shown that biomass accumulation is linearly related to cumulative transpiration. In theory, this means that to obtain maximum productivity, soil evaporation should be minimized and crops should extract as much water as possible. There are high risks associated with this strategy in environments with a variable water supply because the crop may exhaust the available soil water before maturity. A more conservative strategy—where water use is less than the expected supply—would lead to greater yield stability.

Since soil evaporation depends largely on the radiation reaching the soil surface when it is wet, transpiration from a crop that reaches full groundcover quickly constitutes a high proportion of water used in regions where rains are frequent. Where there is little soil evaporation to save, however, such as when growth depends entirely on soil water stored at sowing, or where the expectation of precipitation is low during grain growth, rapid early growth could leave insufficient soil water to complete grain filling. With annual row crops, soil evaporation, which depends strongly on precipitation

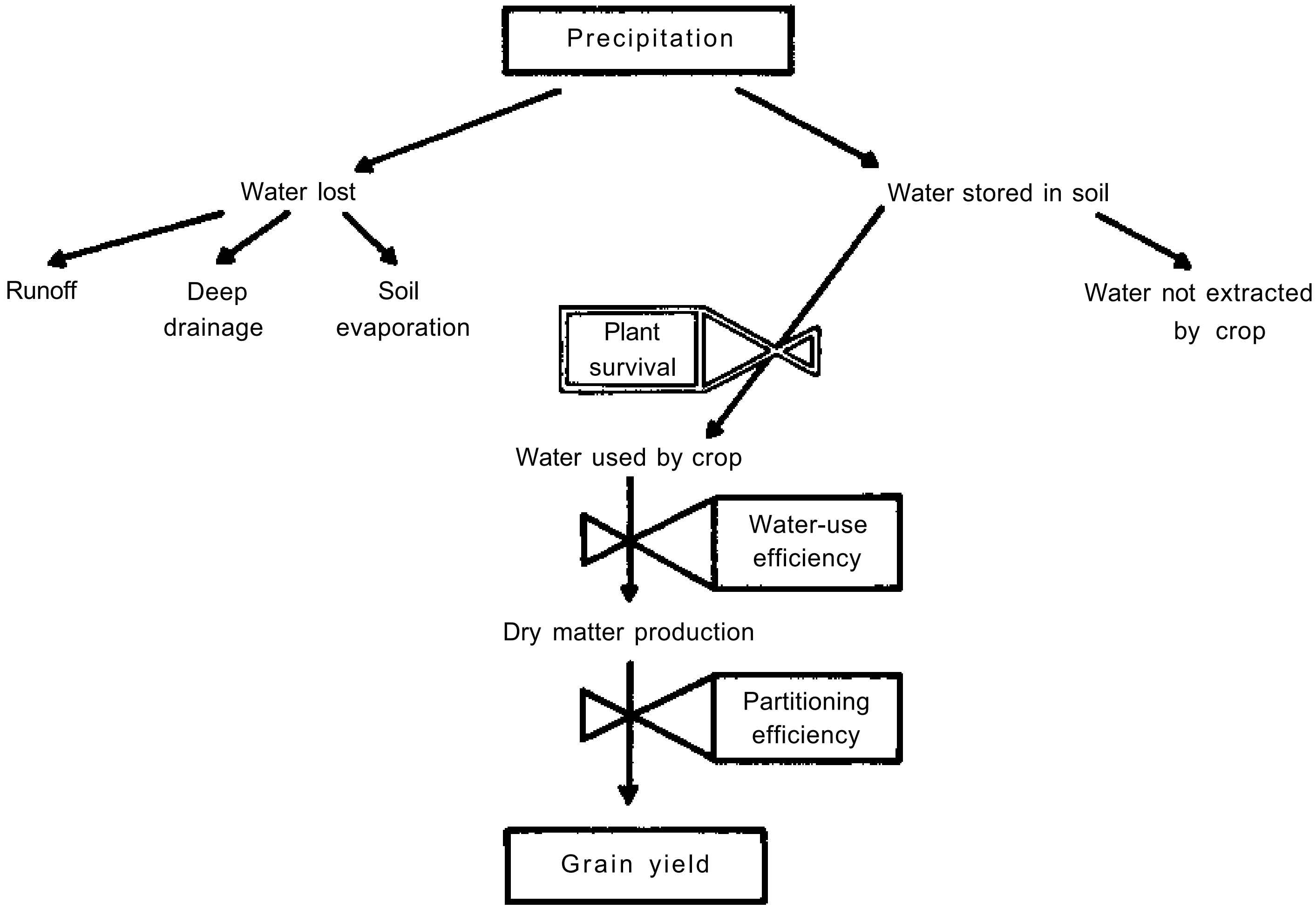

Figure 1. Schematic relationship between precipitation and grain yield.

patterns, is highly variable until leaf area index is about 2.5-3.0. Singh and Russell (1979) estimated that direct evaporation loss from a sorghum crop growing on an Alfisol was 21% of the total seasonal available water during the monsoon season, and 23% during the postrainy season. These values compare favorably with the 30-60% estimated loss for Mediterranean environments (French and Schultz 1984, Cooper et al. 1983), but still represent a considerable loss of potential productivity. It is difficult to assess the scope for further reduction of evaporation losses because of the high prevailing temperatures and consequent rapid canopy development when water is not limited in the semi-arid tropics.

While Passioura's (1977) approach requires measurement of transpired water, most data simply combine transpiration and soil evaporation. There is a need to estimate soil evaporation so that the potential benefits from manipulating this component may be assessed.

Water-use Efficiency

The efficiency of water use is defined here as the ratio of shoot biomass production (root biomass is rarely measured) to the total amount of transpired water. This has been termed the T-efficiency (in contrast to the ET-efficiency, which includes soil evaporation) by Tanner and Sinclair (1983), who have thoroughly discussed the influences on it from leaf to whole-crop level. They concluded that water-use efficiency was inversely related to the saturation deficit of the air. Differences among crop species were related to carboxylation pathway (which is twice as high for C_4 as for C_3 species) and the energy required to produce biomass containing different proportions of protein, lipid, and carbohydrate.

Similarly, the apparent difference in water-use efficiency (ET-efficiency) between cultivars of the same species and among several food legumes reported by Muchow (1985) can be related to differences in soil evaporation and in the chemical composition of the dry matter. In addition, Wilson and Jamieson (1985) found that 11 wheat crops had the same water-use efficiency, once an allowance was made for saturation deficit of the air. The claim by Maruyama et al. (1985) that indica rice showed higher water-use efficiency than japonicas in pots in the field, is flawed by the absence of any measure of evaporation from the free water surface in each treatment. We are therefore not aware of any proven differences in water-use efficiency within a species or within groups of C_3 or C_4 plants in the field (Tanner and Sinclair 1983, Angus et al. 1983).

At the whole-crop level, water-use efficiency appears insensitive to drought, salinity, and soil fertility (de Wit 1958, Hanks 1983, Fischer and Turner 1978). This may seem surprising since in theory mechanisms at the leaf level such as leaf movement, increased leaf reflectance, and temporary stomatal closure during periods of peak evaporative demand should improve water-use efficiency. However, maintenance respiration may rise in response to elevated leaf temperatures caused by stomatal closure, thereby negating the increase. Perhaps more importantly, the amounts of carbon fixed and water lost during drought are probably so small compared with seasonal totals of biomass and transpiration, that the effect on seasonal water-use efficiency is negligible. Water-use efficiency could be raised if respiration rate was decreased and more dry matter was partitioned to the shoots (Passioura 1983, 1986).

Harvest Index

Harvest index is defined here as the ratio of economic (grain) yield to shoot biomass at maturity. Over the past century, raising the harvest index has improved the genetic yield potential of the major field crops (Gifford et al. 1984). Harvest index depends inter alia on the relative proportion of pre- and post-anthesis biomass and on the remobilization of pre-anthesis assimilate to the grain. A severe water deficit at a critical growth stage (e.g., flowering) greatly decreases seed numbers and harvest index. The water supply pattern also has a large effect on harvest index. For example, Bond et al. (1964) observed in sorghum that with adequate water supply until heading, followed by drought, a large biomass but small harvest index was obtained, while the reverse sequence of water supply resulted in nearly as much grain although from much less biomass. Similarly, in crops that rely predominantly on stored water, the harvest index is related to the amount of water available after anthesis (Passioura 1977).

In summary, relatively few principles underlie crop modifications that provide efficient precipitation use in crop production. Crop breeding should aim to maximize transpiration at the expense of soil evaporation and drainage. Basically this involves extending canopy cover as long as practical to minimize evaporation, matching the crop life cycle to the seasonal water availability, and modifying rooting behavior to increase soil water supply or change the timing of withdrawal. Breeding can influence the partitioning of dry matter to economic yield and timing of flowering to maximize harvest index. Since breeding has failed to increase the maximum photosynthetic capacity of crops (Gifford et al. 1984), the prospect for improved efficiency of water use would seem to be low. The best prospects for improving grain yield are to increase the amount of water transpired, and maintain harvest index.

Determinants of Plant Survival

Plants must survive intermittent short-term water deficits if they are to contribute to economic yield. Moreover, in a terminal stress, the longer that leaves and other plant parts can survive during grain filling, the more likely they are to contribute to yield either directly by supplying carbon to the developing grains, or indirectly by preventing lodging (in sorghum). Consequently, we are interested in how plants survive drought and how traits influence yield by enhancing the determinants of survival (Fig. 2).

In order to survive periods of water deficit, higher plants may use one of two main strategies (Begg and Turner 1976; Turner 1979; 1982, 1986a, b). Desert epheremals and short-season annuals in arid environments with low and variable rainfall have such a short life cycle that they germinate after rain, grow rapidly, flower, and set seed before the soil water is exhausted. These plants are said to *escape* drought or water deficits in their tissues (Fig. 2). However, the "cost" of such a strategy is lost opportunity and low yield in better-than-average seasons.

Drought escape

Drought resistance
  Dehydration avoidance
    (Maintenance of turgor and volume)
    - Maintenance of water uptake
    - Reduction of water loss
    - Changes in tissue characteristics

  Dehydration tolerance
    - Protoplasmic tolerance

Figure 2. Ways plants survive drought (adapted from Levitt 1980).

Longer season annuals and perennials survive drought stress by one of two drought *resistance* strategies (Fig. 2). The first group *avoids* water deficits in their tissues, despite the absence of rainfall and hot, dry air, by maintaining cell turgor and cell volume. This can be done by maintaining water uptake, reducing water loss, and by changing tissue characteristics, such as osmotic adjustment or increasing tissue elasticity. The second group resists drought because their tissues are able to *tolerate* dehydration, usually because of superior protoplasmic tolerance of desiccation.

Putative traits that improve yield per unit of precipitation by enhancing plant survival must act through one or more of the determinants of survival given in Figure 2.

Critical Assessment of the Contribution to Yield of Putative Traits

Approaches to Determine the Contribution of Putative Traits

It is difficult to unequivocally prove the value of a trait, so perceptions are often based on opinion rather than fact. Unless a trait has been shown to contribute to one or more components of yield or determinants of survival, there seems to be little value in breeding for it. However, Blum (1983) argues that it is not worth attempting to prove the value of a trait because of the difficulties involved, and that, if a trait appears desirable even on theoretical grounds alone, it should be introduced into a breeding program with simultaneous selection for both the trait and high yield under nonstressed conditions. Only after the trait and yield potential have been combined are genotypes tested in water-limited environments. Only time will tell whether Blum's more pragmatic approach is effective, and the degree to which the value of traits needs to be assessed before they can be advocated as selection criteria to improve production per unit of precipitation.

One useful approach for assessing the value of traits is to compare grain yields of isogenic or near-isogenic lines or populations (genotypes with a similar genetic background), but which contrast in the expression of the trait (Richards 1987). This approach is restricted to traits that are controlled by one or only a few genes, because isogenic lines cannot be developed for quantitatively inherited characters. Another approach is to use simulation modeling (Jordan et al. 1983a, Jones and Zur 1984, Loomis 1985, Muchow and Sinclair 1986, Sinclair et al. 1987); simulations are performed with all other factors held constant, while the trait is absent or present to varying degrees.

The value of maturity, osmotic adjustment, and deep-rootedness in wheat, sorghum, and other crops has been assessed in this way (Jordan et al. 1983a; Jones and Zur 1984). While this approach is rigorous, unequivocal, and intellectually appealing, its application depends upon an adequate simulation model for the particular crop and sufficient understanding of the trait and its mode of operation. Good simulation models are now becoming available (e.g., Sinclair 1986), but we lack sufficient understanding of many of the putative traits. There is a need for more research to understand the mode of action of traits and to apply simulation models to assess their value.

