

## Response to fertilizer nitrogen and water of post-rainy season sorghum on a Vertisol. 1. Biomass and light interception

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### SUMMARY

In parts of peninsular India, sorghum (*Sorghum bicolor* L.) is grown during the dry season using water stored in the root zone. The optimum application of nitrogen is difficult to assess because no comprehensive model exists for the interaction of water and N. To explore this system as a basis for modelling in the first instance and ultimately for better management, sorghum (cv. SPH-280) was grown in the post-rainy season at ICRISAT (Andhra Pradesh, India) with and without irrigation and at six rates of nitrogen from zero to 150 kg/ha applied before sowing. The biomass of top components was measured weekly and of roots every 2 weeks. Interception of solar radiation was monitored continuously in all treatments.

Leaf expansion was strongly influenced both by water and by N, whereas specific leaf area was almost independent of treatment. In the irrigated treatment, the Biomass Radiation Coefficient ( $e$ ) for the main growth period was almost independent of N application at 1.3–1.4 g/MJ and was also independent of leaf N. In consequence, the main source of differences in yield was a decrease in radiation interception with decreasing N. In contrast, without irrigation, biomass, yield,  $e$  and leaf N were all maximal at 60 kg/ha N.

At 33 days after emergence (DAE), root mass was almost independent of N whether water had been applied or not, but was somewhat smaller with irrigation. Later, root, leaf, and panicle mass all responded to N and to water, but stem mass was unresponsive to N with irrigation. There was evidence of translocation from stem to grain in most treatments. With irrigation, a maximum grain yield of 4.8 t/ha was obtained at 150 kg/ha N and without irrigation the maximum was 3.2 t/ha at 90 kg/ha.

### INTRODUCTION

In parts of peninsular India where the monsoon is unreliable, sorghum (*Sorghum bicolor* L.), is sown on Vertisols (deep black clay soils) at the end of the rainy season. Thereafter, it grows on water stored in the soil profile, sometimes supplemented by small amounts of rain. Grain yields on farmers' fields are usually < 1 t/ha and only occasionally > 3 t/ha without irrigation (Tandon & Kanwar 1984). Sorghum rarely responds to nitrogen (N) applied during the post-rainy season, apparently because of very restricted extraction from soil near the surface which dries rapidly and is rarely rewetted. Because

relatively little is known about the direct impact of drought compared with its indirect effects on the mobility of nutrients, fertilizer practice is based entirely on empirical conclusions drawn from field experience specific to site and season.

In common with many other cereals, most previous work on sorghum has examined responses either to a nutrient in the absence of drought or to a shortage of water following the application of fertilizer. For example, in detailed comparisons by Muchow (1988*a, b*) and Muchow & Davis (1988) of sorghum and maize responding to nitrogen in a dry environment, all treatments received 40 mm of water every 4 days. Lafitte & Loomis (1988) measured the response of N of sorghum stands that were furrow irrigated every 11–14 days.

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Because the interaction of water and nitrogen has received little attention, attempts to find more effective ways of applying fertilizer in the post-rainy season have made slow progress. There is particular need for a better understanding of how rates of water and N uptake are related, on the one hand, to the extension of roots which provide a 'supply' to the rest of the plant and, on the other hand, to the growth of shoots which determine a 'demand'.

To establish values for the major parameters that determine resource capture by shoots and roots, a multidisciplinary experiment was designed with two main objectives: (i) to measure and compare the investment of biomass in foliage and roots in stands receiving different amounts of nitrogen and water; and (ii) to interpret these differences in terms of resource capture and the efficiency with which resources were used to generate biomass and yield.

This paper is primarily concerned with the production of dry matter (DM) by shoots in relation to the capture of light by leaves. A sequel describes the uptake of water by root systems (Piara Singh *et al.* 1998). Both papers provide sets of nitrogen-dependent parameters that can be used in models of crop growth such as the RESCAP model initiated at ICRISAT by Monteith *et al.* (1989) and subsequently developed in the PARCH model of Bradley & Crout (1993).

## SITE AND SYSTEM

### *Environment and measurement*

The experiment was conducted from October 1988 to February 1989 at the ICRISAT Centre, Patancheru, near Hyderabad, India (17.5 °N, 78.5 °E, 545 m altitude) on a Vertisol (Kasireddipally series, very fine, Montomorillonite, Isohyperthermic Typic Pellustert). A cover crop of maize was grown on the experimental site during the preceding rainy season in an attempt to establish a uniformly low background of N across the whole site. Soil samples collected after harvesting the maize were analysed to provide the information in Table 1 which shows that extractable N was uniform below 15 cm and relatively large in relation to normal demand.

Records of climate at the ICRISAT Meteorological Station, located *c.* 600 m from the site display a characteristic decline in temperature and radiation until the winter solstice followed by a rise (Table 2). The post-rainy season in the Deccan is usually very dry and only 9 mm of rain was recorded between the emergence and harvesting of the sorghum. Responses to water and nitrogen reported for this experiment in a single year may therefore be extrapolated to other seasons but not necessarily to other sites where rooting depth, for example, could be constrained by compaction.

The cultivar SPH-280 was grown at two rates of water (main plot treatments) and six N rates (subplots) with three replicates of all treatments. The water regimes were (i) dry: soil profile recharged to field capacity by irrigation at sowing with no irrigation thereafter; and (ii) irrigated: soil profile recharged to field capacity at sowing followed by irrigation estimated to restore the profile to field capacity in Weeks 1, 3, 5 and 8 after emergence. The total amount of water which was supplied through perforated pipes was therefore 150 mm.

