Challenges in Dryland Agriculture — A Global Perspective

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79

Steps in Crop Climatology*

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Status of Crop Climatology

"To many people at the present time, the content and scope of climatology is only this - the measuring, recording, and averaging of standard meteorological elements. I need not remind you that climatology when circumscribed in this way is sterile and unrewarding."

That was written by C.W. Thornthwaite (1958) in a review which he prepared for a symposium on Arid Zone Climatology sponsored by UNESCO and held in Canberra in 1956. As we meet 32 years later to take stock of success and failure in tackling the problems of dryland farming, it is appropriate that the subject of climatology should receive attention at an early stage in the proceedings. If Warren Thornthwaite had been here, he would certainly have contributed to the debate about the severity of drought in the U.S. this year; he would also have been concerned with the application of climatological principles to crop production in parts of the world where rain is always scarce and erratic and where the physiological consequences of drought are often complicated by extremes of temperature.

What aspects of climatology would make Thornthwaite unhappy today? I suspect he would have been a little disappointed by our failure to make better use of the tremendous wealth of information about crop-weather relations which we have acquired over the past 30 years from work in the field and in controlled environments. He would appreciate that we have used this information in several ways. We have tried to correlate yields with sets of arbitrarily chosen weather variables using statistical techniques. I am fairly certain that he would have described such exercises as "sterile and unrewarding" because the relations they produce are site and season-specific and because they shed so little light on physical and physiological processes. But he would have been astounded by progress in the simulation of crop growth and crop water use using large computer models. Perhaps, having heard references to "black boxes," he would have used the same word to describe models that I once heard him applying to his own formula - "magic"! He would quickly have appreciated the potential application of these models for planning and for management; but he would have criticized us for making our models esoteric and for doing too little to bridge the gap between the somewhat academic predictions we make from models and the needs of farmers who are more impressed by quick and dirty solutions to problems of production than by the efficacy of magic wands!

Seeking both focus and structure for this paper, I decided that it would not be profitable either to attempt some kind of classification of the many diverse climates in which dryland farming is practiced (because descriptions will appear where they are needed in other papers) or to get involved in the use of black boxes to relate production to climate. Instead, I shall try to put a few new steps into the staircase that ascends from the raw statistics of climate to predictions of how yield depends on major elements, principally radiation, rainfall, and saturation vapor pressure deficit.

In this exercise, I have adhered to Occam's razor - "Do not multiply hypotheses" - supported by the words of Bacon - "Truth proceeds faster from error than from confusion." Progress in understanding and predicting the response of crops to climate is usually most rapid when we succeed in identifying conservative quantities - those which do not change much from site to site or from season to season. Bacon would certainly allow us to turn a blind eye to a bit of variability for the sake of reducing confusion!

Growth, Water, and Radiation

Types of Environment

To start, I distinguish between two types of environment to which crop plants may be exposed at different times during a growing season:

(a) an environment where roots have access to such abundant supplies of water that transpiration proceeds throughout the day at a maximum or "potential" rate determined mainly by solar radiation;

(b) an environment where the uptake of water by a crop depends for at least a part of each day on the size and rate of extension of the root system and on the state of water in the surrounding soil.

I shall refer to these types as energy limiting (EL) and water limiting (WL).

Dry Matter and Water

For both types of environment, there is substantial evidence from field measurements on many species that the amount of dry matter produced by a crop per unit of

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*Submitted as conference paper no. 477 by the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) water transpired (q) is almost inversely proportional to the mean value of the saturation vapor pressure deficit (D) of the atmosphere to which the canopy is exposed during the day. This implies that qD is a conservative quantity - a response detected long ago by Kiesselbach (1916). Its physiological basis - conservatism of the intercellular CO_2 concentrations of leaves - has been elucidated only recently, as described by Tanner and Sinclair (1983).

For dryland agriculture, the dependence of q on D implies that the humidification of the atmosphere which always accompanies rain may be comparable in significance with wetting the soil. In monsoon climates, about one third of the benefit of rain in terms of crop production can be ascribed to a decrease of vapor pressure deficit (Monteith, 1986). We should therefore be extremely cautious about accepting production functions from line-source or rain-shelter systems where the natural coupling between water supply and D is broken. Moreover, production functions should never be transferred from one site to another without correcting for differences of D where they exist.

A convenient way of allowing for the influence of D on the relation between dry matter and rainfall (or irrigation) is to divide the amount of water (in mm, say) by the appropriate mean value of saturation deficit (in kPa) and then to multiply by D_n = 1 kPa to give a "normalized" rainfall which still has units of millimetres. Unless this is done, parameters expressing the relation between dry matter gain and water loss have dimensions of pressure - a source of confusion. The amount of dry matter equivalent to one unit of normalized water is simply qD. (Note that D_n must be expressed as the equivalent of 1 kPa if a different unit is chosen for D. For example, with D expressed in mbar, D_n = 10 mbar.) In what follows, D_n = 1 kPa and the units of qD/Do = qD are g dry matter per m^2 per mm of normalized water which has the same numerical value as g dry matter per kg normalized water.