Another, less satisfactory, approach is to compare lines which differ in a trait while having as similar a genetic background as possible (especially phenology), but which are not necessarily isogenic or near-isogenic. This approach depends upon understanding the steps or processes between the presence or the degree of the trait and grain yield, and establishing the *internal consistency* in correlations for each of the intervening steps. For example, in Figure 3, not only must the presence or strength of the trait be correlated with grain yield, but there also needs to be a continuous and consistent series of correlated steps along at least one of the paths in this hypothetical scheme. J. Santamaria, Ludlow and Fukai (per-

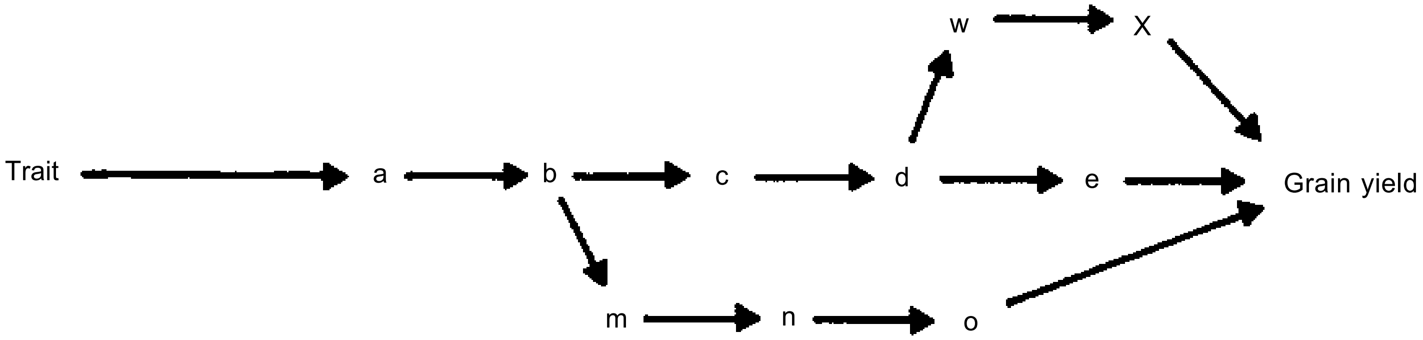

Figure 3. Schematic diagram of internal consistency of the intervening steps in three hypothetical pathways between possession of a trait and grain yield.

sonal communication, University of Queensland, St. Lucia, Queensland) have used this approach to assess the contribution of osmotic adjustment to grain yield in sorghum from three maturity groups. For example, there was internal consistency in the following sequence when Texas 671 and E 57 were subjected to a pre-anthesis stress: high osmotic adjustment (E 57), better turgor maintenance, more root growth and soil water extraction at depth, higher dry matter production, higher grain number, and higher grain yield (see also Wright and Smith 1983).

Further discussion on both the need for and approaches to determine the value of traits can be found in Stewart and Hanson (1980), Hanson and Hitz (1982), Richards (1982, 1987), and Passioura (1986).

Here we use evidence from all these approaches where possible to critically assess the contribution of putative traits to grain yield via the components of yield or the determinants of survival.

Putative Traits

The demonstrated and proposed benefits of each trait for grain yield are assessed in terms of contribution via the production components (Fig. 1) and the determinants of survival (Fig. 2), yield potential, and yield stability, together with the cost of production (Table 1).

Matching Phenology to the Water Supply

Genotypic variation in growth duration is one of the most obvious means of matching seasonal transpiration with the water supply and thus maximizing transpired water. Early flowering tends to give higher yield and greater yield stability than later flowering if there is no rain during the latter half of the growing season. Moreover, if it enables a cultivar to escape drought during the critical reproductive stages, harvest index is improved. Development of short-season varieties provides benefits where rainfall is reasonably predictable, but in unpredictable environments potentially transpirable water may be left in the soil at maturity in better years and yield is sacrificed. This is shown in the study by Jordan et al. (1983a) on sorghum and by Muchow and Sinclair (1986) on soybeans, where simulated yields for an early-maturing genotype were higher only when yields were reduced by at least 40% by low water supply. In contrast, later flowering may be beneficial where drought occurs early in the growing season or where grain maturation after the humid season has ended lowers the incidence of grain molds (Curtis 1968).

Thus, while matching phenology and season is valuable, particularly in terminal stress situations, it is a conservative approach and may contribute to lower yields in unpredicable intermittent stress situations, although yield stability would be improved. There is genetic variability for phenology, and the inheritance is known in some cases (Fery 1980).

Photoperiod Sensitivity

Photoperiod control provides a mechanism whereby the flowering time coincides with the average date of the end of the rainy season despite variation in planting time. This has been shown for sorghum (Bunting and Curtis 1970), bulrush millet (Cocheme and Franquin 1967), and cowpeas (Summerfield et al. 1974) in the Sudanian and Sahelian Zones of Africa. Photoperiod control provides similar benefits to matching phenology to the soil water supply as discussed earlier. However, a major problem with photoperiod-sensitive cultivars is that they are narrowly adapted. Consequently, many cultivars must be available for different latitudes and rainfall regimes or for planting during different seasons. Moreover yields are sometimes low.

Consequently, we believe it is an appropriate trait for both intermittent and terminal stress environments in subsistence agriculture, but of less importance in modern agriculture. There is genetic variability for this trait (Curtis 1968) and its inheritance is known in some cases (Fery 1980).

Developmental Plasticity

Developmental plasticity is the mechanism whereby the duration of the growth period varies depending on the extent of water deficits. Drought-induced early maturity may be advantageous in dry years, but, because it is a faculative response, the plant is still able to respond to longer seasons and produce a larger yield during wetter years. Turk and Hall (1980) observed differences between harvest dates as large as 21 days for cowpeas that were sown at the same time, but which were grown under limited or abundant water supply. In addition. Lawn (1982a) found that the developmental plasticity of cowpea contributed to its superior performance over soybean in water-limited environments.

Indeterminate flowering could also be superior where water supply during flowering is uncertain or total seasonal supply is highly variable, because this permits fruiting to occur in flushes during favorable periods. In determinate crops, there is only a single chance for successful reproduction, unless lateral flower heads and panicles on tillers are produced. Most of the sorghums grown in the semi-arid tropics do not produce tillers (Seetharama et al. 1982), whereas tiller number in millet adjusts to the water supply (Mahalakshmi and Bidinger 1986).

Plasticity in the length of the growing season, indeterminancy, and tillering and branching all have the disadvantage of uneven maturation, which tends to lower harvest index with mechanized harvesting. However, delayed reproduction until water deficits are relieved, combined with hand harvesting during the growing season in subsistence agriculture, could increase the harvest index. Developmental plasticity would seem advantageous for genotypes in both modern and subsistence agriculture where unpredictable intermittent water deficits occur, but would be of little advantage in terminal stress situations where late rains are unlikely to occur.

Remobilization of Preanthesis Assimilate to Grain

The relationship between carbon accumulation and the amount of transpired water (Tanner and Sinclair 1983), and the correlation between harvest index and postanthesis water use (Passioura 1977), suggest that grain yield is strongly dependent on biomass accumulation after anthesis in water-limited environments. However, some workers (Blum et al. 1983b, Turner and Nicolas 1987) have suggested that the contribution to yield of preanthesis reserves could be significant under drought. While it is difficult to accurately assess from biomass data the absolute contribution of reserves, as dry matter losses (particularly leaf and root mass changes) are seldom measured, Bidinger et al. (1977) observed that up to 20% of the grain yield can be due to preanthesis assimilates in drought-stressed wheat. A high transfer of assimilates to the grain would maximize the harvest index and reduce the proportion of dry matter produced early in growth that is left as stover. This trait would have no effect on the amount of transpired water and water-use efficiency, nor on any survival trait.

Remobilization of assimilate in response to water deficits per se should not affect yield potential. However, under adequate water conditions, Daniels et al. (1982) observed that high grain yield in spring barley was associated with large positive increases in stem dry mass after anthesis, indicating that there was more assimilate available than that required to fill the grains. The question remains whether cultivar differences in assimilate partitioning are similar under adequate water and water-limited conditions. Assimilate remobilization would tend to improve yield stability by acting as a buffer against the effects of water deficits on current assimilation. The exception to this would be where remobilization results in increased susceptibility to lodging (e.g., sorghum, Rosenow et al. 1983).

Blum et al. (1983b) have suggested that there may be useful genetic variation in remobilization

Table 1. Critical assessment of putative traits via their contribution to components of yield and determinants of survival. The cost to production and contribution to yield potential and yield stability, and the possibility for genetic manipulation are also given. Traits are recommended or not for intermittent and terminal stress environments for both modern and subsistence agriculture.[1]

Putative trait	Matching phenology to water supply	Photoperiod sensitivity	Developmental plasticity	Remobilisation of preanthesis dry matter	Rooting depth & density	Low hydraulic conductance	Early vigor	Leaf area maintenance
Yield components								
water transpired	+[2]	+[2]	(0)	(0)	+[5],0	-,0	+	(0,+)
water-use efficiency	(0)	(0)	(0)	(0)	(0)	(0)	(0)	(0)
harvest index	+[2]	+[2]	+[3]	+	+,0	+	0,-[11]	(+,-)[12]
Survival determinants								
drought escape	+	+	+	(0)	(0)	(0)	(0)	(0)
drought avoidance	(0)	(0)	(0)	(0)	+	+[9]	(-)	–
drought tolerance	(0)	(0)	(0)	(0)	(0)	(0)	(0)	(0)
Cost of trait?	(no)	(no)	(no)	(no)	no[6]	no	(no)	no
Contribution to yield								
yield potential	(0)	(0)	(0)	(0)	0,-[6]	0[10]	(+)	0,-
yield stability	+	+	+	+[4]	+,0	+	(+,-)[12]	+,-[12]
Genetic variability?	yes	yes	yes	yes	yes	yes	yes	yes
Heritability known?	yes	yes	yes	?	?	yes	?	yes
Recommended for:								
Modern agriculture								
Intermittent stress	yes	no	yes	yes	yes	no	yes	yes
Terminal stress	yes	no	no	yes[4]	yes[7]	yes	yes	no
Subsistence agriculture								
Intermittent stress	yes	yes	yes	yes	yes	yes	yes	yes
Terminal stress	yes	yes	no	yes[4]	no[8]	yes	no[8]	no

Contd...

Table 1. *Contd...*

Putative trait	Osmotic adjustment	Low lethal water status	Reduced stomatal conductance	Leaf movements	Leaf reflect-ance	Low epidermal conductance	Transpiration efficiency	Heat tolerance of seedlings
Yield components								
water transpired	+	(0)	-	(0)[15]	0[15]	(0)[15]	(0)[17]	(+)
water-use efficiency	0	(0)	(0)	(0)[16]	+	(0)	?	(0)
harvest index	+[7]	(0)	(0)	(0)	0	(0)	(0)	(0)
Survival determinants								
drought escape	(0)	(0)	(0)	(0)	(0)	(0)	(0)	(0)
drought avoidance	+,-[12]	(0)	+	+	+	+	(0)[18]	(0)
drought tolerance	+	+	(0)	(0)	(0)	(0)	0	?
Cost of trait?	no	(no)	yes	(no)	(no)[15]	(no)	(no)[18]	(no)
Contribution to yield								
yield potential	0,+[13]	(0)	-	(0)[15]	(0)	(0)	(+)[17]	(0)
yield stability	+[7]	(+)	(+)	(+)	+	(+)	(0)	(+)
Genetic variability?	yes	yes	yes	yes	yes	yes	yes	yes
Heritability known?	yes	?	yes	?	yes	?	yes	?
Recommended for:								
Modern agriculture								
Intermittent stress	yes[7]	yes	no	yes	yes[20]	yes	yes	yes[19]
Terminal stress	yes[7]	no[14]	no	no	yes[20]	no	yes	yes[19]
Subsistence agriculture								
Intermittent stress	yes[7]	yes	yes	yes	yes[20]	yes	yes	yes[19]
Terminal stress	no[8]	no[14]	no	no	yes[20]	no	yes	yes[19]

1. Contributions are assessed as positive (+), negative (–), or none (0). Parentheses are used when the contributions are expected from theory or first principles but they have not been shown. When information is unavailable or unknown a question mark is used. Cost is defined in terms of carbon or energy.
2. Could be negative in other than average seasons.
3. Only if hand harvested in developing countries.
4. As long as crop does not lodge.
5. Only if existing root length density or root depth is insufficient to extract all available soil water and if deep water is recharged each year.

Contd...