After preparation of a good seedbed, nitrogen was applied uniformly as ammonium sulphate along with phosphorus (single superphosphate at 20 kg/ha P) and zinc (zinc sulphate at 10 kg/ha Zn). The six N rates were 0, 30, 60, 90, 120 and 150 kg/ha N, hereafter designated N0, N30, etc. The fertilizer was broadcast and mixed with a rotovator before sowing seed in 60 cm rows with a tractor on 29 October and the site was irrigated on the following day to bring the profile to field capacity.

Figure 1 gives subplot dimensions, sampling details, and the position of access tubes for neutron probes. Growth was monitored by harvesting plants every week from a 0.96 m<sup>2</sup> area that included elements of two rows both above and below ground. The material was later separated into stem, leaf sheath, leaf blade, panicle and root. The green leaf area of each sample was determined using a leaf area meter (Li-Cor, model 3100) and all components were then dried in an oven at 70 °C for 3 days before weighing. These samples were ground for chemical analysis. Grain and

Table 1. *Soil chemical characteristics as function of depth at field site*

Depth (cm)	pH (1:2 soil:water)	EC dS/m (1:2 soil:water)	Organic carbon (%)	Extractable nutrients (mg/kg)						
				N		P	K	Zn	Fe	Mn
				(NH <sub>4</sub> )	(NO <sub>3</sub> )					
0-15	8.2	0.17	0.49	7.7	7.3	3.3	161	1.4	10.1	19.1
15-60	8.3	0.16	0.40	6.4	4.1	1.8	137	0.8	9.4	14.1
60-120	8.3	0.22	0.31	6.5	6.1	1.1	162	1.4	10.2	16.0
120-150	8.3	0.28	0.76	6.1	7.7	1.3	193	2.0	9.7	20.1
150-210	8.3	0.29	0.65	6.4	7.2	1.2	197	2.1	8.5	23.3

Table 2. Climatological record at ICRISAT meteorological station, 4 November 1988–22 February 1989

Days after emergence	Mean of maximum and minimum screen temperature (°C)	Mean vapour pressure deficit (kPa)*	Mean solar irradiance (MJ/m <sup>2</sup> per d)	Precipitation (mm)
1–10	25.4	2.04	17.0	2.3
11–20	24.0	2.41	21.7	0.0
21–30	23.4	2.37	20.1	0.0
31–40	23.6	2.23	17.3	0.0
41–50	20.6	2.05	18.6	0.0
51–60	21.1	2.08	16.5	0.0
61–70	19.8	1.88	16.0	0.0
71–80	20.1	1.73	13.1	6.7
81–90	20.7	1.87	16.6	0.0
91–100	20.4	1.83	16.3	0.0
101–110	20.6	1.92	17.7	0.0
1–28 (GS1)	24.3	2.25	19.7	2.3
29–72 (GS2)	21.4	2.07	17.2	0.0
73–109 (GS3)	20.5	1.82	15.9	6.7

\* Mean for observations at 07.00 and 14.00 h Indian Standard Time.

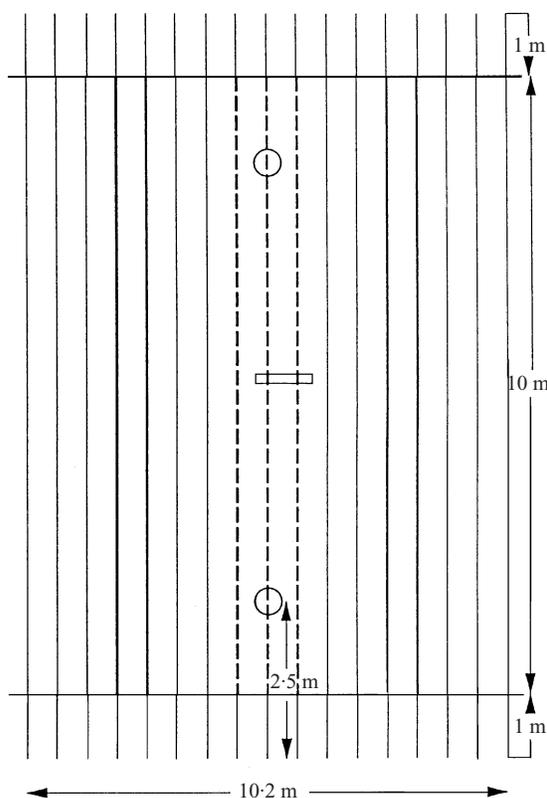


Fig. 1. Plan of subplots: sequential sampling (—), final harvest (---), neutron access tube (○), tube solarimeter (□). Row spacing 0.6 m, number of rows 17.

Table 3. Mean coefficients of variation (%) for biomass of sorghum cv. SPH-280 at three stages of development

Days after emergence	33	68	95
Leaf	8.7	5.0	6.7
Stem	10.5	6.7	8.1
Root	30.0	17.0	16.3
Panicle	—	11.3	9.3

Table 4. Timing of development of sorghum cv. SPH-280 in days from emergence (mean and range)

	Panicle initiation	50% flowering	Hard dough	Physiological maturity
Irrigated	28 (27–29)	72 (71–77)	96 (96–99)	109 (108–112)
Dry	27 (26–28)	70 (69–74)	94 (93–98)	105 (104–107)

stover yield were computed from final harvests of 18 m<sup>2</sup> taken from each subplot and dried to constant weight at 70 °C.

Coefficients of variation were evaluated for measurements of biomass at three stages of development and mean values across all rates of N are in Table 3.

In all treatments, the interception of total solar radiation was monitored continuously with tube solarimeters installed above and below the canopy. Soil moisture was monitored every week to a depth of

1.65 m by the neutron-scattering method. Details of the analysis are given by Piara Singh *et al.* (1998).

