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SOLAR ENERGY UTILIZATION BY TROPICAL SORGHUMS

Part I. Seasonal patterns and productivity*

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ABSTRACT

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Data on global solar radiation, phenology and seasonal drymatter production of sorghum, grown at ICRISAT Center during the rainy and postrainy seasons over a three-year period (1978—80), were used to compute net potential productivity and compare it with actual productivity over three growth phases: GS1, GS2, and GS3. The largest difference in sorghum productivity (expressed as % of net potential productivity) occurred in the GS2 phase; and the difference in the rainy season was nearly twice that in the postrainy season. Measurements of intercepted photosynthetically active radiation and dry-matter production for sorghum, grown in different row spacings and on different soil types, showed that improved management can enhance interception of radiation by the crop, thereby leading to higher production. The productivity levels reported here could serve as a base for comparing sorghum productivity elsewhere in the tropics and in the temperate regions.

INTRODUCTION

Sorghum [*Sorghum bicolor* (L.) Moench] ranks fourth in terms of world cereal production, and is the major food crop in regions where other cereals such as wheat, rice, and maize are not so well adapted (Miller, 1982). Although grown widely in the tropics, sorghum yields have remained quite low. To elaborate, 38% of the world sorghum production comes from Asia (FAO, 1981) but average yields in that region (1005 kg ha^{-1}) are much lower than those of Europe (3650 kg ha^{-1}), North America (2818 kg ha^{-1}) and South America (2095 kg ha^{-1}). Efforts to achieve more stable and higher sorghum yields in the tropics should be based on an understanding of the potential productivity of the environment where the crop is grown, and actual productivity under good management.

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Crop productivity at a given location depends on the potential of the genotype used; availability of factors that promote crop growth such as water, carbon dioxide, nutrients, and solar radiation; and factors that limit growth i.e., pests and diseases. Where water and nutrients, diseases and insects are not limiting, crop growth is determined by the amount of solar radiation intercepted and carbon dioxide assimilated. Light interception and utilization assumes great importance because light use efficiency can be improved through choice of appropriate crop management practices such as changing canopy architecture, plant population, and genotype (Raghunatha and Jagannath, 1976).

Witt et al. (1972) reported that, at Manhattan, Kansas, light interception by sorghum planted in 51 cm rows was about 15% greater than in 102 cm rows, averaged over two seasons. From studies at Nebraska, Clegg et al. (1974) found that visible radiation intercepted by sorghum canopies was greater in 51 cm rows than in 76 and 102 cm rows. Raghunatha and Jagannath (1976) reported from India that light interception efficiency with regard to biological yield was favoured by triangular and square plantings at lower populations, and by square planting at higher population.

The actual productivity of sorghum in India in relation to the potential net productivity has so far not been studied. About 60% of the sorghum in India is grown during the rainy season, and the remaining during the postrainy season. About 66% of the annual production comes from the rainy season crop, and 34% from the postrainy season (Sivakumar and Virmani, 1982). It is important to compare sorghum productivity between the two seasons because physical environment in the rainy season is different from that in the postrainy season.

The objectives of this study were: (1) To compare potential and actual productivity in different growth phases of sorghum, cultivated during the rainy and postrainy seasons, using phenological data and global solar radiation, over a 3-year period (1978–1980) at ICRISAT Center. (2) To assess how efficiently intercepted photosynthetically active radiation (PAR) is converted into dry-matter by sorghum grown in rainy and postrainy seasons, using measured PAR varies, and to ascertain the differences in sorghum productivity computed from global solar radiation and intercepted PAR.