Table 1. *Contd...*

6. If a unit of carbon invested in roots results in more water uptake than the reverse of water-use efficiency the investment will not have a net cost compared with investing that unit of carbon in the shoot.
7. As long as available soil water is not exhausted before maturity.
8. Risk of exhausting soil water before maturity is too high.
9. Unless low conductance causes relative water content to fall to lethal levels under hot, dry conditions.
10. Only if seminal roots have low conductance.
11. If early vigor causes exhaustion of soil water before maturity.
12. Positive if soil water is not exhausted, negative if it is.
13. Morgan et al. (1986) find yield potential is enhanced in wheat.
14. Unless the relative water content for leaf expansion and photosynthesis also decrease, this trait only prolongs time until lethal values are reached, and consequently it makes no contribution to production in a terminal stress.
15. Generally negative but probably insignificant for crop water use or performance.
16. Generally positive but probably insignificant for crop water use efficiency.
17. Could be negative if higher transpiration efficiency is due to transpiration being reduced more than photosynthesis, but production would suffer, and vice versa.
18. Could be positive if higher transpiration efficiency is due to transpiration being reduced more than photosynthesis, but production would suffer, and vice versa.
19. In environments where soil surface temperatures cause seedling mortality.
20. The scope for improvement may be small if current varieties are glaucous or bloomed.

that offers scope for improvement in wheat. Constable and Heam (1978) found large differences between two soybean cultivars in the effect of water deficits on the contribution of stem storage to yield. Wright et al. (1983a) found no difference between two sorghum cultivars in remobilization, but Santamaria (1986) found considerable remobilization of preanthesis dry matter when accessions of grain sorghum were subjected to drought stress during grain-filling. Accessions with high osmotic adjustment retranslocated more preanthesis assimilate to grain than those with low osmotic adjustment. While the evidence is inconclusive, we cautiously recommend this trait in the four stress situations. However, further work is required to assess the consequences of this trait on yield potential and lodging (in some crops), and upon root growth and nitrogen fixation in food legumes, particularly in intermittent stress situations.

Rooting Depth and Density

Differences in rooting patterns change the amount and timing of water availability to the crop. Greater depth and extent of soil water extraction could increase the amount of water transpired, and if this avoids water deficits at critical growth stages it could increase the harvest index. The traditional view is that a large vigorous root system, through avoidance of plant water deficits, is a major feature of drought resistance. The implicit assumptions are that water is available deep in the soil profile and is replenished each year, and that the existing root length density is insufficient to extract all the water (Clarke and Townley-Smith 1984).

Where water remains in the soil at maturity, usually below the root zone, greater rooting depth should lead to improved grain yield stability. However, where the soil water is not replenished at depth between crops, greater rooting depth would be of little advantage, and could even be disadvantageous in limiting the frequency with which the crop may be grown (Bremner et al. 1986). Jordan et al. (1983a) used the crop simulation model SORGF to assess the consequences of deep rooting in sorghum over a 30-year period. The simulations showed that deeper roots increased yield by 20% in about one-third of the years, because in wet years soil water was not limiting, and in the very dry years there was little available water deep in the soil profile. Similarly, an increase in the simulated root zone depth has been shown to increase leaf area growth, photosynthesis and transpiration (Jones and Zur 1984), and yield (Muchow and Sinclair 1986) of crops under drought. The assimilate cost of deeper rooting was not incorporated into these models, so the yield advantage may be overestimated.

Passioura (1982. 1983) has questioned the value of deep roots because of the carbon costs; the water transpired to produce the carbon may offset the extra water gained. Furthermore, the costs of root growth and maintenance represent clear diversions of assimilate which might have been used for shoot growth and thus may decrease yield potential. Passioura (1983) concluded that selection for a smaller root system, particularly in the topsoil where rooting densities appear much larger than needed to extract all the water at a reasonable rate, might actually increase the above-ground yield. Such a proposal has merit in soils where crops extract all the available water from the soil each year. Moreover, it is supported by the observation of Blum et al. (1983a) that the only wheat variety in their study that did not show promoted root growth under mild stress using PEG solutions, had the largest top growth.

It is difficult to resolve the question of the carbon cost of a deeper root system, and the consequences on yield potential. Sorghum roots weigh about 50 µg cm^{-1} (Merrill and Rawlins 1979), so an additional 50 cm of roots at a density of 0.5 cm cm^{3} would require only 125 kg ha^{-1} more dry matter, plus some additional respiration cost. This cost seems small when above-ground biomass at maturity can exceed 10 000 kg ha^{-1} (Wright et al. 1983a). Alternatively, a deeper root system could have little additional assimilate cost if the root length density was distributed more uniformly down the soil profile (i.e., fewer surface roots, but more of them deeper in the soil). Furthermore, several workers have shown that a greater rooting depth is associated with improved performance under water-limiting field conditions (e.g., sorghum, Wright and Smith 1983; wheat, Hurd 1974).

Considerable genetic variation in rooting characteristics has been reported in sorghum (Jordan and Miller 1980), in soybeans (Raper and Barber 1970), and in wheat (Hurd 1974, Blum et al. 1983a), but inheritance of rooting traits does not appear to have been studied.

Measurements of rooting depth and root length density do not necessarily give an estimate of the ability of a genotype to extract soil water. A root length density greater than 0.5 cm root cm^{-3} soil can be adequate for complete extraction of available water, although many crops carry rooting densities to much greater values of 2 to 3, particularly in the surface layers (Passioura 1982). The fact that root length densities can vary from 0.3 to 6.0 cm root cm^{-3} soil in a range of temperate cereals and legumes, with no effect on soil water extraction (R.A. Richards, personal communication, CSIRO, Canberra) suggests that root length densities may be in excess of requirements in some crops and that little will be gained by increasing root length density. However, water is frequently left behind in the subsoil by a water-limited crop despite the fact that the crop's roots can be present at that depth (e.g., sorghum, Jordan and Miller 1980). At depth, root length density may be insufficient to extract all the water, although calculations by Passioura (1983) suggest that the frequencies of sorghum roots in the deeper profile should be sufficient to extract all the water available, unless only a portion of the roots is extracting the water, or the roots are constrained to certain limited regions of the soil such as fracture planes and the channels of former roots or earthworms. Alternatively, the hydraulic resistance to water flow in the plant may limit water uptake by the crop, which could affect the extent of extraction.

Given the potential to increase the amount of water transpired, greater rooting depth and density is recommended in opportunistic situations, despite the risk of running out of water and the possible carbon cost on above-ground growth. In conservative situations of intermittent stress, greater root activity should enhance stability by reducing the incidence and slowing the development of water deficits. However, the risks of running out of water before maturity would make greater rooting depth and density undesirable in a conservative terminal stress situation.

Root Hydraulic Resistance

Increased root hydraulic resistance has been proposed by Passioura (1972, 1977) for crops growing predominantly on stored soil water. By restricting early water use, more water is available for grain-filling, resulting in higher harvest index. This trait should not affect the amount of water transpired in terminal stress situations where the soil water store is exhausted at maturity, but in intermittent stress situations it may reduce uptake and lower the amount of water transpired. In terms of survival determinants, high root hydraulic resistance should enhance dehydration avoidance, providing the higher resistance does not result in the relative water content reaching the critical value at which leaves die.

In wheat, increased root hydraulic resistance can be achieved by decreasing the diameter of the main xylem vessel in the seminal roots (Richards and Passioura 1981a, 1981b). Subsequent work (Richards 1987) has shown that, in dry environments, wheat lines with small xylem vessels yielded more than lines with larger vessels. In good seasons, there was no yield penalty in having small xylem vessels as the nodal root system overrode the effect of small xylem vessels in the seminal roots when the topsoil was wet. Thus in wheat this trait would increase yield stability, but have no effect on yield potential in terminal stress situations. In sorghum roots, hydraulic resistance is likely to depend on the number of fully functional nodal roots as the seminal root system ceases axial growth about 2 weeks after emergence (Blum et al. 1977, Bremner et al. 1986). The number of nodal roots penetrating deep into the profile depends on the surface soil water content during the early stages of nodal root growth (Blum and Ritchie 1984).

This environmental effect combined with the relatively large size of these xylem vessels (R.A. Richards, personal communication, CSIRO, Canberra) suggests that there may be little room to manipulate root hydraulic resistance in sorghum. Similarly in dicots, root hydraulic resistance tends to be low since their capacity for secondary thickening may lead to large xylem cross sections (e.g., Meyer and Ritchie 1980). There is genetic variation for this trait in wheat and it is heritable (Richards 1987).

This trait is recommended in some cereals for both opportunistic and conservative terminal stress situations so that sufficient water remains for grain-filling, and hence enhanced grain yields. In intermittent stress situations, reduced water uptake via higher resistance would seem disadvantageous, although in conservative situations this trait would slow the development of water deficits and enhance yield stability.

Early Vigor

Genotypes with early vigor and good seedling establishment ability would tend to enhance transpiration at the expense of direct soil evaporation, particularly where the surface soil is wet by frequent rains. For 22 wheat lines growing on light-textured soils in a mediterranean-type environment, Turner and Nicolas (1987) found that vigorous early growth resulted in high dry matter yields by anthesis and improved grain yields with no decrease in harvest index. They suggested that on deep sandy soils, vigorous early growth enabled greater root development so that yields were not restricted by water limitations at the end of the season.

If this increased water use occurred in the cool, early part of the growing season, then early vigor may increase water-use efficiency. However, in some situations, early vigor may result in rapid early water use, followed by severe water deficits at critical growth stages and consequent reductions in harvest index. This would be the situation for crops growing on a limited store of soil water using the arguments of Passioura (1977). In terms of survival determinants, this trait would have a negative influence on dehydration avoidance due to increases in water use, commensurate with greater leaf area.

Early vigor would be expected to have a positive influence on yield potential due to increased radiation interception in cereals, but not necessarily in food legumes. This is particularly relevant for cereals in the tropics where high temperatures are associated with rapid development and the yield potential of the crop is largely set in the first 2-3 weeks after sowing (Rawson 1986). Early vigor may have a positive or negative effect on yield stability, depending on the pattern of water availability. No cost to production would be associated with this trait per se. Early vigor is recommended for an ideotype in all situations except in a conservative terminal stress situation where conservation of early water use would enhance yield stability.

Leaf Area Maintenance

Reduced leaf growth and accelerated leaf senescence are common responses to water deficits. While these responses tend to enhance survival by conserving water, they can be detrimental to productivity upon the relief of water deficits. This is because radiation interception is lower and transpiration is reduced as a proportion of evapotranspiration since radiation interception and transpiration increase up to a leaf area index of about three. Consequently maintaining leaf area is seen as a trait contributing to yield but at the same time is a potential threat to survival. Maintenance of leaf area is determined by lethal leaf water status (discussed later), the nitrogen economy of the plant, and sink demand by the developing grains.

Leaf area maintenance under water deficits per se should have no effect on yield potential. However, expression of this trait in terminal stress situations may be associated with low yield potential, because low-yielding sorghum genotypes with a small grain sink size relative to the vegetative growth remained green ("stay-green" or "nonsenescing") during post-flowering drought compared genotypes with a high grain yield (Rosenow et al. 1983). The nonsenescing cultivars also tend to be resistant to charcoal rot and stalk lodging.

In terms of yield stability, leaf area maintenance would improve yield stability in intermittent stress situations due to better radiation interception when water is available, whereas the opposite would be the case in terminal stress situations because leaf area maintenance would increase the rate of water use and increase the probability of the crop running out of water before maturity. Consequently, leaf area maintenance is recommended for an ideotype in intermittent stress situations, but not in terminal stress situations.

There is genetic variation for leaf area maintenance and it is under genetic control in grain sorghum (Rosenow et al. 1983, Duncan et al. 1981).

Osmotic Adjustment

Osmotic adjustment results from the accumulation of solutes within cells, which lowers the osmotic potential and helps maintain turgor of both shoots and roots. This allows turgor-driven processes such as stomatal opening and expansion growth to continue, although at reduced rates, to progressively lower water potentials (Hellebust 1976; Turner and Begg 1977; Zimmerman 1978; Turner 1979, 1982, 1986a, b; Turner and Jones 1980; Ludlow 1980a, 1987; Blum et al. 1983a; Wyn Jones and Gorham 1983; Morgan 1984). The ways in which osmotic adjustment in roots, shoots, and panicles influences plant processes and grain yield in sorghum are summarized in Figure 4.

Osmotic adjustment has no effect on water-use efficiency (Morgan et al. 1986, McCree and Richardson 1987, Table 2, D.J. Flower, personal communication, University of Queensland, St. Lucia, Queensland) but it contributes to grain yield in water-limited conditions by increasing the amount of water transpired and by either increasing or maintaining harvest index. Increases in transpired water result from stomatal adjustment, maintenance of leaf area, and increased soil water uptake. Osmotic adjustment reduces the rate of leaf senescence (sometimes called stay-green character in grain sorghum) (Wright et al. 1983b, Morgan 1984, Hsiao et al. 1984, Blum and Sullivan 1986), because it increases both avoidance and tolerance of dehydration (discussed later). Furthermore, osmotic adjustment appears to be the main mechanism of stomatal adjustment, a process that allows stomata to remain partially open at progressively lower leaf water potentials as drought stress increases (Ludlow 1980a, 1987; Ludlow et al. 1985). This does not, however, result in more carbon fixed if accompanied by a rapid decline in leaf water status (McCree and Richardson 1987).

Genotypes of wheat and sorghum with high osmotic adjustment produce more root biomass, greater root length density, and extract more soil water (particularly from lower parts of the soil profile), than genotypes with low osmotic adjustment (Wright et al. 1983a, Morgan and Condon 1986, Santamaria 1986). For example, Morgan (1984) reports increases in transpiration of 26 mm for wheat growing on a clay-loam soil, and 24 and 64 mm for two sorghum crops growing on a heavy clay soil, associated with the higher osmotic adjustment. The enhanced root growth in genotypes results from maintenance of turgor by osmotic adjustment in the *root* (Turner 1986a), and from additional carbon fixed associated with osmotic adjustment in the shoots, which allows photosynthesis to continue, although at a reduced rate as leaf water potential falls (Ludlow 1987).