#### Crop history

Seedlings emerged on 4 November and were thinned 1 week later to leave 16 plants/m<sup>2</sup>. Timely plant protection avoided damage throughout growth. By the end of Growth Stage 1 (GS1), irrigation had delayed panicle initiation by *c.* 1 day and the remaining stages of development by 3–4 days, presumably as a response to lower temperature (Table 4). In the lowest and highest N treatments, panicle initiation was *c.* 1 day later than in intermediate treatments. In the N0 treatment, flowering (end of GS2) was delayed by 5 days, hard dough stage by 3 days and physiological maturity (end of GS3) by 4 days.

High winds lodged plants at the hard dough stage (95 days after emergence (DAE)) and blew away many dead leaves. This problem was most severe in irrigated plots receiving > 90 kg/ha N and we have therefore not reported biomass measurements other than grain after 95 DAE.

#### LEAVES AND LIGHT

Figure 2 shows that leaf expansion responded strongly both to supplementary irrigation and to N up to the highest rate of application. In all treatments, green leaf area index increased rapidly from *c.* 20 DAE to a maximum at *c.* 55 DAE, about 2 weeks before anthesis, and then declined almost as rapidly until the last harvest. Both in the irrigated and in the dry treatments, the decline was markedly slower in the

unfertilized plots which, at final harvest, carried a slightly larger leaf area than those that had received nitrogen. We attribute this response partly to the conservation of water in plots which had a smaller leaf area initially (as frequently observed during the post-rainy season at this site); and partly to the conservation of N in the leaves of plants with little grain. In general, the decline during GS3 was much faster than reported for irrigated sorghum by Muchow (1988*a*).

In the N150 treatments, interception of solar radiation (Fig. 3) reached 90% in GS2 with irrigation and ranged between 80 and 90% even without. A similar pattern of interception was reported for the sorghum cv. CSH-6 grown during the rainy season at this site by Sivakumar & Huda (1985). Interception by stands in the irrigated N0 treatment was particularly poor, presumably because much mineralized N was lost by leaching.

Specific leaf area (SLA) was virtually independent of N and water (Fig. 4), decreasing from *c.* 40 m<sup>2</sup>/kg at 10 DAE to an almost constant value of *c.* 20 m<sup>2</sup>/kg from 40 DAE onwards. Differences in leaf area between treatments therefore represent differences in the allocation of DM rather than in leaf expansion per unit of allocation. In contrast to SLA, nitrogen per unit leaf area or leaf nitrogen density (LND) increased with N application whether water was applied or not. As the trend with time was similar at all N rates, only mean values are shown in Fig. 5. LND increased from the first harvest at 12 DAE to a maximum at *c.* 27 DAE and decreased at an almost constant rate throughout reproductive growth. Towards the end of GS3, there was substantially more N

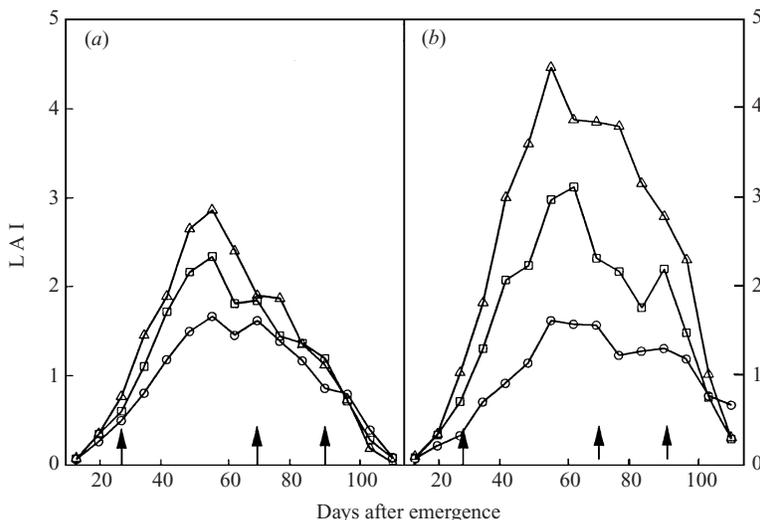


Fig. 2. Leaf area index (LAI) of a sorghum crop as a function of time and N rate: 0 (○), 30 (□), 150 (△) kg/ha N on (a) unirrigated and (b) irrigated plots. (†) Growth stages end/begin (see text).

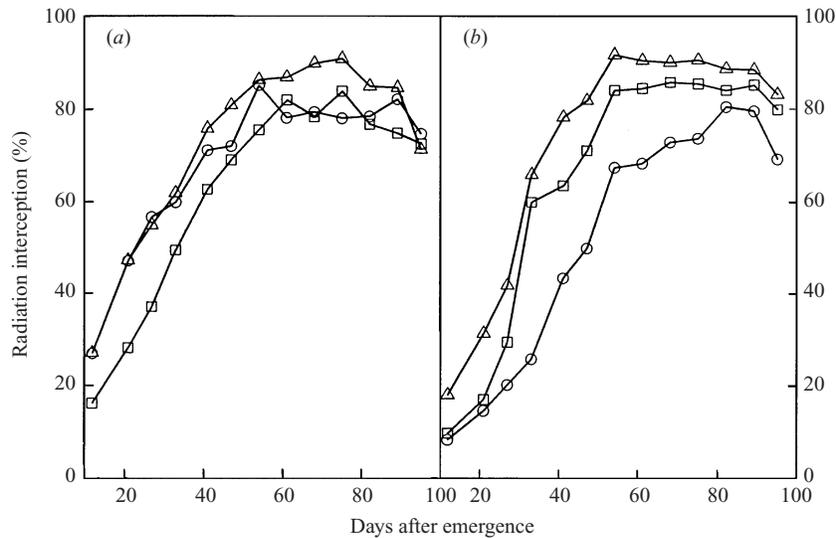


Fig. 3. Interception of solar radiation (%) by a sorghum crop as function of time and N rate: 0 (○), 30 (□), 150 (△) kg/ha N on (a) unirrigated and (b) irrigated plots.