MATERIALS AND METHODS

The experiments were conducted at the ICRISAT Center, Patancheru, India (17°32′N, 78°16′E), during the rainy (June to September) and postrainy (October to February) seasons of 1978, 1979, and 1980. A general description of the experiments conducted during the rainy and postrainy seasons is given in Tables I and II. The experiments were conducted on both Alfisols (fine, clayey mixed, hyperthermic member of the family of Udic Rhodustalfs) and Vertisols (fine, clayey, montmorillonitic, calcareous,

TABLE I

Experimental details of trials conducted during the rainy season at ICRISAT Center (cultivar: CSH-6 hybrid)

Expt.	Soil type	Date of sowing	Date of emergence	Plant population (1000 pl ha^{-1})	Duration of growth stages (days)		
					GS1	GS2	GS3
I	Vertisol	24 Jun '78	02 Jul '78	150	19	35	29
II	Vertisol	28 Jun '79	09 Jul '79	170	18	34	30
III	Vertisol	13 Jun '79	29 Jun '79	105	26	37	26
IV	Alfisol	30 Jun '79	10 Jul '79	141	19	37	31
V	Alfisol	19 Jun '80	23 Jun '80	170	18	35	33
VI	Vertisol	01 Jul '80	04 Jul '80	130	20	34	30
VII	Alfisol	24 Jun '81	28 Jun '81	178	19	37	30

hyperthermic member of the family of Typic Pellusterts). The crops were all grown at optimum population and high fertility levels. The postrainy season crops were grown without irrigation on stored soil moisture.

Canopy interception of PAR in all experiments was measured using four quantum sensors (LI-COR Ltd, Lincoln, Nebraska, USA)*, as described by Sivakumar and Virmani (1980).

Data on PAR interception, recorded at 7—10 day intervals during the growing season, were plotted and interception for each day calculated. Daily solar radiation data for ICRISAT were used to calculate PAR values for each day from the relationship between solar radiation and local PAR (Sivakumar, 1983). Cumulative intercepted PAR on a daily and seasonal basis for each canopy was calculated.

TABLE II

Experimental details of trials conducted during postrainy season at ICRISAT Center (cultivar: CSH-8 hybrid)

Expt.	Soil type	Date of sowing	Date of emergence	Plant population (1000 pl ha^{-1})	Duration of growth stages (days)		
					GS1	GS2	GS3
I	Vertisol	20 Oct '77	25 Oct '77	180	24	44	37
II	Vertisol	14 Oct '78	18 Oct '78	270	25	44	38
III	Alfisol	01 Nov '79	05 Nov '79	187	21	41	35
IV	Alfisol	19 Nov '79	22 Nov '79	125	20	41	38
V	Vertisol	26 Oct '79	01 Nov '79	180	24	44	40
VI	Alfisol	10 Oct '80	13 Oct '80	130	22	44	40

*Mention of commercial products or companies does not imply endorsement or recommendation by ICRISAT.

In each experiment, above-ground whole plants were sampled at 8–10 day intervals. Each plant was separated into leaves, stems, and heads. Plant parts were dried to constant weight in a forced draft oven at 65°C, and weighed.

The phenological observations recorded in each experiment were: days to seedling emergence, panicle initiation (PI), anthesis, and physiological maturity (PM). For computing potential and actual productivity, the three growth stages of sorghum, as defined by Eastin (1972), were used. These were: GS1 (emergence to PI), GS2 (PI to anthesis), and GS3 (anthesis to PM).

The daily potential net productivity was calculated using the procedure suggested by Loomis and Williams (1963). The procedure takes into consideration the daily visible solar radiation (or PAR) incident on the crop. From PAR, the total quanta (Einstein m^{-1}) available to the crop are calculated, after accounting for losses due to albedo and inactive absorption. On the assumption that 10 quanta are required to reduce each mole of CO_2, the amount of carbohydrate produced is computed. After accounting for respiratory losses — equal to 33% of total photosynthesis — the daily potential net productivity is computed.

