Crop Growth in Semi-Arid Environments

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1626

Abstract

Methods are presented for analyzing growth and yield of crops when water is limiting and not limiting. Examples are given from collaborative research between ICRISAT and the University of Nottingham, UK, on pearl millet grown in a range of controlled and natural environments.

Résumé

Croissance des cultures en milieux semi-arides : *La communication présente les méthodes d'analyser la croissance et le rendement des cultures sous conditions hydriques à la fois adéquates et déficitaires. Des exemples sont tirés des études effectuées en collaboration entre l'ICRISAT et l'Université de Nottingham en Angleterre, sur le mil cultivé dans une série d'environnements allant de naturel à contrôlé.*

Introduction

The semi-arid tropics is a region distinguished by large seasonal differences in important environmental factors. Rainfall is the dominant factor and influences to varying degrees solar radiation, air and soil temperatures, and the saturation vapor pressure deficit of the atmosphere (D). Generally, crops are grown during two contrasting seasons: the rainy season, when at least part of the soil profile is periodically rewetted by rain; and the postrainy season, when there is very little rainfall and the crop usually grows on a store of water in the soil. Of the other variables, saturation deficit changes most and is most tightly coupled to rainfall. It is unusual to find large saturation deficits when rain falls frequently and vice versa. However, the coupling between rainfall and D is broken for isolated patches of irrigated land, which have little effect on the atmosphere around them.

At ICRISAT Center, where mean annual rainfall is 800 mm, mean monthly D ranges from 1-4 kPa, mean daily maximum temperature from 20-30°C, and insolation from 15-24 MJ $m^{-2}d^{-1}$. In certain other areas, daily mean temperature may rise above 30°C and saturation deficits above 4 kPa (Sivakumar et al. 1984), but these are probably extreme conditions during growing seasons.

In this review, growth and yield are examined in relation to two sets of conditions within the ranges experienced at Hyderabad, India (latitude 18°N). In the first set, rainfall is frequent, and consequently soil moisture is often near field capacity and D is 1.0-1.5 kPa (10-15 millibar). In the second, the crop is sown on a soil profile near field capacity; thereafter rainfall is sparse or absent, and D is generally

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Submitted as CP 375 by the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT).

ICRISAT (International Crops Research Institute for the Semi-Arid Tropics). 1987. Proceedings of the International Pearl Millet Workshop, 7-11 April 1986, ICRISAT Center, India. Patancheru, A.P. 502 324, India: ICRISAT.

much larger, about 2-4 kPa. Different environmental factors are limiting in these different circumstances, and they are examined separately for convenience. (Where appropriate, growth and yield are also considered in relation to the independent effects of D itself).

Examples are given from work mainly on pearl millet (*Pennisetum americanum*) and groundnut (*Arachis hypogaea* L.) which forms part of a collaborative research program between ICRISAT and the Department of Physiology and Environmental Science at Nottingham University, UK. The central analysis compares five stands of the pearl millet hybrid BK 560 grown in conditions ranging from the controlled environment greenhouses at Nottingham to very dry, postrainy seasons at Hyderabad and Niamey, Niger (latitude 14°N) (Table 1).

Terms used in this paper, and units, where appropriate, are defined as follows:

- e = amount of dry matter formed per unit radiation intercepted (conversion coefficient) (g MJ^{-1})
- f = fraction of mean daily insolation intercepted by the canopy
- lv = root length per unit soil volume (cm cm^{-3})
- p = fraction of total dry matter allocated to an organ
- q = amount of dry matter produced per unit of water transpired (g K^{-1})
- t = time (d)
- D = saturation vapor pressure deficit (kPa)
- E = amount of water that the crop extracts from the soil (kg m^{-2})
- K = extinction coefficient
- L = leaf area index (area of foliage per unit ground area)
- Lm = maximum leaf area index
- S = total radiation (daily mean) (MJ m^{-2})
- T = mean daily temperature (°C)
- Tb = base temperature (°C)
- W = dry matter production (kg m^{-2})
- α = water extraction front velocity (cm d^{-1})
- θ_1 = thermal duration from sowing to 0.5 f (°Cd)
- θ_2 = thermal duration from sowing to maturity (°Cd)

Dry Matter Production When Water is Not Limiting

The dry matter (W) produced by a stand growing on moist soil can be represented by

$$W = Sfet \quad (1)$$

This form of analysis is appropriate when radiation is limiting, either because the foliage is too sparse to intercept all the available radiation or because it exists for a small fraction of the year.

Interception of Solar Radiation

The area of foliage, represented by leaf area index (L), most strongly determines f at any time. For many tropical cereals and legumes grown at typical narrow row spacings, f can be related to L by an extinction coefficient (K) that depends mainly on the orientation and distribution of foliage. The value of K may change slightly with time if the organs intercepting most of the radiation change their orientation, or if the foliage becomes more randomly

Table 1. Stands of pearl millet.