Osmotic adjustment has been shown either to maintain harvest index in wheat (McGowan et al. 1984, Morgan and Condon 1986) and sorghum (Santamaria 1986), and probably also in barley (Legg et al. 1979) when subjected to mild water deficits, compared with unstressed plants, or to increase it in wheat subjected to high water deficits (Morgan and Condon 1986). Maintenance of harvest index by osmotic adjustment involves a number of specific effects (Fig. 4):

- improved tiller and floret survival, and improved seed set in wheat (Morgan 1984);
- improved head exsertion and reduced spikelet abortion in sorghum (Wright et al. 1983b, Santamaria 1986);
- increased assimilate supply during grain-filling by

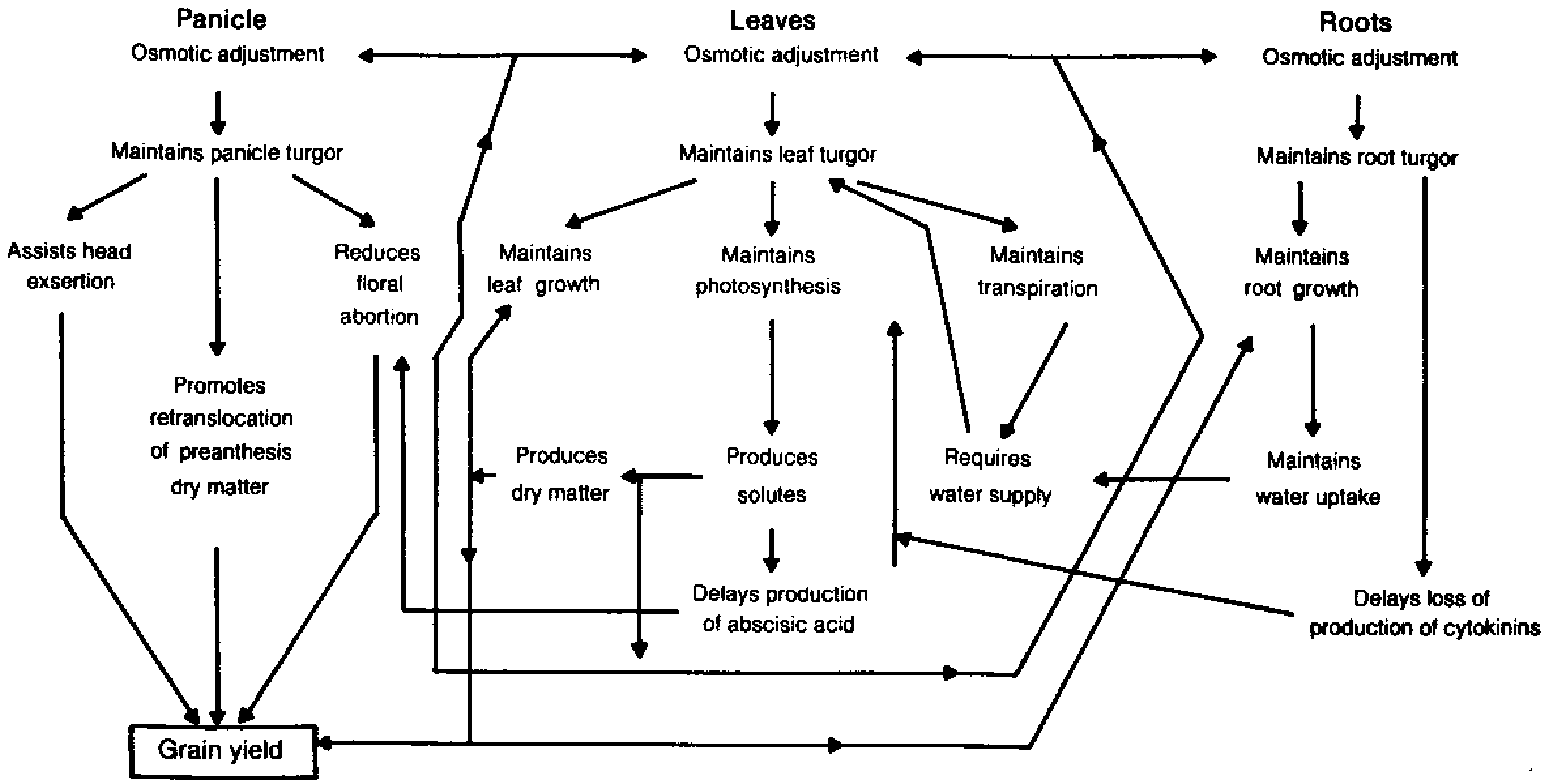

Figure 4. Schematic diagram of the possible consequences of osmotic adjustment of panicle, leaves, and roots in grain sorghum (adapted from Turner 1986a).

Table 2. Water-use efficiency, based on evapotranspiration, of grain sorghum from three maturity groups with either high or low capacity for osmotic adjustment, measured over two periods. The entries were sown at different times in an attempt to minimize the effects of maturity differences, and the intervals represent days after the sowing of the late entries, which were sown first. Line SC 219-9-19-1 is a selection from material originating from the Sorghum Conversion Program of the Texas A&M University (from Santamaria 1986).

Maturity group and entry	Capacity for osmotic adjustment	Water-use efficiency (g DW mm^{-1} H_2O)	
		37-71 d	71-112 d
Early			
Goldrush	high	3.4	4.8
TX 610	low	4.1	4.2
Intermediate			
E 57	high	4.1	4.2
TX 671	low	4.9	4.6
Late			
DK 470	high	6.2	3.1
SC 219-9-19-1	low	4.6	3.3
Mean	high	4.5±1.0	4.0±0.5
	low	4.5±0.3	4.1+0.4

reducing leaf senescence (Wright et al. 1983b, Morgan 1984, Santamaria et al. 1986) and by maintaining photosynthetic activity of remaining leaves (Hsiao et al. 1984); and

- by increasing the use preanthesis assimilates in grain-filling (Santamaria 1986, Wright et al. 1983a).

Some of the consequences of osmotic adjustment promote dehydration avoidance and some reduce it (Fig. 4). The continued water loss caused by maintenance of green leaves, delay of leaf rolling (Hsiao et al. 1984), and stomatal adjustment reduces dehydration avoidance. An inevitable consequence is that leaf water potential falls progressively (Morgan 1984), which can cause leaf and plant death if critical leaf water potentials or relative water contents are reached, or if the soil water is exhausted, irrespective of the dehydration tolerance of the species (Ludlow et al. 1983; M.M. Ludlow, unpublished data). Thus species like soybean and some forage legumes, which have high osmotic adjustment and are more dehydration tolerant than cowpea and siratro, die first (Ludlow et al. 1983, Sinclair and Ludlow 1986).

However, when osmotic adjustment promotes root growth and exploration, and consequently soil water extraction, dehydration avoidance is enhanced. The balance between these two opposing effects will determine whether osmotic adjustment improves or reduces dehydration avoidance. This will vary with species, soil type, the environment, and the time when drought stress occurs during the development of the crop.

Richardson and McCree (1985) and McCree (1986) have shown that the metabolic cost of storing photosynthate and using it for osmotic adjustment in grain sorghum was *less* than the cost of converting it into new biomass. This suggests that there is no particular "cost" of osmotic adjustment above that of normal growth. This is supported by the fact that rather than reducing yield potential under non-stressed conditions, high osmotic adjustment increases wheat yields by about 10% (Morgan et al. 1986). However, the greatest contribution of osmotic adjustment is to yield stability under water-limited conditions. Averaged over the three maturity groups, entries of grain sorghum with high osmotic adjustment had a 15% higher yield when drought stress occurred during the preanthesis period, and yield was 24% higher when the stress occurred during the postanthesis period, compared with low osmotic adjustment entries (Santamaria 1986). Similarly, in wheat the advantage of high compared with low osmotic adjustment increased towards 50% as water supply became more limiting in dryland crops (Morgan 1983, Morgan et al. 1986).

Genetic variability in osmotic adjustment has been found in wheat (Morgan 1977, 1983, 1984; Blum et al. 1983a; Morgan and Condon 1986; Morgan et al. 1986), grain sorghum (Ackerson et al. 1980, Wright et al. 1983b, Santamaria et al. 1986, Blum and Sullivan 1986), millet (Henson 1982), cotton (Karami et al. 1980), rice (Turner et al. 1986b), soybeans (M.M. Ludlow, unpublished data), and pigeonpea (Rower and Ludlow 1987). Although there are, at present, insufficient data to enable conclusions about the heritability of osmotic adjustment to be drawn, data for wheat are consistent with the proposition that only one or a few genes are involved, and that the trait is simply inherited (Morgan 1983, Morgan et al. 1986).

If the aspects of osmotic adjustment that reduce dehydration avoidance and promote transpiration do not exhaust the soil water before maturity, we see osmotic adjustment as a highly desirable characteristic for both intermittent stress environments and in the terminal stress environments in modern agriculture where a greater risk of low yield can be tolerated. However, it is questionable whether it is a desirable trait for terminal stresses in subsistence agriculture if it is associated with an increased risk of exhausting soil water. We are more confident of recommending this trait because, unlike most other traits, the association with yield components, determinants of survival, and yield have been *demonstrated* rather than merely postulated. Apart from the risk of exhausting the soil water supply and the need to develop rapid screening procedures, we see few problems in such a trait being used in dryland crop breeding programs with good prospects of increasing potential yield and stabilizing yields during drought.

Low Lethal Water Status

The degree to which plant parts withstand desiccation is expressed as the relative water content or water potential at which leaves die; these have been called critical or lethal values. Low lethal water status refers to more negative leaf water potentials and low relative water content. The criterion for deciding when to measure critical values varies: when 50% of leaves are dead, when 50% of the surface area of a leaf is dead, or when there is only one leaf remaining on a plant subjected to a slow soil drying cycle (Ludlow et al. 1983, Flower and Ludlow 1986).

Recent work has shown that leaf survival is determined by relative water content rather than by leaf water potential (Flower and Ludlow 1986). While the leaf water potential at which leaves of 33 C_4 forage grasses died varied between -9 and <-13 MPa, the relative water content was 25 ±1 (SE)% (Z. Baruch, M.M. Ludlow and J.R. Wilson, unpublished data, CSIRO, Brisbane, Australia). It is interesting to note that both cowpea and sorghum are very sensitive to dehydration. Consequently their ability to survive water deficit periods in the semi-arid tropics must be due to avoidance rather than tolerance of water deficits (Santamaria et al. 1986; M.M. Ludlow, R.G. Kerslake and D.J. Flower, unpublished data).

Because low lethal water status influences survival, it has no *direct* effect on yield components. However, it contributes to dehydration tolerance, leaf survival of intermittent drought stress (Bower and Ludlow 1986, Sinclair and Ludlow 1986), and hence to yield stability. Turner (1979) questioned whether considerable research effort to increase tolerance was warranted, because he argued dehydration tolerance and yield potential were "mutually exclusive". He based this conclusion on the fact that xerophytic plants, which are reputed to have high dehydration tolerance, grow slowly and have low yields (Begg and Turner 1976, Fischer and Turner 1978). While such a relationship may exist, there is no a priori reason why it should be causal. In fact, within agricultural plants, which is a more relevant comparison than between agricultural plants and desert species, there is no clear relation between dehydration tolerance and yield.

The lethal leaf water potential of C_4 grasses varies from -3 MPa in sorghum and millet (Sullivan and Eastin 1974, Santamaria et al. 1986) to -13 MPa in a range of forage grasses (Ludlow 1980b; Wilson et al. 1980; Z. Baruch, M.M. Ludlow, J.R. Wilson, unpublished data, CSIRO, Brisbane), but these C_4 grasses have a similar yield potential for dry matter production. Similarly, while the lethal leaf water potential of food legumes varies from -1.8 MPa in cowpea (Sinclair and Ludlow 1986) to -6.3 MPa in pigeonpea (Flower and Ludlow 1986), and -10 MPa in groundnut (M.M. Ludlow and R.G. Kerslake, unpublished data), they do not differ appreciably in potential for dry matter production (Lawn 1982b, Angus et al. 1983, Muchow 1985).

There is genetic variability in lethal leaf water potential in grain sorghum (Sullivan and Eastin 1974, Blum 1979, Sullivan and Ross 1979, Jordan and Sullivan 1982, Santamaria et al. 1986), wheat (Blum and Ebercon 1981), pigeonpea (Flower and Ludlow 1987), and cotton (Quisenberry et al. 1981). Although heritability of this trait has not been determined, the "relatively consistent performance of some parents (that differed in lethal leaf water potential) in hybrid combination suggests that selection for high or low desiccation tolerance is an attainable goal in a breeding program" (Jordan and Sullivan 1982). However, we are not aware of any program where low lethal water status is used as a selection trait, despite the fact that both cowpea and grain sorghum have poor desiccation tolerance and there is no proven cost of this trait for potential yield.