RESULTS AND DISCUSSION

Environment during rainy and postrainy seasons

Before discussing the potential net productivity differences in the rainy and postrainy seasons, it is important to examine the differences in the environment between the two seasons. During the rainy seasons of 1978, 1979 and 1980 total rainfall of 101, 61 and 73 cm, respectively, was received while during the postrainy seasons for the corresponding years it was 12, 10 and 2 cm respectively. Average global solar radiation during the postrainy season was 18.3, 17.9 and 19.3 MJ m^{-2} day^{-1} during 1978–79, 1979–80 and 1980–81 respectively. These values, with the exception of the second season are higher than the values of 16.5, 18.5 and 16.3 MJ m^{-2} day^{-1} recorded during the rainy season for the corresponding years. Although the average maximum air temperatures were similar for the rainy and postrainy seasons, the average minimum air temperatures were 5 to 7°C lower during the postrainy season (Sivakumar and Virmani, 1982).

Computed potential net productivity

Based on the observed phenology of sorghum during the three growing seasons, data on total global solar radiation in each of the three growth phases of sorghum i.e., GS1, GS2, and GS3, and the seasonal totals were obtained. From these data, potential net productivity of sorghum was computed. The data for the two seasons (Tables III and IV) show that the potential net productivity was higher in the postrainy season. This is not

TABLE III

Total solar radiation and computed potential net dry matter in three growth phases of sorghum during rainy season at ICRISAT Center

Expt.	Total solar radiation (MJ m^{-2})				Potential dry matter (g m^{-2})			
	GS1	GS2	GS3	Total	GS1	GS2	GS3	Total
I	324	515	529	1368	1215	1934	1986	5135
II	358	566	548	1472	1345	2121	2057	5523
III	512	635	483	1630	1922	2381	1813	6116
IV	377	659	543	1579	1415	2472	2035	5922
V	295	503	534	1332	1107	1887	2003	4997
VI	338	486	527	1351	1269	1823	1976	5068
VII	324	586	522	1432	1214	2199	1957	5370
Mean	361	564	527	1452	1355	2117	1961	5447
CV (%)	20	12	4	8	20	12	5	8

unexpected since the potential net productivity computations were based solely on the solar radiation, which was higher during the postrainy season than in the rainy season. The mean values for the two seasons indicate that during the postrainy season, the solar radiation was 15, 27 and 22% higher in the GS1, GS2 and GS3 phases, respectively. For the season as a whole, the potential productivity was 68.3 t ha^{-1} for the postrainy season and 54.5 t ha^{-1} for the rainy season. The potential dry-matter production works out to 64.8 g m^{-2} day^{-1} during the postrainy season as against 61.4 g m^{-2} day^{-1} in the rainy season. The variability in net productivity was also more during the rainy season (Table III) compared to the postrainy season (Table IV), which is a reflection of the shorter growing season and higher variability in solar radiation during the rainy season. At an average

TABLE IV

Total solar radiation and computed potential net dry matter in three growth phases of sorghum during postrainy season at ICRISAT Center

Expt.	Total solar radiation (MJ m^{-2})				Potential dry matter (g m^{-2})			
	GS1	GS2	GS3	Total	GS1	GS2	GS3	Total
I	412	667	634	1713	1544	2501	2380	6425
II	477	788	656	1921	1790	2957	2461	7208
III	404	677	631	1712	1515	2540	2367	6422
IV	332	700	744	1776	1247	2625	2789	6661
V	393	720	763	1876	1473	2699	2860	7032
VI	460	798	668	1926	1725	2995	2505	7225
Mean	413	725	683	1821	1549	2720	2560	6829
CV (%)	13	8	8	5	12	8	8	5

daily solar radiation of 16.4 MJ m^{-2} for the rainy season or 17.3 MJ m^{-2} for the postrainy season, the potential net productivity computed above represents a conversion efficiency of 5.9% of total solar radiation or 11.7% of PAR.