Stand	Location	Year	Season	Daily maximum D (kPa)	Soil water	Planting density (m^{-2})	Reference
I	Nottingham	1979	-	1.4	W[1]	28.6	Squire et al. 1984b
II	Hyderabad	1978	Rainy	1.5-2.0	W	22.2	Reddy & Willey 1981 Marshall & Willey 1983 Gregory & Reddy 1982
III	Hyderabad	1977/78	Postrainy	2.4	W	26.6	Gregory & Squire 1979
IV	Hyderabad	1977/78	Postrainy	2.4	D[2]	26.6	Squire et al. 1984a
V	Niamey	1980/81	Postrainy	4.0	D	11.5	Azam-Ali et al. 1984a, b

1. W = rainfed or frequently irrigated.
2. D = irrigated to field capacity at sowing, and then irrigated no further.

oriented as the canopy closes but generally K may be treated as a constant for a given species and cultivar grown in wet conditions

The total amount of radiation intercepted by a stand also depends on the period over which an intercepting surface is present The extent and size of this surface was examined in terms of f for four of the stands of pearl millet shown in Table 1 which began intercepting radiation at about 10 days after sowing (DAS), and were harvested at about 75 DAS (Fig 1) Stand I intercepted most radiation and grew in a humid atmosphere and moist soil in a glasshouse with controlled environment at Nottingham It achieved a maximum L of about 6 corresponding to a maximum f for total radiation (S) of 0 85 (0 93 for photosynthetically active radiation) Mean f was 0 34 between sowing and anthesis (45 DAS) and 0 83 S thereafter From sowing to maturity mean f was 0 54 averaged over a year it was 0 11

se values of f were achieved by stands for emergence was successful for which the canopy expanded rapidly in the absence of drought and nutrient deficiency and for which there was negligible senescence after anthesis Such successful emergence and rapid expansion of the canopy have also been observed in wet conditions in the semi-arid tropics but there leaf area usually decreases as a result of senescence to reduce f by about 10% after flowering (Reddy and Willey 1981 Alagarswamy and Bidinger 1985) Fractional interception may be reduced considerably more than this in the field by a shortage of nutrients but there is a dearth of reliable quantitative information on such effects when water is also not limiting

In a simple model of light interception by pearl millet canopies well supplied with water and nutrients Squire et al (1984b) showed mean f to depend on three main factors (a) maximum f (b) the time from sowing to the time when f achieved half its maximum value and (c) the time from sowing to maturity Work in controlled environments at Nottingham showed that variation in solar radiation

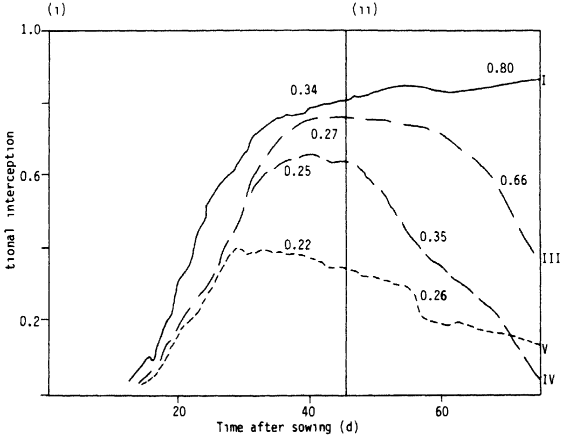


Figure 1. Fractional interception of total solar radiation (f) for four stands of pearl millet (BK 560) (i) before and (ii) after anthesis. Numbers I-V refer to crops in Table 1 Numbers above each curve show mean f.

over the range that occurs in the field, had little effect on any of these factors, but temperature strongly affected (b) and (c), although it had little influence on (a). Temperature governed (b) through its control of emergence (Mohamed et al. 1986), initiation of leaf primordia (Ong 1983a), and expansion of leaf laminae (Squire and Ong 1985), the rates of which increased linearly with temperature above a common base of 10°C. Consequently, the period between sowing and when f was half its maximum could be represented by a thermal duration (θ_1), which is an integral of time and temperature above an appropriate base (Squire et al. 1984a). Most of the period between sowing and final harvest was also strongly governed by temperature (Fussell et al. 1980, Ong 1983b), and was represented by a second thermal duration (θ_2). As temperature increases, the duration of the foliage (θ_2-θ_1) decreases and the canopy intercepts less radiation whereas, if temperature decreases, the canopy grows more slowly over a longer period, and therefore intercepts more radiation.

Conversion of Intercepted Radiation

The conversion coefficient (e) is the weight of dry matter produced per unit of solar radiation intercepted. In a range of moist environments including

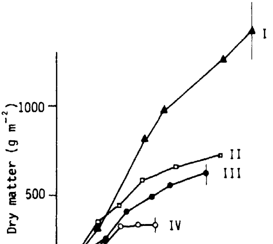


Figure 2. Dry matter production (above ground) and intercepted total solar radiation for five stands of pearl millet (cv. BK 560). Table 1 gives details of crops.

northern Australia (Begg 1965), Hyderabad in the rainy season (Reddy and Willey 1981, Marshall and Willey 1983, Alagarswamy and Bidinger 1985), and the controlled environments at Nottingham (Squire et al. 1984b), e measured over several weeks was around 2.5 g MJ^{-1} of the total radiation (for further discussion see Ong and Monteith 1985). This maximum value of e was achieved from sowing to harvest only by stand I (Fig. 2). At Hyderabad, this maximum was measured only between sowing and anthesis, and was reduced thereafter by senescence as shown by stand II. Senescence clearly had a considerable effect on productivity, but it is not known why it was absent in stands grown at Nottingham (Squire et al. 1986).

