Agricultural and Forest Meteorology, 66 (1993) 211–227
Elsevier Science Publishers B.V., Amsterdam

Temperature and soil water status effects on radiation use and growth of pearl millet in a semi-arid environment

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(Received 18 August 1992; revision accepted 5 April 1993)

Abstract

In semi-arid environments, crops are frequently subjected to a combination of high air temperatures, large atmospheric saturation vapor pressure deficits, high soil temperatures and reduced soil water status. To explore the performance of pearl millet (*Pennisetum typhoides* S. and H., cv. CIVT) from panicle initiation to flowering (GS 2) when grown in the field under combinations of these conditions, experiments were conducted in northern Nigeria in three seasons in which daily mean air temperatures during 18 days of this stage averaged 22, 27 and 33°C, and saturation vapor pressure deficits averaged 3.7, 4.0 and 5.2 kPa, respectively. In each experiment, half of the crop was irrigated, while the other half received no water after panicle initiation. For irrigated millet, radiation use efficiency (RUE) did not vary significantly ($P = 0.05$) for the three experiments (1.7 g MJ^{-1}). RUE of non-irrigated millet was significantly reduced (0.8 g MJ^{-1}) only during the season with the highest temperature. Radiation interception as a function of thermal time was similar in the irrigated and non-irrigated treatments except in the season with the highest temperatures, when radiation interception was reduced about 25% in the non-irrigated relative to the irrigated treatment. Stem extension of non-irrigated millet did not decline relative to irrigated millet, despite the almost complete extraction of plant available water in the upper 30 cm of the soil, except during the season with the highest temperatures, when stem extension rates began to decline as soon as water was withheld. Under high air temperatures and saturation vapor pressure deficits, dry matter accumulation in both irrigated and non-irrigated millet during GS 2 could be reasonably predicted from RUE and radiation interception. However, when high soil temperatures (daily mean at 5 cm of 34°C) occurred in the non-irrigated treatment, both RUE and radiation interception decreased relative to all other treatments.

Introduction

The semi-arid tropics are characterized by variable and/or inadequate rainfall (400–1000 mm within 2.5–6 months), high radiation loads (e.g. 25 MJ m^{-2} day^{-1}), high air and soil surface temperatures and high atmospheric saturation vapor pressure deficits (greater than 3 kPa). Crops often must

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survive long, hot, dry periods in which stored soil water is not recharged by rain. We were interested in discerning the importance of these environmental factors on pearl millet growth from panicle initiation to flowering (GS 2).

The approach we used compared the growth of irrigated to non-irrigated millet established during the same season and also compared these treatments when millet was established at the same site, but during different seasons. We used a simple model of dry matter (DM) production (RESCAP), proposed by Monteith (1972) and utilized by others (Huda, 1988; Monteith et al., 1989; Muchow, 1989) to evaluate the effects of high temperature, high saturation vapor pressure deficit and declining soil water status on millet growth. In the RESCAP model (Monteith et al., 1989), DM production is the product of intercepted light and solar conversion efficiency (RUE), that is, the efficiency with which intercepted radiation is converted to DM. Light interception is a function of the leaf area index (LAI). LAI is incremented daily by assuming an increasing fraction of dry weight is partitioned to leaves throughout GS 2 while the specific leaf area (SLA, the ratio of leaf area to leaf dry weight) remains constant (Monteith et al., 1989). The rate of canopy development during GS 2 is therefore not explicitly considered temperature dependent. RUE is considered conservative, that is, it changes little when water is not limiting. In contrast, when water is limiting, Monteith et al. (1989) considered DM production to be a function of water extracted from the profile and the efficiency with which this water is converted to DM. The aim of this study was to evaluate in the field the range of environmental conditions (i.e. temperature, vapor pressure deficit and soil water status) under which the RESCAP model is applicable.

Materials and methods

Location

Research was conducted at the Kano substation of the International Institute for Tropical Agriculture (IITA) experimental farm in Minjibir, Nigeria (12° 8′N, 8° 40′E; altitude = 500 m). Experimental plots were 100 m south of a lake. The site is well drained with 0–1% slope.