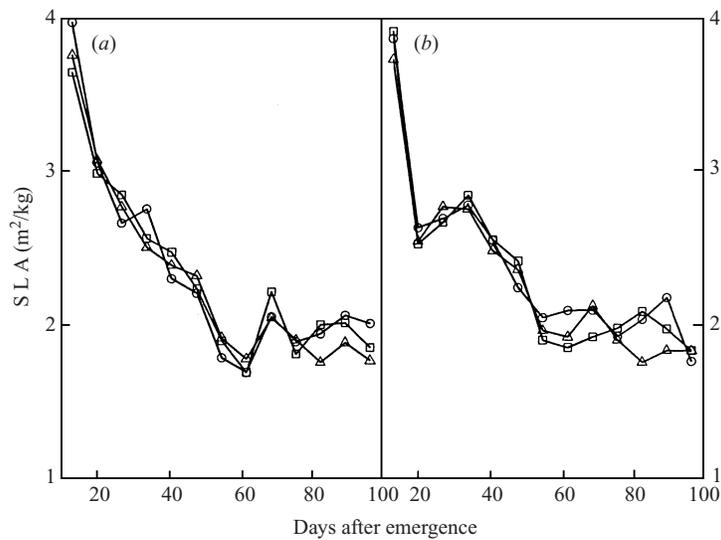


Fig. 4. Specific leaf area (SLA,  $\text{m}^2/\text{kg}$ ) of a sorghum crop as function of time and N rate: 0 (○), 30 (□), 150 (△) kg/ha N on (a) unirrigated and (b) irrigated plots.

in the leaves of plants that had been irrigated, especially at the higher rates of N.

Because SLA was virtually independent of treatment, the trend with time of nitrogen concentration (g N per g leaf) was almost identical to the trend in LND.

## TOTAL BIOMASS

### *Crop growth rate*

The production of biomass responded positively to water as well as to N at almost all rates of N (Fig. 6). Exceptionally, biomass in the N0 treatment was

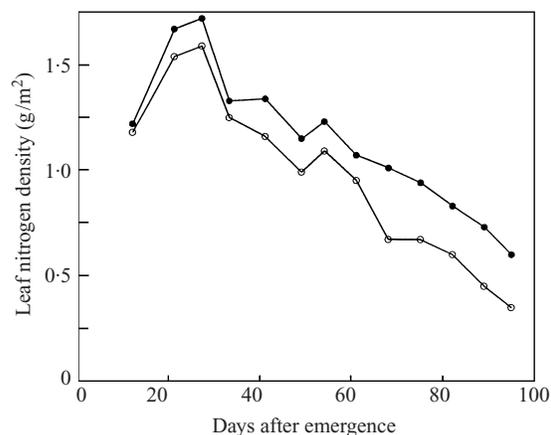


Fig. 5. Leaf nitrogen density ( $\text{g}/\text{m}^2$ ) of a sorghum crop as function of time averaged across all rates of N on unirrigated ( $\circ$ ) and irrigated ( $\bullet$ ) plots.

decreased by irrigation, consistent with the anomalous interception of radiation already noted. Corresponding values of the mean crop growth rate (CGR) during the main growth period (Table 5) were obtained by regressing total biomass on time for harvests between 41 and 95 DAE inclusive, the period in which the crop growth rate appeared to be effectively constant for most treatments. The range of CGR was small when the zero N treatment was excluded; *c.*  $15 \text{ g}/\text{m}^2$  per day without and  $20 \text{ g}/\text{m}^2$  per day with irrigation. The latter figure is close to the fastest whole-season growth rates recorded for both sorghum and millet at this site (Monteith 1987).

#### Biomass and radiation

To explore biomass accumulation as a function of radiation interception, total biomass was regressed against accumulated intercepted radiation for two periods over which the CGR appeared to be almost constant (41–68 DAE and 41–95 DAE). The mean slopes for the two periods were similar but were more consistent across treatments for the longer period with more observations. For each treatment, interception was measured throughout the season with solarimeters in fixed positions to avoid damage to the crop. Successive measurements were therefore not independent, as formal analysis requires. Assuming

Table 5. Maximum crop growth rate (CGR) ( $\text{g}/\text{m}^2$  per day) estimated from linear regression of biomass on time from 41 to 95 days (9 harvests) and solar radiation interception over this period ( $S_i$ ) ( $\text{MJ}/\text{m}^2$  per day)

Treatment	N (kg/ha)					
	0	30	60	90	120	150
Dry						
CGR	12.0	13.3	15.0	16.2	15.7	15.8
S.E. ( $\pm$ )	1.00	0.88	1.10	1.81	1.13	0.98
$S_i$	14.4	12.9	13.6	13.3	15.1	16.6
Irrigated						
CGR	13.4	19.5	20.8	21.2	21.8	24.4
S.E. ( $\pm$ )	1.30	1.79	1.60	1.33	1.17	1.66
$S_i$	13.0	13.8	14.8	15.7	15.9	17.2