High desiccation tolerance is suited to intermittent stress environments, where it assists survival of leaves and plants until the next rainfall. However, we do not believe it serves a useful purpose in terminal stress environments, because it only lengthens the time between when growth and photosynthesis cease, and when leaves die, which makes no contribution to dry matter production. For example, leaf turgor is lost at -2.5 MPa in pigeonpea, and both leaf expansion and net photosynthesis cease at -2 and -3.5 MPa, respectively, whereas leaves do not die until -6.5 MPa (Flower and Ludlow 1986, Flower 1986). If, however, it allows time for preanthesis dry matter to be retranslocated, it would contribute to harvest index and hence grain yield in a terminal stress environment

Reduced Stomatal Conductance

Various stomatal characteristics, such as low conductance, high sensitivity to leaf water status and saturation deficit, and abscisic acid accumulation have been suggested as desirable traits to improve the drought resistance of crops (Jones 1979,1980,1987; Turner 1979, 1982, 1986a, b; Clarke and Townley-Smith 1984). All these characteristics reduce water loss and lower the probability of dehydration. Moreover they have the attractive feature that they are reversible when the stress has abated. However, because stomata influence the influx of CO_2 into leaves as well as the loss of water vapor, reduction in stomatal conductance to conserve water inevitably means lowered photosynthetic rate. Consequently, the value of reduced stomatal conductance depends upon this trade-off between loss of production, and the need to prevent dehydration.

Inherently low stomatal conductance and a reduction of stomatal conductance in response to low leaf water potentials, high saturation deficit, and high ABA production reduce crop water loss (Jarvis and McNaughton 1986). For example, the crop water use of cowpea (203 mm), mung bean (247 mm), and soybean (328 mm) crops from sowing until day 64 is consistent with the differential sensitivity of their stomates to water deficits (Lawn 1982a; R.C. Muchow and M.M. Ludlow, unpublished data). However, the reduction is not as much as might be expected because most short, uniform agricultural crops are not as well coupled with the atmospheric environment as tall, rough vegetation, and the reduced water loss in crops is proportionately much less than the reduction of stomatal conductance (Jarvis and McNaughton 1986).

In leaves with osmotic adjustment, stomata remain partially open to progressively lower water potentials. This stomatal adjustment, therefore, has the opposite effect to the traits just discussed, and it promotes continued water loss and a progressive decline in leaf water potential. It also promotes growth of grain sorghum during drought stress (Blum and Sullivan 1986).

The main response to reduced stomatal conductance, by whatever means, is dehydration avoidance (Blum et al. 1981, Ludlow et al. 1983). For example, cowpea with stomates more sensitive to water deficits avoids dehydration better than mung bean, which in turn avoids it better than soybean and pigeonpea (Lawn 1982a; M.M. Ludlow, R.G. Kerslake and D.J. Rower, unpublished). Lowered conductance should improve the yield stability because it reduces water loss and lowers the probability of exhausting the soil water before maturity. However, it will reduce yield potential, with the highest reduction in plants with inherently low conductance rather than in ones where stomates close in response to lowered leaf water potential, high saturation deficit, or ABA accumulation, which are reversible. Consequently, because of the trade-off between CO_2 and H_2O exchange, a reduced stomatal conductance will have a production cost

This trade-off could be acceptable for subsistence agriculture in intermittent stress environments, if it prevents crops from dying before the next rain, and in terminal stress environments it prevents exhaustion of soil water before maturity. We believe, however, that the cost of these stomatal traits is high for comparable environments in modern agriculture.

Genetic variability has been demonstrated in various stomatal characteristics (Jones 1980, 1987; Clarke and Townley-Smith 1984), and while there are no definitive studies, it appears that they are highly heritable (Roark and Quisenberry 1977, Jones 1987). However, obtaining consistent measurements of stomatal characteristics in the field is very difficult. Jones (1979. 1987) has discussed the attendant problems and limitations of attempting to select for stomatal traits. One such problem is the lack of stomatal response to water deficit after flowering in grain sorghum (Garrity et al. 1984). Jones concludes that it would be better to select for characteristics closer to yield or survival than to select for stomatal traits. Recent evidence that suggests signals from roots in response to soil dehydration can override the control of stomatal conductance by leaf water status (Turner 1986a) is an added complication. Despite the potential benefits of stomatal traits and the existence of genetic variability, it is premature to consider them as selection criteria.

Leaf Movements

Leaf movements include rolling, folding, and wilting (floppiness), as well as diaheliotropic and paraheliotropic movements in response to water deficits (Rawson 1979, Begg 1980, Wilson et al. 1980, Ludlow and Bjorkman 1985). Like glacousness and hairiness, leaf movements help shed radiation absorbed on leaves and reduce leaf temperatures and water loss (O'Toole et al. 1979). Consequently they increase avoidance of dehydration (Begg 1980, Fisher and Ludlow 1983, Ehleringer and Forseth 1980, Forseth and Ehleringer 1980), and should contribute to yield stability in environments with intermittent drought stress by enhancing the chance of plant survival until the next rain. However, because these leaf movements do not occur in the absence of drought stress and because they are reversible and light interception returns to normal after the stress is relieved (Turner et al. 1986a), there would be no yield penalty. Because leaf movements are essentially survival traits, they have little influence on the components of yield. In rice, cultivars with leaves that rolled more did maintain higher leaf water potentials (increased dehydration avoidance) but this had no detectable effect on water transpired or dry matter produced during a 10-day stress (Turner et al. 1986b).

Leaf movement would seem a desirable trait in intermittent stress environments because it enhances survival until the next rainfall. However, we see no benefit from it in terminal stress environments where it will only reduce the water loss rate and delay the time until the water runs out, unless it allows more time to retranslocate preanthesis dry matter. Moreover, if leaf movements occur only after stomates are closed, they will do little for production. If, however, leaf movements prevent leaf death by high temperatures or if they allow the crop to survive into the cooler part of the season when water-use efficiency is enhanced, the trait would be valuable in terminal stress environments as well.

There is genetic variability in the capacity for leafrolling in grain sorghum (Begg 1980, Santamaria et al. 1986) and rice (Chang et al. 1974, Turner et al. 1986a). Although there are obvious differences among tropical food legumes in their ability for paraheliotropic leaf movements (Lawn 1982a; M.M. Ludlow and R.C. Muchow, unpublished data), we are not aware of any studies to characterize differences among genotypes of the same species.

We have observed that appreciable paraheliotropic leaf movements do not occur in the tropical forage legume siratro *(Macroptilium atropurpureum)* until stomates are almost closed. Blum and Sullivan (In press) also found leaf rolling did not occur until after stomatal closure in sorghum and millet. The linkage between these two responses could be via leaf turgor; consequently, it may not be possible to breed or select for either response separately. However, because these two traits may have co-evolved to reduce leaf temperature after stomates have closed, it may be undesirable to do so in any case.

Blum and Sullivan (In press) advocated leaf rolling as a selection criterion for osmotic adjustment before heading in grain sorghum (leaf rolling does not occur after heading). They found high osmotic adjustment to be negatively correlated with the relative water content when leaves rolled; the lower the relative water content at which rolling occurs, the higher the osmotic adjustment.

Leaf Reflectance

Leaves of different species, and ad- and abaxial leaf surfaces, vary considerably in the extent to which they reflect visible light. Increased leaf reflectance reduces leaf temperature, the leaf-air vapor pressure difference, and hence water loss (Johnson et al. 1983). In wheat, for example, glaucous leaves were 0.7°C cooler than nonglaucous leaves, and the rate of leaf senescence was lower in the former (Richards et al. 1986). The reflectance is caused by the presence of epicuticular wax; the trait is called glaucous (cf. nonglaucous) in wheat and bloomed (cf. nonbloomed or bloomless) in grain sorghum. As well as increasing reflectance, the epicuticular wax is thought to lower epidermal conductance (Blum 1975, Jordan et al. 1984). Bloomed grain sorghum leaves have lower rates of photosynthesis and transpiration than nonbloomed leaves, but, because transpiration is reduced more than photosynthesis, transpiration efficiency increases in grain sorghum leaves (Chatterton et al. 1975) and in ears of wheat (Richards et al. 1986). Night transpiration is reduced as well (Blum 1975, Richards et al. 1986), presumably because of lower epidermal conductance. The net result of these responses is an increased water-use efficiency, but there is no effect on transpired water or harvest index (Richards 1983, 1987; Richards et al. 1986).

Glaucous or bloomed character increases the yield stability in water-limited environments (Jordan and Sullivan 1982, Johnson et al. 1983, Richards 1983), and even though it has not been shown conclusively, Richards et al. (1986) argue that it probably will not reduce potential yield. Theoretically, glaucousness should have a cost to production because of the reduced photosynthesis associated with the increased reflectance. There are, however, a number of factors that could compensate for this potential loss:

- If the reflected light is absorbed by lower leaves in the canopy, the light may not be lost and the efficiency of light-use could be increased.
- The accompanying lower transpiration rate both in the light and dark may mean that leaves can photosynthesize longer into the stress. For example, Richards et al. (1986) have calculated that a reduction of 0.5°C for 6 hours per day could extend the duration of grain-filling by more than 3 days.
- The accompanying benefits such as lower epidermal conductance and lower leaf senescence may also contribute to longer duration of photosynthesis.

Increased reflectance usually results from the onset of drought stress and is therefore an inducible trait. While the waxiness does not disappear when stress is relieved, the most reflective surfaces, which are exposed during the stress, are usually abaxial and are less exposed after stress is relieved.

There is genetic variation in the bloom trait in grain sorghum (Ebercon et al. 1977, Jordan et al. 1983b) and for glaucousness in wheat (Richards 1983). The inheritance of traits is understood for these two cereals. However, the heritability of bloom in sorghum is quite low (Jordan et al. 1983b). Moreover, the amount of epidermal wax is strongly influenced by the environment (Jordan and Sullivan 1982, Jordan et al. 1983b), increasing with the degree of drought stress.

The contribution of epidermal wax to dehydration avoidance is an advantage in environments with intermittent drought stress. Moreover, its contribution to improved water-use efficiency is an advantage in all four situations. Many of the current cultivars of wheat (Richards 1983) and grain sorghum (Jordan et al. 1983b) have some degree of epidermal wax and the yield advantage of bloomed or glaucous over nonbloomed or nonglaucous is a maximum of 15% in grain sorghum (Jordan et al. 1983b), 16% in barley (Baenziger et al. 1983), and *1%* in wheat (Johnson et al. 1983). Therefore, the yield gain by increasing the epidermal wax content of an already bloomed or glaucous cultivar may be very small indeed.

We are not aware of any studies on the epidermal wax content of tropical food legumes, although visually there are differences in leaf reflectance among food legumes, among genotypes of the same legume, and between the ad- and abaxial leaf surfaces.

High Temperature Tolerance

High temperature tolerance has often been advocated as a highly desirable trait for tropical cereals such as maize, sorghum, and millet (Sullivan 1972, Sullivan and Ross 1979, Jordan and Sullivan 1982). We make a distinction between the high temperature tolerance of leaves and germinating seedlings. In addition, we are concerned with temperatures that threaten survival rather than effects on growth and development.

In many areas of the semi-arid tropics, soil surface temperatures may exceed 60°C (Peacock 1982). Such temperatures can cause considerable seedling mortality, more in maize than in grain sorghum, which ultimately limits yield because of poor stand density (Peacock 1982; McCown et al. 1980. 1982). In addition, the growth of surviving seedlings is sometimes impaired until maturity. Similarly, germination and seedling emergence of cowpea (Onwueme and Adegoroye 1975) and soybean (Emerson and Minor 1979) are impaired by high soil temperatures.

Improved high temperature tolerance would enhance grain yield by promoting transpired water because the plant population would also be improved. Moreover, it should contribute to yield stability but have no penalty for yield potential. Genetic variability has been found in grain sorghum (Wilson et al. 1982). but the inheritance of this trait is unknown. It seems to us a very desirable trait for crops grown in those areas of the semi-arid tropics where very high soil temperatures can occur.

The case for high temperature tolerance of leaves is more equivocal. Sorghum leaf temperatures often exceed 40°C in the semi-arid tropics and values as high as 55°C have been recorded (Peacock 1982). Recent work (M. Paje, M.M. Ludlow, J.M. Peacock, and D.J. Flower, unpublished data, CSIRO, Brisbane) indicates that irreversible high temperature injury does not occur in high temperature-acclimated grain sorghum until temperatures of 52-55°C are reached. Consequently, injury from high temperatures will occur only under extreme conditions. We believe leaf-firing during droughts is mainly due to desiccation, because grain sorghum leaves are relatively sensitive to dehydration compared with other crops (Santamaria et al. 1986).