The usefulness of D as a normalizing factor is well illustrated by the work of former colleagues at the University of Nottingham who grew pearl millet (*Pennisetum glaucum*) in glasshouses there and also in the field at the WMO Center in Niamey, Niger, and at ICRISAT Center near Hyderabad, India. Table 1 contains values of q and D and demonstrates that qD for each species was conservative over a wide range of environments.

Other values of qD reported in the literature are in Table 2. For C_3 species, qD is smaller than for C_4, corresponding to a well-documented difference in the characteristic intercellular CO_2 concentration of the two groups. However, the values for C_3 species grown in cool, temperate climates is less than would be expected on this basis. It is likely that where values of D are less than 0.5 kPa during much of the growing season, the specification of a representative mean daytime value is less accurate than in drier climates where the quantity is larger. Another possible explanation lies in the correlation between evaporation rate and D (Tanner and Sinclair, 1983) which is much stronger in EL than in WL environments.

As the analysis which follows pertains mainly to dryland agriculture in warm or hot regions, a round number of 9 g/kg kPa will be adopted for C_4 species and 4 g/kg kPa for C_3.

The values of qD reported here refer to shoot biomass only whereas it is total biomass that should be proportional to transpiration. The ratio of total plant biomass to transpiration is rarely reported from field experiments because root systems are difficult to harvest and because total water loss cannot readily be partitioned into transpiration and evaporation from the soil. Fortunately, the ratio of root to shoot biomass is usually small, at least over the whole life of a crop, but the increase in root:shoot ratio often observed in response to stress would be expected to make qD **appear** to decrease as available water decreased.

Dry Matter and Radiation

Another conservative quantity of major importance in crop ecology is the amount of dry matter produced per unit of radiation intercepted by foliage (e) when light is a major limiting factor. The conservatism of e appears inconsistent with the non-linear relation between photosynthesis rate and irradiance repeatedly demonstrated in the laboratory. However, intercepted radiation is the product of two quantities: radiation incident on a crop stand per unit area (S) and the fraction of that radiation which is intercepted (f). In climates where there is little cloud or where cloud is fairly randomly distributed in time, daily totals of radiation averaged over periods of 10 days or more change little over the growing season. The corresponding mean efficiency of photosynthesis is therefore conservative and the main discriminant of growth rate is the fraction of incident radiation absorbed by foliage, a quantity depending on the area and structure of foliage as determined by factors such as plant population, water supply, or nutrient availability.

Because crop plants respond to a shortage of water or nutrients by investing a larger fraction of assimilate in root systems at the expense of shoots, both the shoot growth rate and transpiration rate increase less rapidly with the age of a stand than they would in the absence of stress. If demand and supply were kept in perfect balance by this mechanism, e would not respond to stress. In practice, the supply of and demand for water or nutrients are rarely exactly matched. For example, Day et al. (1978) found that when barley (*Hordeum vulgare*) grown on water stored in a soil profile was compared with irrigated barley in adjacent plots, the fraction of radiation intercepted over the growing season declined by 42% but the value of e was only 20% less. The decrease of e reported as a response both to dry soil and to a dry atmosphere is likely to be a consequence of stomatal closure in a WL environment.

Values of e for a range of species and environments are in Table 3. Those for tropical C_4 and temperate C_3 species do not reflect the difference that would be expected from relative rates of maximum photosynthesis. It is likely that environments were predominantly EL and occasionally WL for measurements in cool temperate

Table 1. Values of dry matter/water ratio q and of normalized ratio qD for pearl millet and groundnut (shoot weights only).

Site	Standing shoot dry weight	q	D	qD	Source
	Mg/ha	g/kg	kPa	g/kg kPa	
			Pearl Millet (*Pennisetum glaucum*)		
Nottingham, UK (glasshouses)	14.4	6.4	1.4	9.0	Squire et al. (1984a)
ICRISAT, India					
dry season, irrigated	6.0	3.9	2.4	9.5	Squire et al. (1984b)
dry season, unirrigated	3.2	4.6	2.3	10.6	- do -
Niamey, Niger	1.7	2.1	4.0	8.4	Azam-Ali et al. (1984)
Mean		4.3 ± 0.8		9.4 ± 0.4	
			Groundnut (*Arachis hypogaea*)		
Nottingham, UK	2.7	5.2	1.0	5.0	Ong et al. (1987)
	2.5	3.0	1.4	4.1	
	2.0	2.6	1.6	4.0	
	1.1	1.5	2.0	2.9	
ICRISAT, India					
dry season, occasional irrigation	2.0	1.6	2.4	3.8	Azam-Ali et al. (1988)
dry season, unirrigated	1.1	2.0	2.1	4.2	Matthews et al. (1988)
Mean		2.7 ± 0.5		4.0 ± 0.3	

ate climates, but predominantly WL and occasionally EL for measurements in tropical climates, even during rainy seasons. Values of e for several legumes are about half those for C_4 cereals in similar environments and a number of factors may contribute to this difference: smaller maximum rates of photosynthesis, energy spent in nitrogen fixation, and the relatively high energy content of oilseeds and pulses.