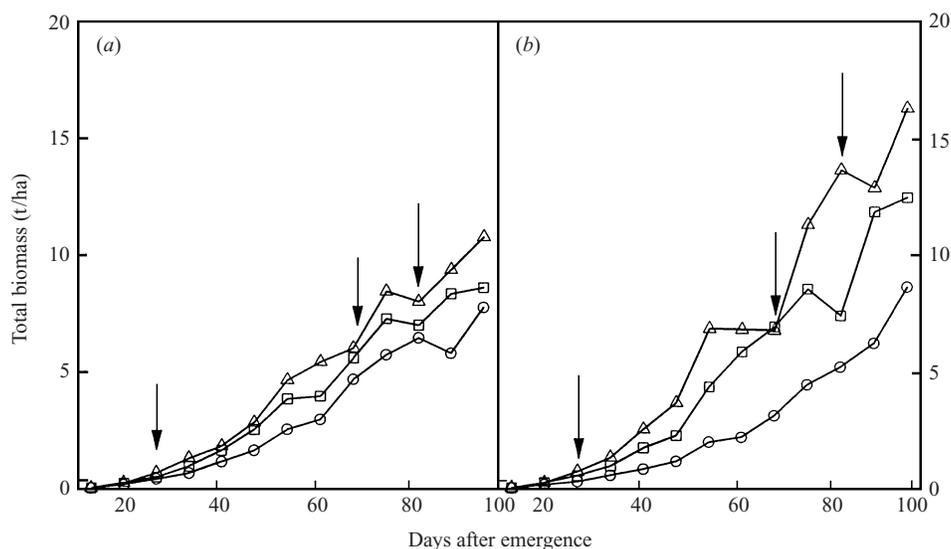


Fig. 6. Total biomass ( $\text{t}/\text{ha}$ ) of a sorghum crop as function of time and N rate: 0 ( $\circ$ ), 30 ( $\square$ ), 150 ( $\triangle$ ) kg/ha N on (a) unirrigated and (b) irrigated plots. ( $\downarrow$ ) Initiation of growth stage.

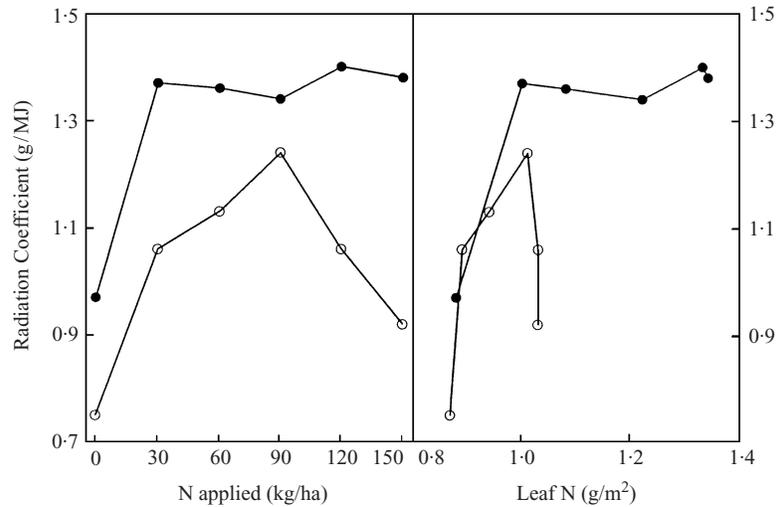


Fig. 7. Biomass Radiation Coefficient ( $e$ ) of a sorghum crop for the period 47–95 DAE as function of (a) N rate and (b) leaf nitrogen density averaged over the same period on irrigated (○) and unirrigated (●) plots.

independence, however, the coefficient of variation of  $e$  fell in the range 3–6%.

In Fig. 7, values of  $e$  are plotted against applied N and leaf nitrogen density. In contrast with the strong correlation between  $e$  and LND reported by Muchow & Davis (1988),  $e$  in the irrigated plots (excluding the N0 treatment) was close to a mean value of 1.37 g/MJ for a range of 1.0–1.4 g/m<sup>2</sup> in LND. Sivakumar & Huda (1985) reported the same value for cv. CSH-6 grown in the rainy season at this site. Without irrigation,  $e$  was maximal at 90 kg/ha N corresponding to an LND of c. 1 g/m<sup>2</sup>.

#### Differential analysis

Biomass  $W$  on day  $p$  may be expressed as:

$$W(p) = e(p) \sum_{n=1}^p [f(n)S(n)] \quad (1)$$

where  $e(p)$  is the mean over  $p$  days of the Biomass Radiation Coefficient obtained by correlating biomass against accumulated intercepted radiation over all harvests.  $S(n)$  is the daily total of incident solar radiation on day  $n$ , and  $f(n)$  is the corresponding fraction of intercepted radiation. Because there was little change in daily irradiance while  $f(n)$  was increasing,  $f(n)S(n)$  can be replaced by  $\bar{S}(p)f(n)$  where  $\bar{S}(p)$  is the daily mean irradiance over  $p$  days. In order to quantify the response to N of (i) the mean efficiency with which incident radiation was intercepted throughout the season and (ii) the mean efficiency with which intercepted radiation was used to syn-

thesise biomass, it is appropriate to take natural logarithms of both sides of Eqn (1):

$$\ln [W(p)] = \ln e(p) + \ln \bar{S}(p) + \ln \Sigma f(n) \quad (2)$$

If the symbol  $\delta$  is used to represent the difference between the value of each term in Eqn (2) for a specified treatment and for the irrigated N150 treatment taken as a reference, then the equation can be written in the finite difference form:

$$\delta\{\ln [W(p)]\} = \delta\{\ln e(p)\} + \delta\{\ln \Sigma f(n)\} \quad (3)$$

(with no term in  $\bar{S}$  because this quantity is the same for all treatments). The two terms on the right hand side of the equation represent differences in efficiency and in interception respectively.

If yield  $Y$  is expressed as the product of  $W$  and the harvest index  $h$ , Eqn (3) can be further expanded to

$$\delta\{\ln Y(p)\} = \delta\{\ln e(p)\} + \delta\{\ln \Sigma f(n)\} + \delta\{\ln h(p)\} \quad (4)$$

Figure 8 displays this analysis for measurements of biomass accumulation and radiation interception from emergence to 95 DAE. The cumulative deficit of  $e$ ,  $f$  or  $h$  with respect to the irrigated N150 treatment can be read either in terms of natural logarithms (left-hand axis, linear scale) or of percentages (right-hand axis, exponential scale). The loss of conversion efficiency for light is represented by the distance between the upper horizontal axis ( $\ln x = 0$ ) and the full lines below it; the loss of interception is given by the distance between full and hatched lines; and the loss of harvest index by the distance between hatched and dotted lines.