Sullivan and Ross (1979) reported a good correlation between high temperature tolerance and grain yield under hot, dry conditions in the field. However, this trait does not seem to have been used as a selection criterion in breeding programs. Passioura (1986) argues that such a trait is "contrived" with no well-articulated connection to grain yield. While theoretically high temperature tolerance of leaves should enhance their survival and contribute to yield by maximizing the amount of water transpired, there have been no studies to demonstrate a causal relationship between high temperature tolerance and grain yield. Until that is done it cannot be considered as a desirable trait.

Epidermal Conductance

Water vapor is lost from leaves through parallel pathways via stomata and the leaf cuticle. When stomates are open, most of the water is lost through that pathway. When stomates are closed, the main pathway of water loss is via the cuticle. However, there may still be some loss via incompletely closed stomata either over the whole leaf surface or in patches. For this reason, we use the term epidermal rather than cuticular conductance. When stomates are closed, water loss from the leaf is determined by the epidermal conductance and the saturation deficit of the air. In these circumstances the time leaves survive depends upon the water loss rate, and the difference in relative water content at which stomates close and leaves die. Therefore, epidermal conductance is one of three plant parameters that govern the survival of leaves.

Low epidermal conductance enhances avoidance of leaf dehydration and, therefore, will promote leaf survival (Sinclair and Ludlow 1986), and should aid grain yield stability. Moreover, because low epidermal conductance will not influence water loss when stomates are open, there should not be any cost of this trait and consequently it should not reduce yield potential. The main advantage of low epidermal conductance would be seen as enhancing plant survival in intermittent stress environments in both modern and subsistence agriculture.

Variation in epidermal conductance has been found in rice (Yoshida 1975, Yoshida and De Los Reyes 1976, O'Toole et al. 1979), grain sorghum (Blum 1979. Jordan et al. 1984), and soybean (M. Paje, M.M. Ludlow and R.J. Lawn, unpublished data, CSIRO, Brisbane). However, we are not aware of any studies on its inheritance. As with bloom on leaves, the environment has a very strong influence on epidermal conductance (Paje et al. unpublished data, CSIRO, Brisbane), especially temperature, relative humidity, and drought stress. Part of the variation could be associated with different amounts of epicuticular wax (Blum 1975). However, there is not always a good correlation between the two (Jordan et al. 1984). In sorghum, epidermal conductance increases with stomatal density (R.C. Muchow and T.R. Sinclair, unpublished data), and these workers hypothesized that once stomata reached minimum aperature, water loss from the cuticle above guard cell teichodes becomes a significant source of leaf water loss.

Transpiration Efficiency

Transpiration efficiency is defined as mass or moles of carbon (C) or CO_2 fixed per unit of water lost from a *leaf.* This contrasts with water-use efficiencies of plants or crops, which is dry matter produced per unit of water lost. Consequently, transpiration efficiency depends upon the balance between photosynthesis and transpiration, which in turn determines the partial pressure of CO_2 (p_i) in the intercellular spaces of leaves (Farquhar et al. In press). More precisely, p_i is determined by the relationship between the stomatal conductance (g) and the assimilation rate (A) of the leaf. Increases in A relative to g cause p_i to fall and transpiration efficiency to increase. For example, values of p. are lower in C_4 than in C_3 plants and hence transpiration efficiency is higher in C_4 plants (Ludlow and Wilson 1972, Tanner and Sinclair 1983).

Farquhar et al. (1982) have shown that p_i is related to the extent to which ^{13}C, the naturally-occurring stable isotope of carbon, is discriminated against in comparison to ^{12}C during CO_2 fixation in C_3 plants. This discrimination, Δ, should theoretically be inversely proportional to the transpiration efficiency of leaves (Farquhar and Richards 1984). Thus, the less the discrimination against ^{13}C, the lower the p_i and the higher the transpiration efficiency. They subsequently confirmed that Δ was inversely proportional to water-use efficiency (dry matter produced per unit of transpired water) in wheat, barley, and groundnuts in pot experiments (Richards 1987; Farquhar et al. In press).

However, it has not yet been shown that differences in transpiration efficiency, identified by differences in Δ, are correlated with differences in water-use efficiency of crops in the field. In fact, Δ was *positively* related to shoot yield (water use was not determined) in field experiments where there was little water shortage. On this basis, selecting for low Δ will result in *lower* yields and water-use efficiency. While it is clear that Δ can be used to select for higher leaf transpiration efficiency, it is too early to say whether this will be translated into improved water-use efficiency of crops in the field.

This work of Farquhar and Richards (1984) is in apparent conflict with the conclusions of Tanner and Sinclair (1983) that there was little scope to improve the water-use efficiency of crops by selecting for a higher leaf transpiration efficiency. Tanner and Sinclair's analysis was based on the assumption from the earlier work of Wong et al. (1979) that p_i did not vary among C_3 or among C_4 plants. Since Tanner and Sinclair's analysis was published, variation in p_i has been found among genotypes of the same species.

In theory, transpiration efficiency should not influence water used, except if it is achieved by high g relative to A, when water use would be reduced and dehydration avoidance enhanced. Higher transpiration efficiency has been shown to result in higher water-use efficiency in potted plants. Although the same should apply to water-use efficiency of crops in the field, this has not yet been demonstrated. Theoretically there should be no cost of higher transpiration efficiency and it should contribute both to yield potential and yield stability. However, if high values of Δ (and hence transpiration efficiency) are associated with low yields as suggested by early results of Farquhar et al. (In press), the high hopes, for this trait may not be realized.

There is genetic variability in transpiration efficiency in wheat, barley, and groundnuts (Richards 1987; Farquhar et al. In press). Corresponding variations in water-use efficiency of potted plants were 2.0 to 3.7 mmol C mol H2O-1 and 0.8 to 1.7 mmol C mol H20-1 for wheat and groundnut, respectively. The nature of inheritance of transpiration efficiency is largely unknown at present, except that it is not simply inherited. Nevertheless it is under strong genetic control, with broad sense heritabilities between 60 and 90% (Farquhar et al. In press, Martin and Thorstcnson 1987).

If improved transpiration efficiency can be shown to increase water-use efficiency of crops in the field, this would be a very desirable trait in both stress environments in modern and subsistence agriculture. Moreover, the fact that Δ can be determined from a single plant part ensures that this trait could be selected in large breeding programs (Richards 1987). While the trait has great potential to increase crop yields in the semi-arid and arid tropics, much more work is needed to demonstrate its influences. Apart from the well known difference in water-use efficiency between C_3 and C_4 plants (Tanner and Sinclair 1983, Angus et al. 1983), many studies have failed to reveal differences among genotypes of the same species once differences in the saturation deficit of the air are taken into consideration (see papers in Taylor et al. 1983, Wilson and Jamieson 1985).

Other Traits

Several traits have been omitted from detailed discussion because we do not believe enough is known for them to be considered seriously. Cell size and tissue elasticity are two such putative traits. It has been proposed that small cells are more tolerant of dehydration (Iljin 1957) and that they enhance osmotic adjustment and turgor maintenance (Cutler et al. 1977, Turner and Jones 1980). Neither the cost nor the value of the trait has been investigated and no genetic variability has been identified. High tissue elasticity in theory assists in volume maintenance by reducing the change in volume per unit of change in turgor. While elasticity varies among species, no genetic variability has been reported within a species (Turner 1986b).

Another such trait is the maintenance of high leaf water status as shown by small leaf-air temperature differences measured by infrared thermometry (Blum et al. 1982). The principle of the technique is that when stomates close because of reduced leaf water status, leaf temperatures rise above ambient air temperature. However, although Blum et al. (1982) found significant relationships between leaf water potential and leaf temperature, they did not always find significant relationships between diffusive resistance and leaf temperature. Therefore the basis of leaf temperature differences may not have been due to differences in water status. Furthermore, recent evidence (Turner 1.986a) suggests that diffusive resistance can rise in response to soil dehydration, independent of changes in shoot water status.

There are also many technical problems associated with infrared thermometry; in addition to leaf water status, leaf temperatures are influenced by windspeed, cloudiness, saturation deficit of the air, and the degree of canopy cover. Recent attempts to use infrared thermometry in rice (Turner et al. 1986a) and in wheat (Turner and Nicholas In press) have been unsuccessful. While Blum et al. (1982) used this approach to find wheat genotypes with good dehydration avoidance (i.e., cooler leaves) via more effective water uptake, Chaudhuri et al. (1986) found that grain yield was greatest in the genotypes of grain sorghum and millet with the *higher* leaf temperatures. Obviously more work is needed before maintenance of leaf water status as measured by infrared thermometry can be considered as a desirable trait.

Trait Combinations

The effects of the simultaneous occurrence of two or more traits has not been considered because they are specific to crop, environment, and farming system. While most of the traits that influence production can be considered as separate entities, the same cannot be said for those influencing survival. There is good evidence that traits are linked in strategies varying from extreme avoidance (e.g., cowpea) to extreme tolerance (e.g., groundnut). The lethal leaf water status is a key determinant of the strategy; crops with high lethal water status have an extreme avoidance strategy and those with low status have an extreme tolerance strategy. Crops with high lethal water status have well-developed traits for enhancing water uptake and reducing water loss. In contrast, those with a low lethal water status have less developed avoidance traits and usually have considerable osmotic adjustment (see Ludlow 1980a, 1980b; Ludlow et al. 1983).

Recommendations

Table 3 lists the traits that we believe will increase grain sorghum and cowpea production per unit of precipitation in the four nominated situations. The recommendations are based primarily on the data in Table 1, with most emphasis on those traits that have been shown to contribute to grain yield, or one or more of the determinants of survival or production, and on those with a good theoretical base. While inclusion of traits in the recommended list is a matter of personal preference, we have attempted to justify our decisions with fact or arguments. Obviously the reader is free to alter the ranking in accordance with personal knowledge or bias.

The two crops chosen as examples, grain sorghum and cowpea, are similar in that their leaves are sensitive to dehydration (Sinclair and Ludlow 1986, Santamaria et al. 1986). However, whereas grain sorghum often has few tillers in the semi-arid tropics and is botanically determinant, cowpea is indeterminant. Consequently, sorghum has only limited developmental plasticity compared with cowpea. Traits for these two crops are considered for intermittent and terminal stress environments in both modern and subsistence agriculture.

Survival traits are of limited value in a terminal stress because all they will do is delay the time until the plant dies or matures, and may not contribute to yield. Hence we have included them only in the environments with intermittent drought stress. In these two cases, we have given them higher emphasis in

Table 3. Recommended traits, in order of priority, for both grain sorghum and cowpea grown in intermittent and terminal stress environments in both modern and subsistence agriculture. Traits specifically for cowpea are shown in parentheses.

Modern agriculture[1] (opportunistic)		Subsistence agriculture[1] (conservative)	
Intermittent stress	Terminal stress[2]	Intermittent stress	Terminal stress[2]
1. Matching phenology to water supply	1. Matching phenology to water supply	1. Matching phenology to water supply	1. Matching phenology to water supply
2. Osmotic adjustment of shoots and roots	2. Osmotic adjustment of shoots and roots	2. (Developmental plasticity)	2. Remobilization of preanthesis dry matter
3. Rooting depth and density	3. Rooting depth and density	3. Osmotic adjustment of shoots and roots	3. Increased leaf reflectance[3]
4. (Developmental plasticity)	4. Increased leaf reflectance[3]	4. Rooting depth and density	4. Photoperiod sensitivity
5. Early vigor	5. Early vigor	5. Increased leaf reflectance[3]	
6. Leaf area maintenance	6. Remobilisation of preanthesis dry matter[4]	6. Low lethal water water status	
7. Increased leaf reflectance[3]		7. Leaf movements	
8. Low lethal water status		8. Low epidermal conductance	
		9. Early vigor	
		10. Leaf area maintenance	
		11. Photoperiod sensitivity	

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1. Seedling tolerance of high temperature is an important trait in environments where soil surface temperatures at emergence exceed 50°C.
2. When lodging of grain sorghum is a problem in a particular environment any trait that is shown to reduce lodging is desirable. It remains to be shown whether stay-green is such a trait without a yield penalty.
3. The scope for improvement may be small if current varieties are glaucous or bloomed.
4. Could be disadvantageous for grain sorghum in some environments if it promotes lodging.

the subsistence compared with modern agriculture because they are conservative and ensure some yield, even if they have a cost to production. However, within both intermittent stress situations the relative rankings will depend upon the probability of the crop experiencing water deficit periods sufficient to endanger its survival. The probability of such lethal deficits depends upon the frequency and intensity of rainless periods, and will be higher on lighter soil with low water-holding capacity than on heavy soils.

Apart from developmental plasticity, a desirable trait for the indeterminate cowpea, the remaining traits chosen are common to both cowpea and grain sorghum. In contrast to the previous section where the value of each trait was assessed, in the following section we attempt to rank in order of priority the traits that we believe are important for each species in each of the four situations.