A New Climatic Index

I have reviewed evidence suggesting that several major crop species produce dry matter at a rate which is proportional to the amount of water they transpire, normalized by the mean saturation deficit of the atmosphere they grow in; and that dry matter is also proportional to radiation - though in many dryland regions this relation must depend to a large extent on the supply of water and nutrients. The conservatism of both e and qD implies that $j = e/qD$ (mm normalized water per MJ/m²) should also be conservative.

Inspection of Tables 2 and 3 suggests that j is about 0.17 (1.5/9) mm of normalized water per MJ/m² for C_4 cereals common in dryland agriculture and that for several legumes widely grown in the tropics and subtropics, j is about 0.16 (0.65/4). In the rest of this paper, a round figure of j = 0.2 is used to cover these two classes. For groundnut (*Arachis hypogaea*), j appears to be about 0.1 (0.4/4), a consequence of the relatively small value for e, but would be closer to 0.2 if the high energy content of kernels were allowed for. For temperate cereals, $j \simeq 0.4$ because qD is very small. The physiological and environmental reasons for this spread of values merits further investigation, but the extremes can be used when they are needed rather than j = 0.2.

When the value of j for a species is known, it should be possible to estimate the **potential** rate of transpiration (E) from a crop at any stage of development from the fraction f of incident solar radiation intercepted by the canopy and the **product** of solar radiation and D (not to the sum of a radiation term and an aerodynamic term proportional to D as in the Penman formula). The appropriate relation is found by writing the rate of accumulation of biomass per unit ground area (C) as:

$$C = e\,f\,S = q\,E \qquad (1)$$

from which

$$E = f\,j\,S\,D\,. \qquad (2)$$

In this equation, the product j S D representing the atmospheric demand for water can be interpreted as a driving force D multiplied by a stomatal conductance proportional to jS. The term j incorporates processes of

Table 2. Values of normalized dry matter/water ratio qD.

Crop	Site	qD	Source
		g/kg kPa	
Maize *(Zea mays)*	W. and mid-W. USA	9.5 ± 0.3	Tanner and Sinclair (1983)
Sorghum *(Sorghum bicolor)*	ICRISAT, India	8.3	Van Evert (communicated)
Pearl millet *(Pennisetum glaucum)*	Various	9.4 ± 0.9	Table 1
Groundnut *(Arachis hypogaea)*	Various	3.9 ± 0.3	Table 1
Chickpea *(Cicer arietinum)*	ICRISAT, India	4.8	P. Singh (communicated)
Soybean *(Glycine max.)*	Kansas, USA	4.0	Tanner and Sinclair (1983)
Wheat *(Triticum aestivum)*	Lincoln, NZ	3.1	Wilson and Jamieson (1984)
Barley *(Hordeum vulgare)*	Rothamsted, UK	2.9	Day et al. (1987)
Potatoes *(Solanum tuberosum)*	Wisconsin, USA Holland	6.5 1.5	Tanner and Sinclair (1983) Tanner and Sinclair (1983)

radiation, carbon dioxide, and water vapor exchange and f depends on the history of foliage expansion as determined by the environmental control of growth and development. Implicit in this simple interpretation of j is the assumption that foliage and air temperature are equal so that D is a foliage - air vapor pressure difference. It is possible to take account of diurnal changes in the difference between foliage and air temperature by appeal to the Penman-Monteith equation (Monteith, 1988).

If the rate of transpiration started to depart from the potential rate early in the life of a crop because of an incipient shortage of water, slowing of leaf expansion would help to stabilize the balance between supply and demand as already described. In dryland farming, supply and demand are rarely balanced. During wet spells, the rate of transpiration is slower than the rate of rainfall and is therefore limited by available energy. During intervening dry spells, the supply of water from the root system may or may not be able to sustain the demand imposed by radiation (determining the effective stomatal conductance of the canopy) and by saturation deficit. To decide whether the climatic environment should be regarded as EL or WL, the appropriate value of j can be compared with the amount of **rainfall** received in a specific time, normalized by the mean saturation deficit for that time and divided by the solar radiation received. This climatological quantity will be referred to as j^*.