Measured or actual productivity

Compared to the computed potential net productivity, actual productivity is usually higher during the rainy season than in the postrainy season, because of better water supply. Water deficits of varying intensity and duration are very common during the postrainy season (Sivakumar et al., 1979). From the data on seasonal drymatter accumulation for each experiment, conducted during the rainy and postrainy seasons, total dry-matter produced in each of the three growth phases as well as average productivity per day were computed (Tables V and VI). Mean actual productivity was highest during GS2 in both the rainy and postrainy seasons. About 53% of the total dry-matter production during the rainy season and 57% during the postrainy season occurs in the GS2 phase. For the season as a whole, productivity of rainy season sorghum averaged over all the experiments, was 30% higher. During the rainy season, mean daily productivity in the GS2 and GS3 phases was on par but, in the postrainy season, it was superior in the GS2 phase.

While potential net productivity during the rainy season was slightly more variable (Table III), the actual productivity (Table V) was less so. For the season as a whole, CV of actual productivity was 17% during the rainy season and 30% during the postrainy (Table V). Highest variability (76%) in the postrainy season occurred in the GS1 phase. The differences in productivity in the GS1 phase between experiments could be because the sowing dates for the two soil types were different. This fact assumes greater relevance during the postrainy season, when the crop grows on residual soil moisture and the early-sown crop has a greater reservoir of profile moisture for its use. For example, the 1978—79 postrainy crop on Vertisols emerged on 18 October, while on Alfisols, due to delayed sowing, the emergence occurred on 5 November. Similarly, during 1979—80, the crop on the Vertisols emerged 22 days earlier than that on the Alfisols. Although the cumulative intercepted PAR was about the same in both cases, i.e. 468 MJ on Alfisols and 464 MJ on Vertisols, increased moisture availability helped higher dry-matter production on Vertisols. The resultant differences in actual productivity in different growth phases are borne out by data for experiments IV and V in Table VI.

Total dry-matter, averaged over the three experiments, was 912 g m on Vertisols, and only 646 g m on Alfisols. The largest differences in actual productivity occurred in the GS1 and GS2 phases, probably due to the increased availability of profile water in Vertisols as compared to Alfisols.

A comparison between the actual and potential productivity in the

TABLE V

Actual productivity in three growth phases of sorghum during rainy season at ICRISAT Center

Expt.	Actual productivity ($g\ m^{-2}$)				Actual productivity ($g\ m^{-2}\ day^{-1}$)			
	GS1	GS2	GS3	Total	GS1	GS2	GS3	Total
I	25	375	342	742	1.3	10.7	11.8	23.8
II	27	568	351	946	1.6	17.2	11.7	30.5
III	86	918	208	1212	3.3	25.5	8.3	37.1
IV	23	722	288	1033	1.3	19.5	9.6	30.4
V	32	479	736	1247	1.8	14.1	23.0	38.9
VI	22	380	725	1127	1.1	11.5	25.0	37.6
VII	59	634	658	1351	3.1	17.6	22.7	43.4
Mean	39	582	473	1094	1.9	16.6	16.0	34.5
CV (%)	57	31	44	17	43	28	42	18

three growth phases of sorghum during the rainy and postrainy seasons is presented in Table VII. The data show that considerable variability exists in the ratio of actual to potential net productivity between the experiments. For example during the rainy season in experiments V, VI and VII productivity levels of upto 25% of the net potential productivity were achieved against 14 to 19% for the first four experiments. Better soil moisture availability particularly during the GS3 phase during the 1980 rainy season could have contributed towards this increased productivity. A detailed analysis of the role of various agroclimatic factors in the observed differences in productivity during different growth phases during the rainy and postrainy seasons described in a companion paper under preparation suggests the agronomic means for achieving higher productivity. In this paper the discussion is limited to the role of solar radiation in sorghum productivity.