The most important trait, we believe, is matching the crop phenology to the average water supply of the environment and ensuring that critical developmental stages occur in periods with higher probability of adequate water. This is easier in a terminal stress than in an intermittent stress environment, because the timing of the stress is unpredictable in an intermittent rainfall environment. Consequently, while it is not possible to select for specific phenologies, it is possible to do so in a more general sense, such as ensuring grain filling occurs after the rains have ceased to reduce the occurrence of head mold in sorghum. By selecting for a phenology to suit the average water supply, yield may be lost in better than average years, and yield may be depressed in low rainfall years. However, selecting for any other phenology is, we believe, fraught with even more danger.

The next most important traits in three of the four situations are osmotic adjustment and rooting characteristics, which maximize water extraction. Neither is recommended for terminal stresses for subsistence agriculture because of the risk of exhausting the soil water, except if available soil water remains at crop maturity. Osmotic adjustment is marginally preferred over inherently deep roots and high root length density for two reasons:

- osmotic adjustment confers other benefits, such as better panicle exsertion and continued photosynthesis during stress, it has no known costs, it is only induced by drought stress, and it disappears after stress is relieved; and
- a deep and dense root system may be beneficial during stress periods, but there may be a dry matter cost to the plant, which could reduce yield potential.

While both of the traits associated with the roots will tend to maximize ET, early vigor should reduce E and maximize T, especially in environments with light soils (Turner and Nicholas In press). Remobilization of dry matter (both carbon and nitrogen) accumulated prior to anthesis is seen to be of value in terminal stresses.

Maintenance of leaf area (stay green character in sorghum) may be a positive trait in intermittent stress environments if it ensures leaf area for growth when the stress is relieved. However, it seems of less importance in terminal stress, because it promotes water loss and increases the probability of the crop exhausting the soil water during grain-filling. This applies more to subsistence than to modern agriculture. Maintenance of green leaf area is a very important trait in grain sorghum if it prevents lodging, or if it allows more time to remobilize preanthesis dry matter.

Increased leaf reflectance is seen as a desirable trait in all four situations because it has no cost and is likely to produce a small but important yield increase. There may, however, be limited scope for improvement because many current cultivars have some degree of waxiness. Its importance is greater in terminal than in intermittent stresses, and in subsistence compared with modern agriculture.

Photoperiod sensitivity is seen to be a useful conservative trait that contributes to yield stability in subsistence agriculture. However, there is the potential for lost opportunities in above-average seasons in sorghum, but not necessarily in cowpea. The need to have different cultivars for different latitudes may also detract from its value in modern agriculture.

Several of the traits that promote water uptake and water loss (e.g., osmotic adjustment, deep roots, early vigor, large leaf/air temperature difference, and leaf area maintenance) are seen as desirable, more so in intermittent than in terminal stresses, as long as the water supply is not exhausted. If they endanger survival they could be seen as undesirable. Their relative importance obviously depends upon the probability of rainless periods and the nature of the soil.

In addition to these characteristics for cowpea, we believe developmental plasticity is a very important characteristic for intermittent stress environments, but not for terminal stresses. Moreover, it is more important in subsistence agriculture where grain can be hand harvested than in modern agriculture where uneven maturity causes problems for machine harvesting.

There are other traits that are potentially important for each of the four situations, but which are not listed because at present there is either insufficient experimental evidence or theoretical analysis to support them. For example, if it can be shown that improved transpiration efficiency is translated into superior water-use efficiency of crops in the field, this trait would be a great asset in any moisture environment. Low epidermal conductance and leaf movements are also potentially useful traits in intermittent stress environments of modern agriculture.

Conclusions

Too much has been written about putative traits for drought resistance in crops, supported by too little analysis of their actual value as opposed to their potential value. There is much information about various traits, but less knowledge and even less understanding of their real value. Only recently have attempts been made to assess their benefits by mathematics, simulation modeling, use of near-isogenic lines, or other techniques discussed in this paper.

Before putative traits are proposed for inclusion in breeding programs their benefits for grain yield must be assessed in terms of the components of yield and determinents of survival. Unless they make a contribution to one or more components or determinants, there seems little use in breeding for them. Simulation models promise to be a very powerful tool for critically assessing the value of putative traits. However, more work is needed in the development and testing of suitable models and in their application for this purpose. Use of near-isogenic lines as opposed to isogenic lines also appears to offer great promise.

More agroclimatic work is required to define the various moisture environments of the arid and semi-arid tropics, especially in terms of the amount, frequency, and probability of rainfall, and the expected soil moisture regime in average seasons. This is necessary so that the most appropriate phenology can be devised. Better techniques are required to measure soil water extraction and soil evaporation so that the amount of water transpired by present cultivars can be determined, and an estimate made of available soil water at maturity as a basis for deciding upon traits to increase transpired water or traits to meter crop water use during development. If all available soil water is not used and it is recharged each year, increasing transpired water seems the most direct and potentially the most important way to increase grain yield.

Because of the success by Morgan with osmotic adjustment in wheat and by Passioura and Richards with low hydraulic conductance of the seminal roots of wheat, we are confident that traits can be identified which improve production per unit of precipitation, and which lead to higher yields of dryland crops. While it has been stated many times before, the probability of such success is greatly enhanced by the close cooperation of physiologists with plant breeders and geneticists.

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Interpretive Summary of Part 4:

Breeding for Improved Plant Performance in Drought-prone Environments

R.J. Lawn[1]

Introduction

Empirical selection for improved variety performance under drought conditions has occurred since antiquity as countless crops have been exposed to the rigors of drought. With the development of modern plant breeding concepts, the process has been progressively refined and hastened with active hybridization using recognizably superior genotypes, followed by selection in a regime involving exposure to drought conditions.

It is difficult to establish unequivocally the extent to which breeding advances that have been made in performance in drought-prone environments have been due to improved specific drought adaptation, or rather to more generalized genetic improvement that expresses equally well in non-drought environments. Nonetheless, there is no doubt that these empirical refinements have led to some success (exemplified by the Indian sorghum variety M 35-1). The problem confronting the breeder is that progress has been slow and expensive.

The scientific reasons for these difficulties have long been recognized, although in some instances largely intuitively: genotype x environment interaction in drought-breeding programs is typically large, and most often nonsystematic. This simultaneously increases the testing necessary as a basis for selection, and reduces the potential for real genetic progress from selection.

Genotype X Environment Interactions in Drought-prone Environments

The environmental and physiological bases of differential genotypic responses in drought-prone environments are being established through agronomic and physiological research. On the environmental side, it is now clear that droughts occur over an almost infinite variation of space and time within what may be defined as "drought-prone" environments, which involve soil, atmospheric, and crop microcnvironmental components. Despite the variation, some generalized patterns have emerged, the most evident of which is that crop performance depends substantially on the timing, duration, and intensity of water deficits relative to crop ontogeny.

Thus the selection environments used by the breeder have been progressively refined to differentiate between terminal drought which occurs where crops are sown before or shortly after the end of the wet season, or where rains end prematurely, and crops mature on stored soil water, and intermittent or transient droughts of varying duration and intensity during crop growth. This latter drought type has been further refined to differentiate between droughts occurring at particular stages of crop ontogeny, or some combination of stages, usually relative to a particular phenology and a

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particular climatic environment. By effectively describing the probability of particular drought regimes in target environments, and then tailoring the selection environment to match, breeders have made gains in selection efficiency.

On the plant side, a range of physiological processes and/or traits influences plant performance. These have been comprehensively summarized by Schulze for natural arid-zone conrmunities, and Ludlow and Muchow for crop plants. The various traits contribute to the escape, avoidance, or tolerance of drought, and, through differential effects on total water used in transpiration, water-use efficiency and harvest index, can differentially influence both yield and stability. Individual traits usually cannot be considered in isolation; they tend to act "in concert", producing response patterns that can be described in adaptational terms as drought response strategies. Not surprisingly, given their differential impact on escape, tolerance, or resistance to drought, the potential value of specific traits varies with drought type. The degree of expression on particular traits, and range of variation among genotypes, vary among crop species.

Given the range of physiological traits contributing to plant response, and the complexity of possible drought patterns within environments, it is hardly surprising that the genotype x environment interaction encountered during breeding for drought-prone environments has been large, complex, and apparently nonsystematic. Nonetheless, the current challenge for those involved in plant improvement is to systematically exploit this agronomic and physiological knowledge to increase the efficiency and rate of genetic gain. This challenge will be most effectively met where there is realistic integration of drought-related physiological and breeding research.

Improving Genetic Advance in Drought-prone Environments

The large genotype x environment interaction confronting breeders of crops for drought-prone environments presents two major difficulties: the efficiency of genetic discrimination and therefore rate of gain through selection is reduced to the extent that the G x E is nonsystematic; and the probability of combining high yield potential with strong stability of performance in variable environments is reduced.

Knowledge of the physiological basis of genotype x environment interaction can be exploited to refine the breeding program to varying degrees. For example, the formulation of initial breeding objectives may be defined in more explicit terms than simply breeding for "drought-resistance". Objectives may be stated either in terms of particular physiological processes (pod setting), or perhaps even specific traits (osmotic adjustment), where adequate information exists to establish their ability to improve performance in drought environments.

More precise selection criteria in turn facilitate the identification and inclusion in the crossing program of parental material with the desired characters. This is particularly relevant where the characters are located in a genetic background unrelated to the best available adapted material, and are therefore less likely to be included on the basis of past experience. At the same time, screening techniques, preferably early in the breeding cycle, can be made more efficient in terms of both time and resources.

Likewise, those test environments that challenge and therefore most efficiently discriminate among advanced selections can be more effectively chosen. The variability of drought-prone environments poses particular problems in terms of defining (often remote) target environments so that appropriate, challenging, test regimes can be established. As with the initial definition of breeding objectives, the level of possible refinement is constrained by the comprehensiveness of the available information. With a low level of sophistication, historical meteorological data, combined with some minimal understanding of crop response, can be used to identify test environments that generally reflect drought patterns which might be expected at more remote target environments. At a somewhat more advanced level, physiological models that predict crop performance on the basis of meteorological inputs might be used where adequate historical meteorological information exists to provide a more useful description of the environment.

With some of the relatively sophisticated physiological models, further refinement in this translocation process may be possible by incorporating traits known to influence response to drought into the modeling process. For example, the response for each set of meteorological data might be examined for an "early", "medium", and "late" genotype. Thus patterns of variation and their probabilities available within historical climatological data might be translated into "historical" agronomic information through the use of physiological information. Alternatively, physiological information can be used to construct largely artificial test environments, for example through manipulation of rainfall, soil type, or depth.

Integrating Breeding and Physiological Research

The potential contribution of physiological research to genetic improvement of crop plants has long been expounded, but the traditional separation of physiological and breeding research tends to persist. Consequently, the impact on breeding methodologies of physiological information about drought responses has occurred slowly and incrementally. The schism is not surprising: a common behavior model for physiologists (that is, those who have at least recognized their obligations to the process of crop improvement) has been to advocate to breeders the selection of particular traits on the basis of studies with a limited range of germplasm, often conducted in isolation from the key objectives of the breeding program, and with limited or no information on heritability, and/or the efficacy of the putative trait. Further, the trait may be difficult to rapidly select for, or exist in nonelite germplasm so that it is linked with undesirable traits. For their part, many breeders have been reluctant to examine alternative methodologies, an approach that is consistent with the role of practicing technologist but not of an inquiring research scientist.

There are however increasing numbers of crop improvement programs successfully integrating breeding and physiological research, exemplifying a range of potential operational models. While details of the approaches vary, a common theme is a framework whereby both breeding and physiological research activities are conceived and implemented jointly. The outcome is increased awareness by the physiologist of the overall goals, specific objectives, constraints imposed by mode of inheritance and heritability, and day-to-day practical needs of plant improvement, which increases the relevance of the research to the breeder. The breeder is exposed to the research at as early a stage as possible, and thus can direct selection at more basic adaptive mechanisms and processes.

Physiological research can help identify potentially useful selection criteria either through a priori analysis of the physiological basis of genotype x environment interaction, or through post-facto analysis of the basis for divergent responses by empirical selection. In practice, the process is an iterative one involving both pathways.

Ideally, the development of a new selection procedure (the adoption of a new screening method, the survey of genotypic variation for a putative trait, the demonstration of its worth in terms of effect on drought performance, and genetic analysis to establish its heritability) should be achieved through collaborative physiological and breeding research. Too frequently this development phase founders because the breeder is reluctant to undertake unproven methodologies, while the role of the physiologist is not seen as encompassing any genetic and breeding research.

Usually, the survey of genotypic variation, genetic analysis, and proving of a putative trait will be best accomplished in a discrete program as an adjunct to the main breeding effort. As such, the process lends itself to collaborative physiological and breeding efforts. Evidence to support the value of the trait can be gained from phenotypic correlations or comparisons of near-isogenic genotypes. The most convincing evidence, however, will be its effect following divergent selection for and against the trait from a population segregating for the trait.

Which Traits for Which Crops?

The key performance goals in most drought-prone environments are to maximize the total amount of water transpired by the crop and to maximize harvest index. The potential to increase water-use efficiency (WUE) at the physiological level (unit carbon fixed per unit water transpired), remains uncertain, as was demonstrated by the differing perspectives of the reviewers: the possibility was raised in the papers of Schulze, and Ludlow and Muchow, but was considered as negligible by Sinclair. Certainly, the effect of any increase in WUE at the physiological level would be small relative to variations in total transpiration and harvest index among genotypes.