For the time being, we shall assume that rain falling on a crop on a particular day is available for transpiration that day, but that none is stored in the soil, and that all incident radiation is intercepted by foliage. Then for any period in which $j^* > j$, crops have more rain than they need to meet the potential demand set by radiation - an EL environment. When $j^* < j$, rates of transpiration and of growth are both limited by the supply of water - a WL environment. Figure 1 shows normalized rainfall plotted against radiation for 2 months at an imaginary station. The solid line through the origin defines a constant value

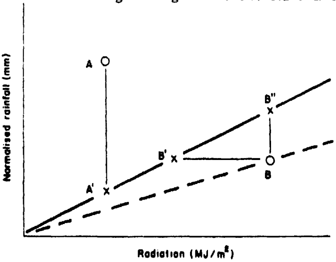


Figure 1. Points A and B represent coordinates for normalized rainfall and radiation at a station in 2 months. AA' is excess water, BB' is excess radiation, and BB" is irrigation used. Full line represents potential value of j and dashed line is possible actual value (see text).

Table 3. Shoot dry matter per unit of intercepted (total*) solar radiation e.

Crop	Site	e*	Source
		g/MJ	
Maize (*Zea mays*)	Davis, USA	1.5	Williams et al. (1965)
Sorghum (*Sorghum bicolor*)	ICRISAT, India	1.45 ± 0.09	ICRISAT Annual Reports (Van Evert, communicated)
	Kimberley, Australia	1.2	Muchow and Coates (1986)
Pearl millet (*Pennisetum glaucum*)	ICRISAT, India	1.5 - 1.7	Marshall and Willey (1983), Squire et al. (1984b)
	Niamey, Niger	1.2	Azam-Ali et al. (1984)
Groundnut (*Arachis hypogaea*)	ICRISAT, India	0.4	Marshall and Willey (1983)
		0.4 ± 0.07	Matthews et al. (1988)
		0.39 ± 0.04	Azam-Ali et al. (1988)
Chickpea (*Cicer arietinum*)	ICRISAT, India	0.68	P. Singh (communicated)
	ICARDA, Syria	0.62	Hughes et al. (1987)
Pigeonpea (*Cajanus cajan*)	Trinidad, West Indies	0.6 - 0.7	Hughes et al. (1981)
Soybean (*Glycine max*.)	Iowa, USA	0.75	Shibles and Weber (1966)
Wheat (*Triticum aestivum*)	Lincoln, NZ	1.19 ± 0.02	Wilson and Jamieson (1984)
Temperate cereals, legumes, and root crops	UK	1.0 - 1.5	Monteith and Elston (1983)

* Where necessary, values of e quoted for photosynthetically active radiation were corrected to a total radiation basis by multiplying by the ratio of PAR to total energy assumed to be 0.5.

of j. Point A represents a month in which j^* is larger than j implying that the amount of water received from rain exceeds the amount that could be transpired by a crop "fully covering the ground," i.e., by the **potential** transpiration for the month. Then excess water represented by the line AA' would have to be lost by percolation or by runoff. (The role of evaporation from the soil surface is assumed negligible here but is discussed later.) From the coordinates of A' it is possible to calculate potential transpiration for the month and the corresponding production of dry matter.

Point B represents a month in which j^* is less than j. To survive in this environment, a crop would have the following three options.

(1) To lose radiation (equivalent to the loss of water in the previous case) either by the adaptive device of restricting leaf expansion earlier in the season, or by the movement or rolling or shedding of leaves to reduce interception. The loss of radiation needed is given by the line BB' and the coordinates of B' specify corresponding amounts of **actual** transpiration and growth.

(2) To reduce by the process of stomatal closure. A line with a smaller value of j (dashed) could then pass through B. Values of e already reviewed suggest that this is a common response.

(3) To increase the value of q, e.g., by decreasing the mean intercellular concentration of CO_2. This response to drought has been reported in some laboratory studies, but as associated changes of q are usually small and unsystematic, the option seems less plausible than (1) or (2).

The dryland farmer has two more options:

(1) to apply irrigation corresponding to the (normalized) amount BB".

(2) to thin stands so that less radiation is intercepted per unit ground area and therefore per unit of rain (but not per plant). Although this drastic procedure is sometimes practiced by farmers in the semi-arid tropics, success obviously depends on rare skill in assessing reserves of water in the soil as well as forecasting rainfall for the rest of the season.