In the irrigated treatment, the smallest rate of

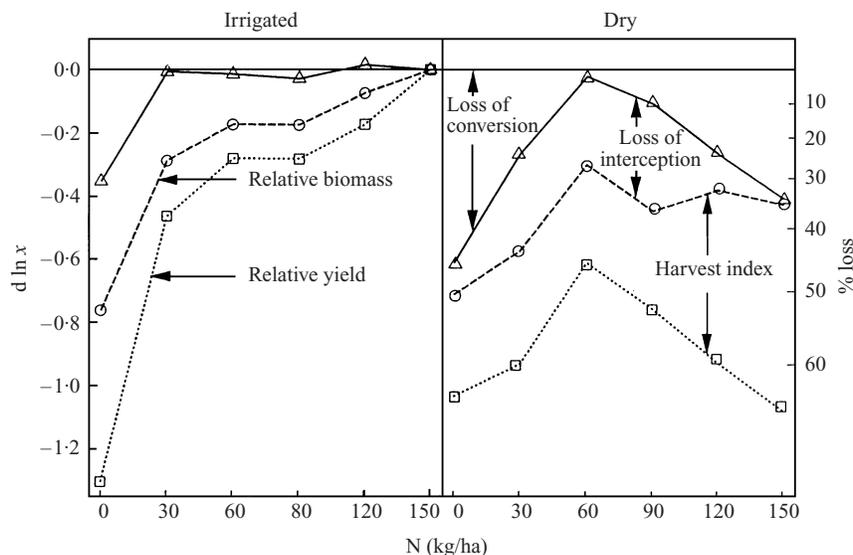


Fig. 8. Differences in Biomass Radiation Coefficient ( $e$ ), radiation interception ( $f$ ), and harvest index ( $h$ ) of a sorghum crop relative to values for the irrigated 150 kg/ha N treatment, plotted according to terms on right side of Eqn (4) (see text). First term ( $\Delta$ ); first two terms ( $\circ$ ); all three terms ( $\square$ ).

30 kg/ha N was sufficient to bring  $e$  to its maximum value. In contrast, interception increased with N up to the maximum rate as did maximum yield. In the dry treatment, efficiency was maximal at 60 kg/ha N but interception increased up to 150 kg/ha N. There was also a compensating increase in harvest index as the N rate fell from 150 to 90 kg/ha. It is likely that the index was constrained by lack of N at < 60 kg/ha and by lack of water at > 90 kg/ha as a consequence of the more profligate use of water by an excess of foliage early in the dry season already mentioned.

#### ALLOCATION OF BIOMASS

To compare the dependence on N for individual organs, the biomass of each was expressed as a fraction of the value for the irrigated N150 treatment. At 33 DAE, and with irrigation, root biomass (solid lines) increased with nitrogen up to a maximum at N60, beyond which it was almost constant (Fig. 9). The biomass of leaves and stems changed similarly and was much more sensitive than roots to the rate of N < 120 kg/ha.

The most striking feature of the 'dry' response is the biomass of the root system which exceeded that in the irrigated treatment at the two highest rates of nitrogen. The fractional allocation to leaves and stems was again almost indistinguishable but was consistently less than with irrigation. The root system therefore responded to drought with an increase in

mass that was large, both relatively (compared with the leaf/stem response) and absolutely (compared with the irrigated response).

By physiological maturity at 95 DAE, there was a clear difference in the priority of biomass allocation to individual organs (Fig. 10). With irrigation, the biomass of stems was almost independent of the nitrogen rate in contrast to other organs, especially panicles. In the dry treatment, however, all components responded similarly to a shortage of N. It appears that the relative insensitivity to water or nutrient stress initially displayed by the root system disappeared during GS2 as a consequence of a preferential allocation of biomass to shoots and presumably as a consequence of demand from panicles during GS3.

The apparent insensitivity to N of stem biomass at 95 DAE in the irrigated treatment was transient. Earlier (see Fig. 9), stem biomass increased with N but later the response became more complex as stored assimilate moved from stem to grain. The mean stem biomass for 103 and 110 DAE was maximal in the N90 irrigated treatment. To interpret these trends, stem and panicle biomass were plotted for the period from 80 to 110 days (Fig. 11). Loss of assimilate from stems appears to have started at *c.* 80 DAE in the irrigated N150 treatment, at *c.* 90 DAE in the unirrigated N150 and both N60 treatments and not until 95 DAE in the irrigated N0 treatment. There was no significant loss in the unirrigated and

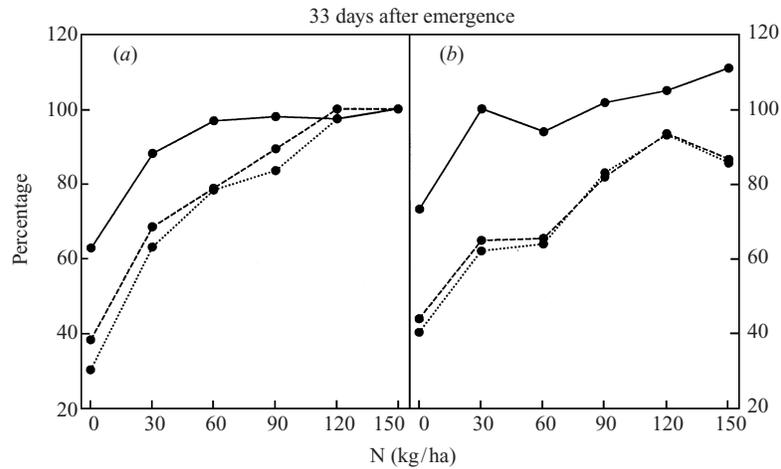


Fig. 9. Biomass of leaves (—), stems (.....) and roots (---) of a sorghum crop at 33 days after emergence on (a) irrigated and (b) unirrigated plots, plotted as percentage of value for the irrigated N150 treatment.