TABLE VI

Actual productivity in three growth phases of sorghum during postrainy season at ICRISAT Center

Expt.	Actual productivity ($g\ m^{-2}$)				Actual productivity ($g\ m^{-2}\ day^{-1}$)			
	GS1	GS2	GS3	Total	GS1	GS2	GS3	Total
I	96	459	52	607	4.0	9.7	1.4	15.1
II	67	581	392	1040	2.8	13.5	10.6	26.9
III	18	476	330	824	0.9	11.9	9.7	22.5
IV	8	276	185	469	0.4	6.9	5.0	12.3
V	37	550	503	1090	1.6	12.8	12.9	27.3
VI	20	275	300	595	0.9	6.4	7.7	15.0
Mean	41	436	294	771	1.8	10.2	7.9	19.9
CV (%)	76	28	49	30	71	27	48	30

TABLE VII

Ratio of actual to potential net productivity (%) of sorghum in three growth phases during the rainy and postrainy seasons at ICRISAT Center

Expt.	Rainy season				Postrainy season			
	GS1	GS2	GS3	Total	GS1	GS2	GS3	Total
I	2.0	19.4	17.2	14.4	6.2	18.4	2.2	9.5
II	2.0	26.8	17.0	17.2	3.7	19.6	15.9	14.4
III	4.5	38.6	11.5	19.8	1.2	18.7	13.9	12.8
IV	1.6	29.2	14.1	17.4	0.6	10.5	6.6	7.1
V	2.9	25.3	36.8	25.0	2.5	20.4	17.6	15.5
VI	1.7	20.8	36.6	22.3	1.2	9.2	12.0	8.3
VII	4.9	28.8	33.6	25.1	—	—	—	—
Mean	2.8	27.0	23.8	20.2	2.6	16.1	11.4	11.3
CV (%)	45	22	44	16	75	28	47	28

The data in Table VII show that during the rainy season it was possible to achieve productivity levels of up to 20% of net potential productivity; in the postrainy season, on the other hand, the percentage was only 11. The greatest differences in productivity between the two seasons occurred in the GS2 and GS3 phases.

Actual productivity as influenced by light interception patterns

In experiment II (Table I), conducted in the rainy season, the PAR interception was measured throughout the growing season. PAR interception was maximum in the narrow rows, and decreased as row spacings increased (Fig. 1). Interception values were lowest in the 150 cm rows. Light interception was low, particularly in the wider rows, during the early stages of crop growth, and increased as the leaf area developed.

Differences in productivity could also be induced by use of different cultivars, since cultivars are known to differ in light interception (Owonubi and Kanemasu, 1982). The relationship between cumulative intercepted PAR and dry-matter for two sorghum hybrids, CSH-6 and CSH-1, grown on Alfisols in experiment IV of the rainy season (Table I) is shown in Fig. 2. The slope of the line shows that for every MJ of PAR absorbed, CSH-6 produced 2.74 g of dry-matter as against 2.15 g by CSH-1. Using the slope value and a calorific value of 17.5 $KJ\,g^{-1}$, the growth efficiency was evaluated as 4.8% for CSH-6, and 3.8% for CSH-1.

The above values for CSH-6 could be compared with gross approximations derived from actual productivity data given in Table V, and the solar radiation data in Table III. The total dry-matter production for the season was 1033 $g\,m^{-2}$. The solar radiation was 1579 MJ, which gives a value of 0.65 g MJ^{-1} for global solar radiation, or 1.31 $g\,MJ^{-1}$ for PAR. This approximation

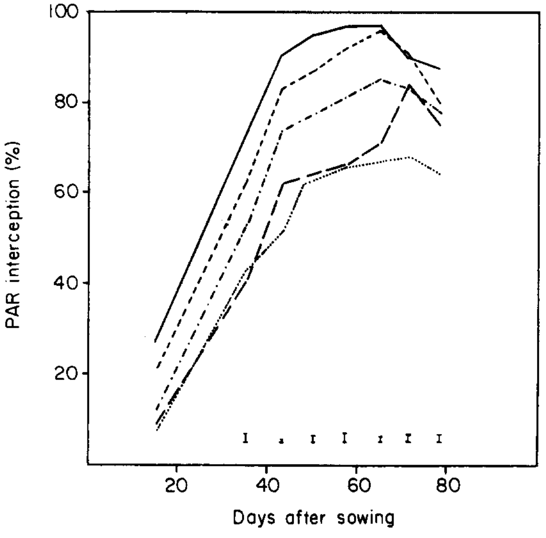

Fig. 1. Changes in interception of PAR by rainy-season sorghum in different row spacings: ——— 30; — — — — 60; —·—·— 90; ——— 120; · · · · · 150 cm.