Moving to a real dryland climate, Figure 2a displays monthly values of normalized rain and radiation at Hyderabad, India, where rain falls during the monsoon between mid-June and early October and in occasional heavy storms outside this period. In the 3 months July to September, $j^* > j$ implying that radiation is the factor

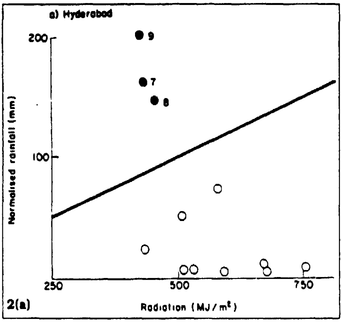
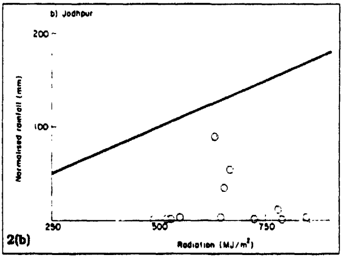
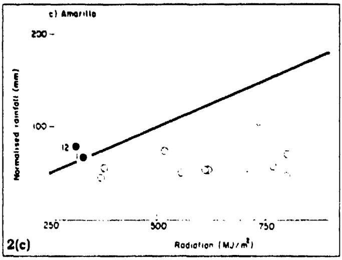
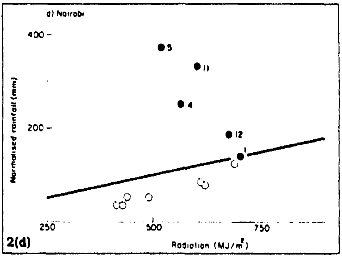


Figure 2. Monthly values of normalized rainfall plotted against radiation with relation j = 0.2 mm per MJ/m² (bold line).
• EL months with month number (j* > j)
○ WL months (j* < j)
(a) Hyderabad (b) Jodhpur (c) Amarillo (d) Nairobi (e) Kuala Lumpur (Data for stations except Hyderabad from Mueller, 1982).







limiting the growth of crops throughout the monsoon in an average year. Rain is the limiting factor in all other months.

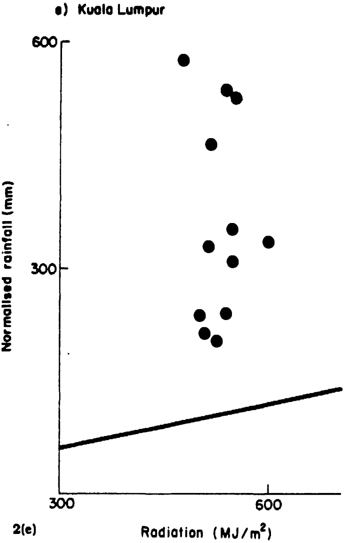
Figure 2b is the corresponding plot for Jodhpur in the Rajasthan desert where monsoon rain is, on average, too little to bring any monthly point above the line. This distribution could be taken as the criterion of an arid climate. On this basis, Amarillo, too, is arid (Fig. 2c), but because winter temperatures are much less than in Jodhpur and because irrigation is available, a completely different type of agriculture is possible.

Figure 2d illustrates the bi-modal distribution of rainfall at Nairobi, almost on the equator. On average, rainfall exceeds the requirements of cereal crops, e.g., maize (*Zea mays*) from November to January and in April and May. For contrast, Figure 2e shows the record for a station in the humid tropics (Kuala Lumpur), where all months are above the line and during the year radiation is much less variable than rainfall. In simple terms, there is never enough radiation to get rid of the rain. Dry matter production is rarely limited by water supply, but leaching and erosion are potential agricultural problems.

This simple climatic analysis does not take us very far but the fact that the distribution of points above and below the line is consistent with known patterns of crop production at the stations chosen for illustration (and at others not shown) suggests that the value of 0.2 mm per MJ/m² chosen for j is widely applicable. It certainly has a sounder basis than the ratio of rainfall to potential transpiration (often used to define the length of growing season at a station) because it combines the state of the atmosphere with essential physiology.

As a step toward relating crop production to climates, the main limitation of Figure 2 is:

(1) no account is taken of the way in which water can be stored in the soil for later uptake by roots;
(2) evaporation from the soil surface is ignored although it is usually a major term in the water balance when ground cover is incomplete;
(3) the distribution of rainfall within months is not accounted for (in effect, both rain and radiation are assumed to be uniformly distributed over each month);
(4) the phenology of crops, as determined by temperature and daylength, for example, is disregarded.



2(e)

We shall now explore ways in which the elementary climatic analysis represented by Figure 2 can be extended to include all four points in this list.

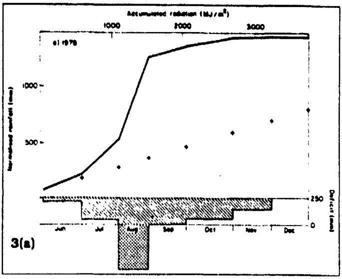
Monthly Water Budget

The next step on the staircase leading to a practical crop model is to estimate monthly budgets for water, assuming a value for the maximum amount of water held in the soil profile and accessible to roots. This type of analysis usually contains the implicit assumption that "available water" is constant throughout the growing season whereas, in reality, it increases as roots penetrate downwards.