Phenology is clearly the most important physiological trait influencing crop performance in terms of both total water use and harvest index. The manipulation of phenology to match the duration of crop growth with the duration of favorable water supply is the most powerful tool available to the breeder in adapting crop varieties to the environment. This point is demonstrated with chickpea at ICRISAT, where on deep Vertisols stored water is sufficient to maximize yield with genotypes of 80-90 days duration. With earlier-maturing genotypes, biomass (and seed yields) are lower because growth ceases before water deep in the profile is exhausted, while later-maturing genotypes exhaust the water earlier during their reproductive growth, reducing harvest index.

Likewise the importance of matching crop duration to water supply is illustrated with groundnuts during the rainy season at ICRISAT. In the absence of terminal drought, the yield potential is 4.5 t ha^{-1} for a genotype maturing in 110 days, and 6.0 t ha^{-1} for a 140-day genotype, whereas if sufficient water exists for only 100 days' growth, the respective yields are 3.0 and 0.7 t ha^{-1}.

The importance of phenology is not restricted to terminal drought patterns: manipulation of phenology also provides the breeder with a mechanism for avoiding the coincidence of sensitive stages of crop growth (e.g., panicle initiation or anthesis in cereals, or pod filling in pulses) with periods where there is a higher probability of midseason drought. It is significant that in most crops, phenology is controlled by daylength and temperature. Thus, in an adaptational sense, the sensitivities to these two largely predictable climatic parameters can be used as "triggers" to enable growth cycles to be matched to seasonal variation in water supply, at least in tropical species. For those crops for which detailed information is available, photothermal sensitivity is largely under qualitative genetic control.

While the manipulation of phenology provides an important tool for the breeder, variation in phenology among individuals within a breeding population can contribute substantially to genotype and environment through direct phenology x drought pattern interactions. Thus, as far as possible, in evaluation tests, the effects of phenological variation need to be explicitly examined. Differential phenological response can also indirectly complicate the interpretation of genotype x environment interaction in drought-related studies, because of different genotypic sensitivities to daylength and temperature. Daylength, and somewhat less predictably temperature, vary with latitude and sowing date, so that relative differences in phenology among genotypes may not persist across sites. The situation may be further complicated by direct effects of drought on phenology so that, as was claimed for sorghum, relatively minor year-to-year climatic variation results in large phenological variation within a site.

A more positive aspect is that developmental plasticity in response to drought, as has been documented for some of the pulses, provides a mechanism whereby individual plants can acclimatize to the chance occurrence of intermittent drought during their growth by adjusting their phenology. Developmental plasticity may be exploited by the breeder, particularly in non-mechanized agriculture, where uniform grain maturity is often less critical.

In contrast to phenology, the potential value of other putative desirable traits varies with species, drought patterns, or remains to be demonstrated. Species vary, for example, in their capacity for osmotic adjustment of shoots and roots, which is pronounced in sorghum and pigeonpea, but limited in many other crops. In various species, osmotic adjustment has been shown to enhance water extraction, and thus increase total biomass or, for terminal drought, to increase or maintain harvest index. Wheat selected for osmotic adjustment has performed well under drought, and research data support its value in several other crops, including sorghum and barley. In others, such as pigeonpea, strong osmotic adjustment appears ubiquitous among genotypes, but modest variation suggests that there is a potential for improvement that remains to be demonstrated. The case to support selection for specific osmoticums such as proline remains to be proven.

In several species, inherent deep rooting exploits subsoil water and can enhance total water use. The potential to manipulate rooting characteristics was demonstrated by Passioura and Richards (cf. Ludlow and Muchow in this volume) who selected for narrow seminal roots with low hydraulic conductance to restrict water use prior to anthesis in wheat, which increased the quantity available during the grain-filling period.

Traits such as dehydration avoidance, leaf movements, low lethal water status, and high leaf reflectance favor leaf survival and thus maintenance of leaf area during drought, and help to maintain growth and productivity during transient, intermittent drought, and improve stability of performance. On the other hand, high remobilization of preanthesis assimilates is of greater importance under terminal drought.

Wide vs. Specific Adaptation?

There are clear advantages associated with broad adaptation in drought-prone environments:

- improved cultivars can be disseminated over a wide range of environments so that fewer environments need be targeted, or alternatively, fewer resources need be invested in drought-related breeding;
- Stability of performance over years within locations can be enhanced, which is particularly relevant given the temporal heterogeneity of drought patterns within locations; and
- fewer resources need ultimately be invested in seed production and distribution facilities once improved cultivars are released.

However, there are almost certainly costs associated with broad adaptation and stability of performance in terms of yield potential in specific environments, particularly in the context of drought. The best broadly-adapted cultivar will have the highest average yield over a broad range of drought environments, but will be lower-yielding than the best specifically adapted line in most drought environments. The complex interaction between drought and plant response is such that the simultaneous achievement of high yield potential and broad adaptation will be difficult and time-consuming, and the cumulative, long-term cost of not taking advantage of positive specific adaptation could be large.

Indeed, to a large extent the two goals of high actual yield and stability of performance are mutually exclusive, at least across the broadest range of possible drought environments. This point is effectively illustrated in the paper by Ludlow and Muchow: many of the traits outlined influence plant performance differentially depending on the nature of the drought; the different traits confer adaptive advantage in different drought environments. For example, developmental plasticity was seen as desirable for intermittent, but not terminal droughts. Further, both these authors and Schulze identify some traits that contribute to stability with a direct cost to yield potential in more favorable environments. The inference is that progress toward simultaneously high-yielding and stable genotypes will be painfully slow, unless attempts are made to limit the range of drought situations over which stability is required.

These considerations were also illustrated with some ICRISAT data for three chickpea genotypes sown at the end of the rainy season, and grown on stored water (Fig. 1). Across the range of environments (water availabilities), average yields of the three selected lines were similar, but their stability of performance varied. Across the range of both genotypes and environments tested, ICC 10448 showed average stability and therefore wide adaptability. Annigeri performed worse than average in poor environments but above average in higher-yielding environments; the reverse was true for ICC 4958.

If average yield is the main criterion for selection, the choice of variety clearly depends on the

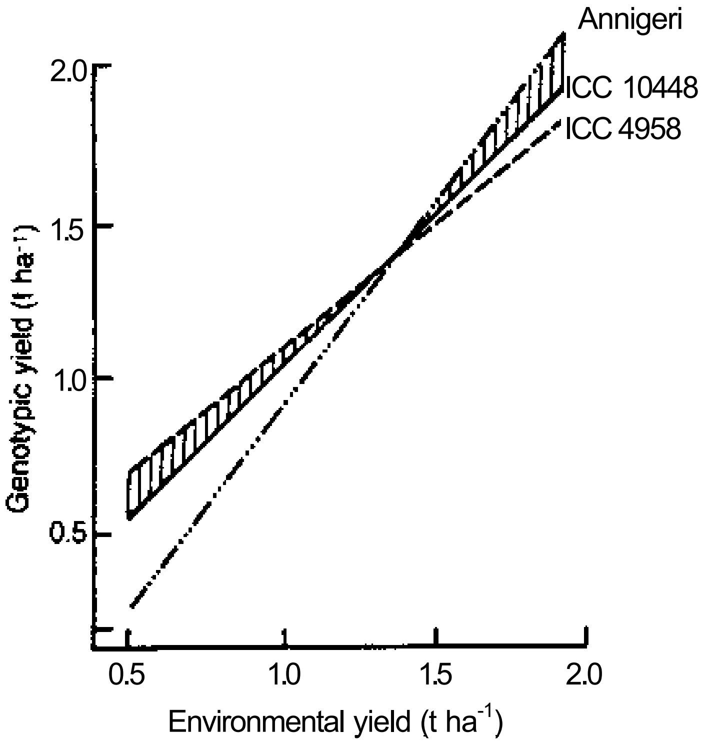

Figure 1. Linear responses for three selected contrasting chickpea genotypes over a range of soil water availabilities at ICRISAT Center, India (adapted from unpublished data of N.P. Saxena, ICRISAT).

target environment: where there is a high probability of low-yielding (< 1.0 t ha^{-1}) environments (due to shallower soils, poor water holding capacity, high evaporative demand, etc.), there would be, on average, an advantage in using ICC 4958. Conversely, the advantage would be with Annigeri where there is a high probability of a favorable (> 1.5 t ha^{-1}) environment (deeper soils with better water-holding capacity, or supplemental irrigation).

Only over the range 1.0-1.5 t ha^{-1} environmental yield (where all three varieties would have generally similar yields), or where environmental conditions are extremely unpredictable, with equal likelihood of yields over the range of 0.5-2.0 t ha^{-1}, can a case be made for choosing the widely adaptable line, ICC 10448. To the extent that the widely adaptable line is grown, rather than those with specific adaptation, there is a yield cost, illustrated by the shaded areas in Figure 1.

However, average yield is not always the sole criterion for selection, such as in subsistance agriculture, where crop failure cannot be tolerated. In these situations, there is clearly a reason to breed for risk aversion (i.e., selecting for either ICC 10448 or even ICC 4958 in Fig. 1). Decisions on the appropriate balance between risk aversion through stability of performance and cost in terms of loss of average yield potential cannot be made in an agronomic context by the breeder alone; socioeconomic information is clearly necessary to weigh the relative costs and benefits of either approach. However, the breeder must supply the breeding information relevant to this decisionmaking, just as the agronomist must provide information on the nature and costs ,of environmental modifications necessary to alleviate risk.

Likewise, decisions on the range of drought environments over which stability of performance is desired within a genotype are not for the breeder alone. Clearly, the broader limits are set by the range of possibilities encountered in the mandate area, and within those limits, choices will be made based on probabilities of occurrence of particular types (intensities, patterns) of drought established from historical agroclimatological information. Decisions will be further modified in the context of agronomic and economic information on the relevance of each drought type in areas where the breeders' crop is a significant component of the farming system. Finally, the breeder, particularly one with a very broad initial mandate, may still be left with a range of target drought-prone environments that encompass a complex of probable drought patterns.

It is within this context that the question of broad vs. narrow adaptation is most relevant. In effect, the question is whether it is more efficient to subgroup drought-prone environments into "drought iso-types" which might be separately targeted in the breeding program, or to breed for the area as a whole. The answer, and the degree of subgrouping, depends on the increased efficiency with which the breeder might make progress, relative to the increased cost of effectively targeting more environments. To a large extent, the principle was already accepted at ICRISAT by the move to subdivide drought into terminal vs. intermittent drought at various stages. Thus the question becomes the extent to which the principle might be extended. Any further subgrouping will be most efficiently done on the basis of similar impact on crop physiological response, rather than on meteorological information alone.

Summary

Empirical breeding methodologies, based essentially on selection for yield in drought-prone envir-onments, have made slow but in many cases very real genetic improvement. Such approaches are, however, costly in terms of research resources as well as time, because of the almost infinite variation over space and time of drought-prone environments and the complex genotype x environment interactions that occur. Substantial research is still needed to unequivocally establish the value of many physiological traits to plant improvement in drought environments. However, sufficient quantitative physiological knowledge is now available for a number of traits, and for a number of crops, to improve the efficiency of breeding programs by complementing empirical methodologies with directed approaches targeting specific physiological traits and/or processes. Achievement of this increased efficiency requires more effective complimentary physiological and breeding research than has occurred to date, and the resolution of apparently conflicting research goals and approaches.

A range of possibilities exist whereby integration of breeding and physiological research can be improved. Where a priori physiological understanding of particular traits exists, the knowledge can be used to more precisely define breeding objectives, identify selection criteria and/or parental material, describe the mode of inheritance and heritability, develop efficient screening techniques, and describe effective test environments. Physiological analysis of contrasting responses generated in the breeding program is also of value to refine understanding of the effects of individual traits. In crops where detailed physiological knowledge remains to be generated, integrated research can more efficiently establish the potential value of specific traits to enhance performance in drought environments, and generate information on their genetic basis, as a prerequisite to designing more efficient breeding methodologies.

The main opportunities to increase yield in drought-prone environments are in approaches that increase total water use and harvest index. Opportunities to increase physiological water-use efficiency are small. Phenology is the most important trait generally available to the breeder, offering the ability to match crop growth to water supply. Most other potentially useful traits such as osmotic adjustment, rooting characteristics, or survival traits such as dehydration avoidance and low lethal water contents, are of advantage to specific drought patterns, or are relevant to specific crops.

There are advantages to breed for broad adaptation in drought-prone environments; specifically, improved germplasm can be disseminated over a wider range of environments, and stability of performance over years within sites can be enhanced. However, physiological responses to drought depend on both its timing and intensity, and are therefore sufficiently complex that specific combinations of traits confer advantages in particular drought environments, and not others. The cost of breeding for broad adaptation may therefore be an inability to exploit specific adaptations in particular environments.

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