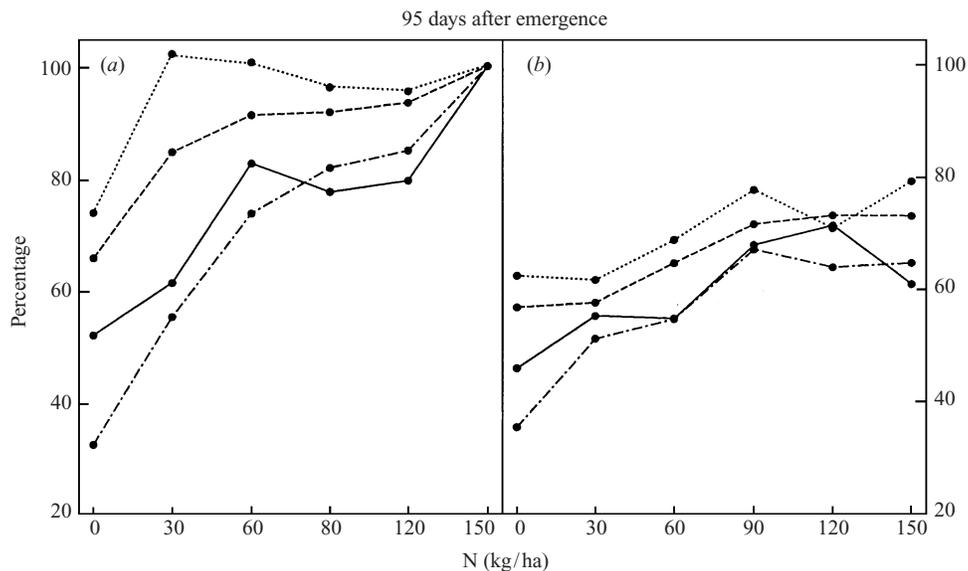


Fig. 10. Biomass of leaves (—), stems (.....), roots (---) and panicles (-.-) of a sorghum crop at 95 days after emergence on (a) irrigated and (b) unirrigated plots, plotted as a percentage of value for the irrigated N150 treatment.

unfertilized treatment. Stem biomass in GS3 was therefore strongly influenced by the time when translocation began as determined by the balance between assimilate demand from the grain and current photosynthesis.

If yield ( $Y$ ) is expressed as the product of grain number per unit area ( $m$ ) and mean grain mass ( $w$ ), the procedure already used to derive Eqn (4) gives:

$$\delta(\ln Y) = \delta(\ln m) + \delta(\ln w) \quad (5)$$

where  $\delta$  represents a difference with respect to the irrigated N150 treatment. Figure 12 shows the components of this equation plotted as in Fig. 8. With irrigation, the rapid decline in yield with decreasing N can be interpreted as a decline in seed number both above and below N90, whereas seed mass was relatively independent of nitrogen over the whole range. Without irrigation, there was less response to N, but the maximum yield was again recorded in the N90 treatment and seed mass was again conservative.

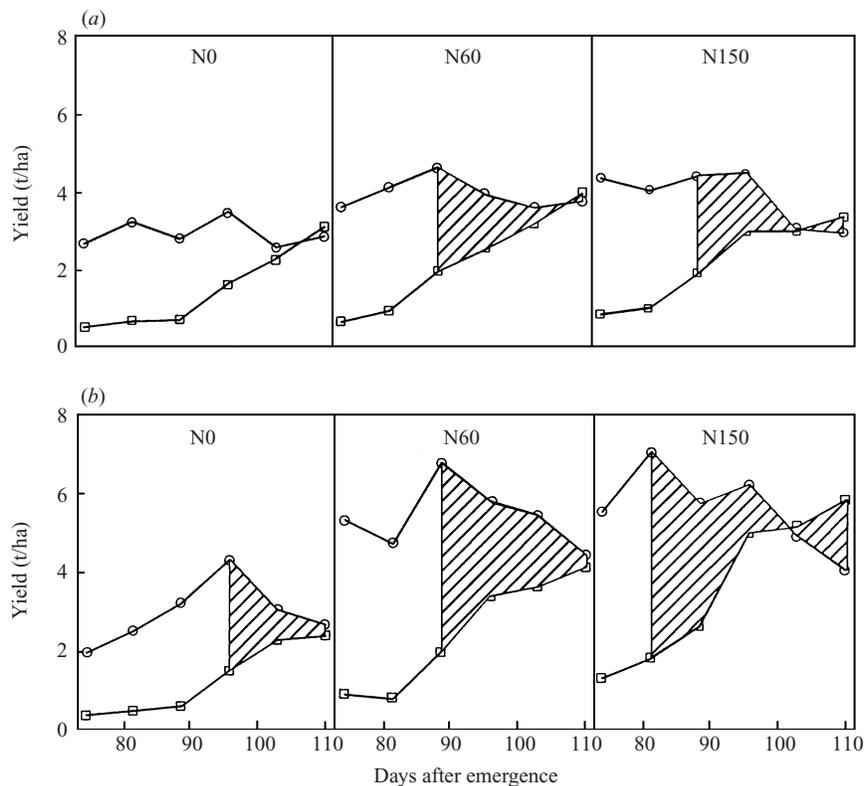


Fig. 11. Change with time of stem mass (○) and grain mass (□) of sorghum during GS3 as function of N rate (0, 60, 150 kg/ha N) and water application on (a) unirrigated and (b) irrigated plots. The period during which stem mass decreases is hatched.