For illustration, and as the basis for the presentation of **daily** water budgets which will follow, I chose records for three contrasting years at ICRISAT Center in the decade 1978-87: the wettest year (1978), the driest (1985), and a season in which rainfall and evaporation remained roughly in balance throughout (1982).

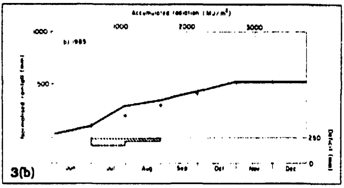
I assumed that crop growth began on an arbitrary date, conveniently chosen as June 1 (in practice, sowing is usually a couple of weeks later than this) and that it continued in each month that rain fell or until stored water was exhausted.

Figure 3 shows cumulative normalized rainfall (full lines, upper part of figure) plotted as a function of cumulative radiation by analogy with Figure 2. Cumulative radiation is used as a surrogate for time so that a plot of y against x has a maximum slope of $j = 0.2$ mm per MJ/m². The lower part of the figure represents the soil water deficit assumed to have a maximum value of 250 mm for a deep Vertisol. The hatched area at the bottom of the graph therefore represents the estimate of water stored in the profile and the stippled area, where it appears, is water lost by runoff or by percolation. (In this type of analysis, it is necessary to make the unrealistic assumption that these components are zero until the soil is at field capacity.) In a wet year (1978, Fig. 3a), the water

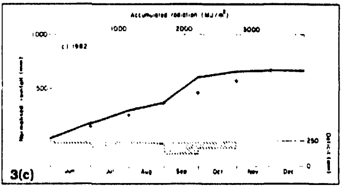


3(a)

Figure 3. Accumulated monthly values of normalized rainfall and radiation at Hyderabad (means for 1978/87) (full line). Crosses represent maximum loss of water by transpiration as limited by water or energy. Soil water deficit and water loss as runoff <art > or as drainage <art > shown below radiation axis (see text). (a) 1978 (b) 1985 (c) 1983.



3(b)



3(c)

equivalent of accumulated dry matter as determined by radiation (+ on graph) is always less than the corresponding accumulated rainfall. The excess is stored in the soil (assumed to hold no water on Jan. 1) or is lost, as in August. Because evaporation proceeds throughout at a potential rate, points representing cumulative monthly totals lie on a line with slope j.

In a dry year (1985, Fig. 3b), the analysis suggests that a limited amount of water was stored in July and August, but for the rest of the year, points fall on the locus of accumulated rainfall showing that dry matter accumulation was limited by water, not light. In an intermediate year (1982, Fig. 3c), water is stored in the profile from June to October and there is just enough rain to prevent the water supply from limiting growth in any month until December.

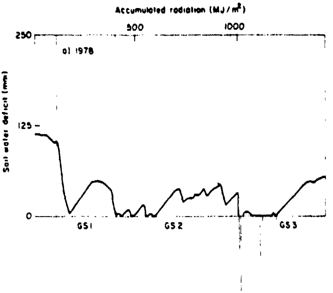
Daily Water Budgets

In the analysis of the last section, the amount of dry matter produced over a period of 6 months ranged from 39 Mg/ha in 1985 to 60 Mg/ha in 1978. These figures are larger by a factor of about 5 than the biomass produced by crops of sorghum (*Sorghum bicolor* (L.) Moench) (var. CSH 5) grown from 1981 to 1987 on a deep Vertisol at ICRISAT. To remove this discrepancy, I estimated the length of major growth stages from mean daily temperature, and introduced evaporation from the soil surface using an algorithm given in the Appendix.

The years 1978, 1982, and 1985 were chosen again to allow comparison with Figure 3. The vertical coordinate in Figure 4 now represents soil water deficit (actual, not normalized water) with a maximum value of 250 mm and a minimum value of zero corresponding to field capacity. The horizontal coordinate is accumulated radiation as before. On any day when the rainfall exceeds the deficit, the water that is "lost" by runoff or percolation is shown below the axis. On any day when the available water is zero, transpiration and growth are assumed to be zero so that radiation is "lost." Reading from left to right, vertical axes represent the origin for radiation, the amount of radiation accumulated up to the date of sowing and amounts accumulated to the ends of growth Stages 1, 2, and 3 (corresponding to panicle initiation, anthesis, and maturity). The initial water content was obtained from an independent water balance study.

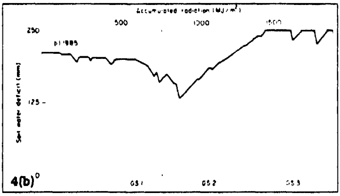
In the wet season of 1978 (Fig. 4a), the profile was more than half full at the beginning of the monsoon season and remained close to field capacity until harvest. Very heavy rain in GS 3 was followed by the loss of more than 300 mm of water. Wet conditions at harvest and some leaching of nutrients earlier in the season may both have been responsible for the poor yields of cereals widespread in this season.