Unlike f, e was only weakly affected by temperature over the range at Hyderabad, although it decreased at temperatures below 20°C (Fussell et al. 1980, Squire et al. 1984b).

Synthesis

In moist environments, where temperature and solar radiation are the main variables affecting productivity, equation 1 can be rewritten as

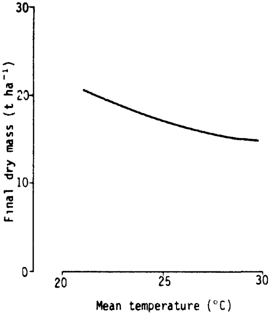
$$W = Se\,(1 - \exp\{- KLm\})\,[(\theta_2 - \theta_1)/T)] \quad (2)$$

(Squire et al. 1984b). As e and Lm are only weakly affected by temperature, W decreases as the duration of the canopy decreases with increasing temperature. Figure 3 shows the modeled response of maximum W to mean temperatures between 20-30°C for stands of pearl millet using maximum values of e, Lm, θ_1, and θ_2 as given by Squire et al. (1984b). Such heavy crops have been grown in the controlled environments at Nottingham and occasionally in very moist conditions in the tropics (Begg 1965, Enyi 1977); but crops of these or comparable cultivars in rainy seasons in the semi-arid tropics are at most h of the mass shown in Figure 3. One of the causes of this is the effect of senescence on e referred to earlier, but other causes may be limiting effects of other environmental factors such as saturation deficit or nutrient deficiency.

Limiting Factors

Saturation Deficit

There is now much evidence from work in controlled environments that the potential transpiration rate,



I _ re 3 Modeled relation between mean temperature and final dry mass of pearl millet BK 560

as represented by the saturation vapor pressure deficit (D), has important effects on dry matter production, even on plants growing in moist soil Saturation deficit affects growth by reducing the rate of leaf expansion and by reducing leaf conductance and thereby the rate of photosynthesis (Schulze and Hall 1982)

There is little direct evidence on which to assess the effect of D by these mechanisms on productivity of stands in the field Work in controlled environments suggests that both f and e may decrease in response to increasing D by about 10% per kPa (Nagarajah and Schulze 1983, Squire et al In press) At a given site in the semi-arid tropics, D is closely coupled to rainfall, but D also varies between sites over a range of about 2 kPa and may therefore affect productivity between different sites during the rainy season to an extent similar to that of temperature shown in Figure 3 Effects of D may be even larger on irrigated crops exposed to drier air

Nutrient Deficiency

The extent to which dry matter production is limited by nutrient deficiency is shown by the very large yield increases in response to fertilizer, both in rainy and dry postrainy seasons (Kanwar et al 1984, Huda et al 1985) However, there is little systematic information on how fertilizer affects interception and conversion of solar energy Work on temperate cereals shows that the main effect of applying nitrogenous fertilizer is to increase the rate of leaf expansion and therefore to increase the seasonal mean value of f In contrast the conversion coefficient is independent of nutrient status over a wide range These responses are generally consistent with those for pearl millet found by Coaldrake and Pearson (1985a and b) but the direct response of e to nutrients has still to be investigated

Dry Matter Production When Water is Limiting

Shortage of water in the soil may reduce the rate of leaf expansion and therefore delay formation of the canopy and reduce its size The shortage may also reduce (1) the effective duration of the crop in that the store of water may be used before the crop has reached maturity and (2) the rate of photosynthesis and thereby e through effects on leaf physiology These effects of water shortage (usually in combination with dry air) reduced f e, and dry matter production in postrainy seasons at Hyderabad and Niamey compared with moist environments considered earlier (Figs 1 and 2) Productivity over 75 d fell from 1 2 kg m $^{-2}$ to 0 15 kg m $^{-2}$ a factor of eight as the climate became drier

It is possible to examine such a range of productivity in terms of the factors in Equation 1 but for that analysis it is necessary to know how the balance between demand for water by the atmosphere and the supply of water from the soil controls water and turgor potentials in the plant and how these, in turn limit physiological processes such as photosynthesis and leaf extension At present, this analysis is impossible, simply because much of the information is fragmentary It is more feasible (and instructive) to analyze productivity in terms of the limiting factor itself the supply of water In this analysis, dry matter production (W) depends on two factors the amount of water that the crop extracts from the soil (E), and the amount of dry matter produced per unit of water extracted (q)

$$W = Eq \quad (3)$$

Extractable Water

The total water supply in the soil depends on physical factors In many soils of the semi-arid tropics, the

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