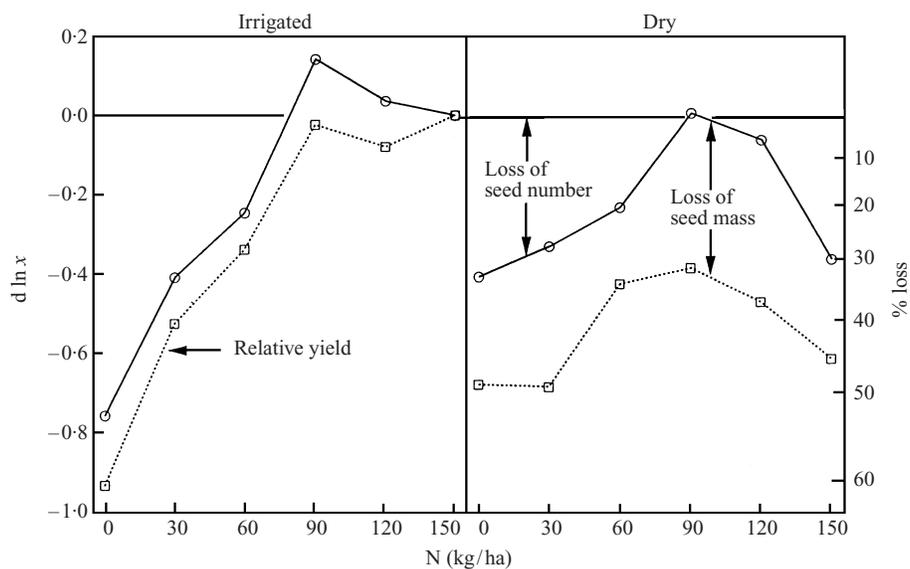


Fig. 12. Seed biomass and number at harvest relative to the value for the irrigated 150 kg/ha N treatment plotted according to Eqn (5) (see text).

## CONCLUSIONS

With irrigation, the main impact of a nitrogen deficit was to reduce the amount of light intercepted rather than the amount of DM accumulated per unit of light interception (Fig. 8). As the specific leaf area was virtually independent of N (Fig. 4), this failure to intercept light can be ascribed primarily to a decrease in leaf biomass accompanied by an almost proportional decrease in area. Because leaf N declined throughout most of the growing season in all treatments (Fig. 5), it is possible that even the highest efficiency of radiation use could have been raised by a late application of N.

Total biomass was strongly dependent on N (Fig. 6) but stalk and leaf biomass were much less responsive than root and panicle biomass (Fig. 10). Despite a substantial movement of assimilates from stalk to grain (Fig. 11), there was a marked decline in yield below N90 related mainly to a decline in grain number (Fig. 12).

At least part of the decrease in  $e$  between the irrigated and dry treatments can be attributed to a smaller concentration of leaf N (Fig. 5). It is therefore probable that limited access to N as well as to water restricted the efficiency with which the energy of intercepted light could be used for photosynthesis as well as the fraction intercepted by foliage (Fig. 8). However, whereas light interception increased with N over the whole range of application,  $e$  increased only up to 90 kg/ha N and then decreased at higher rates. Harvest index followed the same trend.

Figure 13 summarizes the evidence for the adverse impact of high rates of N on sorghum growing on stored water in the post-rainy season. When water was freely available, grain yield responded to N up to the highest rate tested but the largest stem yields were achieved between N60 and N90. Without irrigation, both grain and stover were maximal in this range.

When sorghum is grown on water in the soil profile at the end of the rainy season, rapid drying near the surface severely restricts the uptake of nutrients from this layer. The subsequent impact on growth could be mitigated by the deeper placement of fertilizer and/or by earlier sowing, allowing young plants to benefit from the terminal rains of the monsoon season. Rain harvested and stored during the rainy season can be used efficiently for supplemental irrigation during the post-rainy season only when corresponding amounts of N are applied, are available and are not lost by leaching.

In the absence of irrigation, the rate of nitrogen needed to optimize grain yield was determined mainly by the response of seed number to N which, in turn, depended on the availability of water *per plant* at and following anthesis. Much more information of this kind is needed to develop systematic schemes for (i) matching cultivars to climate as determined by rainfall amount and distribution, by the amount of water available in the root zone and by the potential evaporation rate; (ii) determining the optimum population to achieve maximum yield as determined by the maximum seasonal extraction of stored water; and (iii) estimating the rate of nitrogen needed to achieve maximum yields.

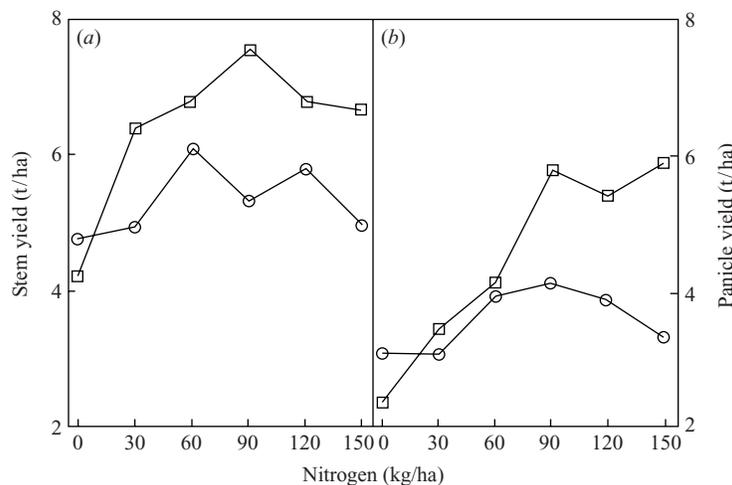


Fig. 13. (a) Stem and (b) panicle yield of sorghum as functions of N rate when unirrigated (○) and irrigated (□).

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