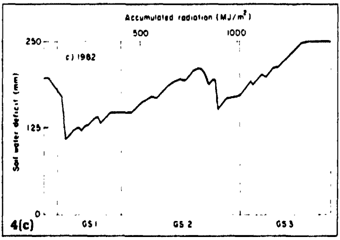
In complete contrast, the monsoon of 1985 was so late in arriving that the date of sowing according to the criterion used (Appendix) was July 4, about 3 weeks later than usual. The profile was never more than half full and little water was available to the crop in GS 3 (Fig. 4b).



4(a)

Figure 4. Daily values of soil water deficit at Hyderabad estimated for a soil with water holding capacity of 250 mm. Details of interpretation in text. (a) 1978 (b) 1985 (c) 1983.





In 1982, the profile again was never more than half full, but the distribution of rain was such that there was a steady decline in available water from about 130 mm early in GS 1 to zero just before the end of GS 3 (Fig. 4c). There were several periods when the input of water from rain almost exactly balanced the output by evaporation.

Over the whole decade (1978/87), the model predicted that water would be lost by runoff or percolation during the growing season in only 3 years whereas runoff was recorded in 7 years. The estimated loss of water by

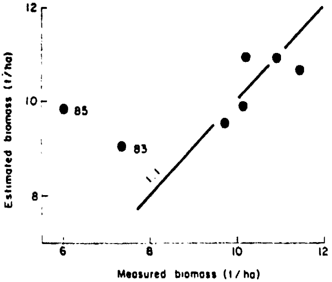


Figure 5. Biomass of sorghum as estimated from model (Appendix) and as measured at ICRISAT Center, 1981-87. Points for 1983 and 1985 identified.

runoff and percolation was 514 mm whereas 600 mm of runoff was recorded. Inspection of daily measurements showed that the model overestimated the amount of rain that could be stored when the top part of the profile was at field capacity and the lower part was less wet.

There were only two seasons - 1982 and 1985 - when radiation was lost in the sense that sunlight was intercepted by a stand whose water supply was exhausted. This implies that rainfall at the site was "assured" in the sense that water appears to have been available in the profile throughout the growing season for 8 years in 10.

A more complex story emerges when measurements of sorghum biomass are compared with estimates from the model (Fig. 5). In 5 of the years - those with maximum biomass production - agreement is excellent. Dry matter production is limited by the amount of radiation intercepted by foliage over a growing season whose length is determined by mean temperature and daylength. In 1985 - the very dry year - production is overestimated showing that the simple model does not handle the effects of drought properly, probably because roots cannot explore the whole profile when growth is inhibited by drought early in the season. The discrepancy in 1983 may be a consequence of an anomalous rainfall pattern: the season was dry initially, but heavy rain in the latter part of GS 2 and in GS 3 led to problems of harvesting.

Even including 1983, the standard deviation of estimates is only ±0.8 Mg/ha or about ± 10% of the mean dry weight, comparable with errors normally reported from final harvests (but not available in this instance). When the 1983 value is excluded, the deviation is only ±5%.

To summarize, the successful prediction of yield in years which are not extreme shows that the radiation component of the model worked well. Failure of the model in very dry or very wet years identifies processes which need to be taken into account in order to ascend the next step of the staircase: the allocation of dry matter to roots and shoots must be dealt with explicitly so that the uptake of water and nutrients by roots can be treated in the same detail as the interception of light by leaves, the coupling of nutrient and water budgets in the soil must be addressed, and a submodel for runoff and percolation must be incorporated.

Conclusion

The scheme described in this paper for relating crop production and transpiration to climate takes account of major effects of solar radiation, rainfall, and saturation deficit. Temperature determines the length of phenological stages and its influence on e, usually small, could be readily allowed for if it were needed. No account is taken of wind - an additional factor determining canopy surface temperature and evaporation rate which would be needed if the the true canopy/air vapor pressure deficit were to be used in place of D.

Despite these limitations, the scheme provides a logical link between climatology and crop physiology, coupling dry matter production and transpiration in a manner consistent with field experience, but overlooked in more sophisticated models which use independent algorithms to describe fluxes of carbon dioxide and water vapor.

References

Azam-Ali, S.N., P.J. Gregory, and J.L. Monteith. 1984. Effects of planting density on water use and productivity of pearl millet. Experimental Agriculture 20:215-224.

Azam-Ali, S.N., L.P. Simmonds, R.C.N. Rao, and J.H. Williams. 1988. Population, growth and water use of groundnut maintained on stored water, 3. Dry matter, water use and light interception. Experimental Agriculture (in press).

Day, W., B.J. Legg, B.K. Friend, A.E. Johnston, D.W. Lawlor, and W. de C. Jeffers. 1978. A drought experiment using mobile shelters. Journal of Agricultural Science, Cambridge, 91:599-623.