is, however, based on total; not intercepted PAR. The relationship between dry-matter and intercepted PAR gave a value of 2.74 g MJ^{-1}. This value compares favourably with 2.2 g MJ^{-1} for wheat and barley reported by Gallagher and Biscoe (1978) and is lower than the values of 3.8 g MJ^{-1} for maize and 4.3 g MJ^{-1} for maize/pigeonpea intercrop reported by Sivakumar and Virmani (1980). The cumulative PAR intercepted by the sorghum crop was 389 MJ, which is about 50% of the total PAR received at the top of the canopy (about 790 MJ).

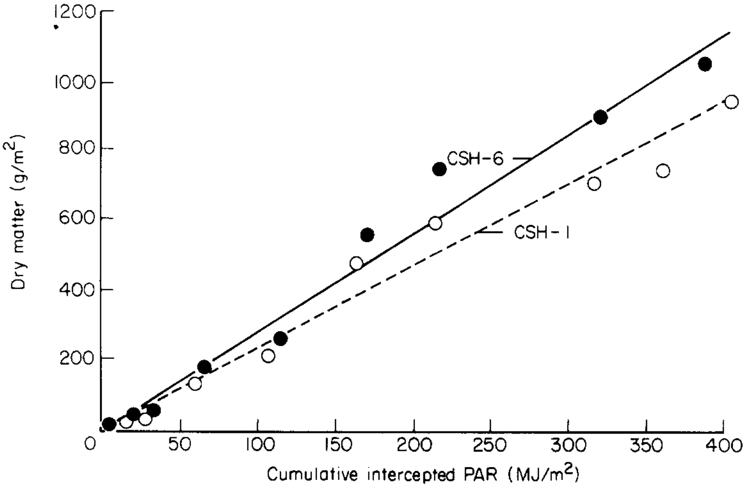

Fig. 2. Relationship between cumulative intercepted PPFD and dry matter produced by two sorghum hybrids grown on an Alfisol during the 1979 rainy season at ICRISAT Center. CSH-6: $Y = 2.74\ (X)$; $r = 0.99$ S.e. = 61. CSH-1: $Y = 2.15\ (X)$; $r = 0.99$ S.e. = 64.

Even during the postrainy season, when water deficits limit crop productivity, there is considerable scope for improving productivity through appropriate management practices, such as selection of appropriate planting time.

CONCLUSIONS

The analysis of net potential productivity, actual productivity, and the relationship between productivity and light interception shows that even for improved sorghum hybrids, grown under good management there is sufficient scope to improve the solar energy utilization. While differences in the productivity between the rainy and the postrainy seasons could be attributed to water deficits, there is evidence to show that with more agronomic attention, high productivity can be achieved. The largest difference in productivity (expressed as % of net production) occurred in the GS2 phase; and in the rainy season the difference was almost twice that of the postrainy season. In years when sowing of postrainy season sorghum was advanced, productivity in the GS2 phase was almost similar to the mean productivity observed during the rainy season. These and other such agronomic means must be investigated thoroughly.

The analysis of sorghum productivity in this paper could provide a basis for comparison of sorghum productivity achieved elsewhere in the tropics, and aid efforts to narrow the gap in productivity between Asia and other sorghum-growing regions of the world. Data collected in experiments at ICRISAT (Krantz, 1981) showed that it is possible to achieve a fourfold increase in productivity through replacement of traditional cultivars and traditional methods of management by improved hybrids and improved fertility and soil and crop management practices.

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