Challenges in Dryland Agriculture — A Global Perspective

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Plenary Paper

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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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 tem...

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/m^2) 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/m^2 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≃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	6.5	Tanner and Sinclair (1983)
	Holland	1.5	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

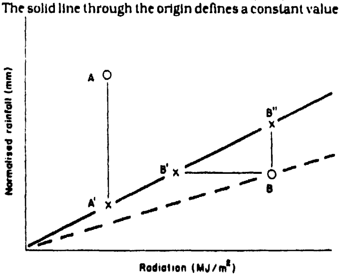

Figure 1. Points A and B represent coordinates for normalized rainfall and radiation at a station in 2 months. AA' is excess water, BB' is excess radiation, and BB" is irrigation used. Full line represents potential value of j and dashed line is possible actual value (see text).