Day, W., D.W. Lawlor, and A.T. Day. 1987. The effect of drought on barley yield and water use in two contrasting years. Irrigation Science 8:115-130.

Huda, A.K.S. 1987. Simulating yields of sorghum and pearl millet in the semi-arid tropics. Field Crops Research 15:309-325.

Hughes, G., J.D.H. Keatinge and S.P. Scott. 1981. Pigeonpeas as a dry season crop in Trinidad, 2. Interception and utilization of solar radiation. Tropical Agriculture (Trinidad) 58:191-199.

Hughes, G., J.D.H. Keatinge, P.J.M. Cooper, and N.F. Dee. 1987. Solar radiation interception and utilization by chickpea crops in northern Syria. Journal of Agricultural Science, Cambridge 108:419-424.

Kiesselbach, T.A. 1916. Transpiration as a factor in crop production. University of Nebraska, Agricultural Experiment Station Bulletin 6.

Marshall, B., and R.W. Willey. 1983. Radiation interception and growth in an intercrop of pearl millet/groundnut. Field Crops Research 7:141-160.

Matthews, R.B., D. Harris, J.H. Williams, and R.C.N. Rao. 1988

The physiological basis for yield differences between four genotypes of groundnut in response to drought. I. Dry matter production and water use. Experimental Agriculture 24:191-213.

Monteith, J.L. 1986. Significance of the coupling between saturation vapour pressure deficit and rainfall in monsoon climates. Experimental Agriculture 22:328-338.

Monteith, J.L. 1988. Does transpiration limit the growth of crops or vice versa? Journal of Hydrology. (in press).

Monteith, J.L., and J. Elston. 1983. Performance and productivity of foliage in the field. p. 499-518. *In* J.E. Dale and F.L. Milthorpe (eds.) The growth and functioning of leaves. Cambridge: Cambridge University Press.

Muchow, R.C., and D.B. Coates. 1986. An analysis of the environmental limitations to yield of an irrigated grain sorghum. Australian Journal of Agricultural Science 37:135-148.

Mueller, M.J. 1982. Selected climatic data for a global set of standard stations for vegetation science. The Hague: W. Junk.

Ong, C.K., L.P. Simmonds and R.B. Matthews. 1987. Responses to saturation deficit in a stand of groundnut. 2. Growth and development. Annals of Botany 59:121-128.

Shibles, R.M., and C.R. Weber. 1966. Interception of solar radiation and dry matter produced by various soybean planting patterns. Crop Science 6:55-59.

Squire, G.R., B. Marshall, A. Terry, and J.L. Monteith. 1984a. Response to temperature in a stand of pearl millet. 6. Light interception and dry matter production. Journal of Experimental Botany 35:599-610.

Squire, G.R., P.J. Gregory, J.L. Monteith, M.B. Russell, and Piara Singh. 1984b. Control of water use by pearl millet. Experimental Agriculture 20:135-139.

Tanner, C.B., and T.R. Sinclair. 1983. Efficient water use in crop production. p. 1-27. *In* H.M. Taylor, W.R. Jordan, and T.R. Sinclair (eds.) Limitations to efficient water use in crop production. Madison: American Society of Agronomy.

Thornthwaite, C.W. 1958. Introduction to arid zone climatology. p. 15-22. *In* Climatology and Microclimatology. Paris:UNESCO.

Williams, W.A., W.G. Loomis and C.R. Lepley. 1965. Vegetative growth of corn as affected by population density. I. Productivity in relation to interception of solar radiation. Crop Science 5:211-215.

Wilson, D.R., and P.D. Jamieson. 1984. Models of growth and water use of wheat in New Zealand. p. 211-216. *In* W. Day and R.K. Atkin (ed.) Wheat growth and modelling. New York: Plenum Press.

Appendix

Model for daily water budget

The main assumptions used to construct Figure 4 were based on observations of sorghum growth at ICRISAT and are as follows:

(1) sowing was assumed whenever the rainfall after June 1 accumulated over 3 days exceeded 25 mm;
(2) the timing of successive growth stages (GS 1,2,3) was calculated from daily mean temperature using algorithms from Huda (1987);
(3) intercepted radiation (f) was assumed to be zero during GS 1 and 0.7 thereafter;
(4) transpiration was calculated from intercepted radiation using a coefficient of 0.2 mm of normalized water per MJ/m^2;
(5) evaporation from the soil was assumed to have a limit of 50 mm in GS 1 and 25 mm thereafter. The rate of evaporation decreased exponentially with time after the last rain and the time constant for the process, dependent on radiation, was about 5 days on average, and
(6) a maximum of 1 mm of water evaporated directly from the surface of foliage on every day with rain exceeding 1 mm.