Experimental design and statistical analysis

Two of the three experiments (Experiments 1 and 3) were planted after the 1989 and 1990 rainy seasons. Experiment 2 was planted prior to the 1990 rainy season. The climatic conditions occurring during the three experiments are presented in Table 1. Within each experiment mean daily air temperature varied very little (Experiment 1: SD = 0.98°C, Experiment 2: SD = 1.10°C,

Table 1
Summary of mean daily climate data during the three 18 day experimental periods

	Expt 1	Expt 2	Expt 3
Sowing date	10 Oct 89	28 Mar 90	10 Sep 90
Air temperature (°)[a]			
Mean	22.3	32.5	27.5
Maximum	32.7	40.3	36.2
Minimum	13.2	26.7	20.6
Soil temperature (°C)[b]			
Mean	23.3	34.4	–
Maximum	29.2	40.2	–
Minimum	18.6	30.3	–
Vapor density			
Mean ($g\,m^{-3}$)	3.8	8.9	9.6
Deficit			
($g\,m^{-3}$)	26.9	33.9	27.9
(kPa)	3.7	5.2	4.0
Solar radiation			
($MJ\,m^{-2}\,day^{-1}$)	19.6	22.2	20.7
Potential ETP			
($mm\,day^{-1}$)			
Penman–Monteith	6.3	9.2	6.3
Priestly–Taylor[c]	7.0	8.4	7.3
Actual transpiration			
($mm\,day^{-1}$)	3.9	4.3	4.4 (low) 4.5 (high)

[a] 2 m.
[b] 5 cm (non-irrigated plots).
[c] $\alpha = 1.5$.

and Experiment 3: SD = 0.94°C). A split plot design was used with one randomized block for the irrigated control and another for the non-irrigated plots. These blocks were separated by approximately 18 m. There were four replications within the irrigated block and four replications within the non-irrigated block. Plot size was 6 m x 5 m, with between-row spacing of 0.75 m, and in-row spacing of 0.15 m. This produced populations of 53 300 plants ha^{-1} in Experiments 1 and 2. Isometric plantings (0.50 m × 0.50 m and 0.33 m × 0.33 m) of 6 m × 5 m plots were used to obtain two density treatments (40 000 and 91 800 plants ha^{-1}) in Experiment 3. A 3 m border of maize surrounded the experimental plots.

Statistical analyses (analyses of variance and linear regressions) were performed with Minitab Release 7 (Minitab, Inc., Valley Forge, PA, 1989). Tests of slopes were made using the method of Snedecor and Cochran (1980). A probability level of 0.05 was used to distinguish the degree of significance between means.

Agronomic details

The soil is a hypothermic, ustic Plinthic Quartzipsamment comprised of 86.7% sand, 6.6% silt, and 6.6% clay in the surface 1 m. Bulk density was 1.6 Mg m^{-3} throughout the profile. Ironstone occurs between 100 and 120 cm. The pH of the soil in water was slightly acid ranging from 6.1 at the surface to 6.7 at a depth of 1 m. Organic matter (carbon lost on ignition) ranged from 1.1% at the surface to 2.2% at 1 m.

Pearl millet (*Pennisetum typhoides* S. & H., cv. CIVT) was obtained from the ICRISAT (International Center for Crops Research in the Semi-Arid Tropics) Sahelian Center (Niamey, Niger). This cultivar requires 50–55 days for flowering.

Plots were disc harrowed and then raked level by hand. Two hundred kilograms of 15–15–15 ha^{-1} (30 kg N, 13 kg P, and 25 kg K ha^{-1}) was broadcast prior to sowing. Three to six seeds were planted per hill and thinned to one plant per hill 2 weeks after planting. Weeding was performed by hand as required.

This study focused on the growth of millet during an 18 day period post-panicle initiation (GS 2). This stage was chosen in order to ensure the crop was firmly established before terminating irrigation, because water stress and/or high temperature early in the plant life cycle can cause complete crop failure. During GS 2 roots, stems, and leaves are still rapidly increasing in DM even though the crop is well established (Maiti and Bidinger, 1981). Crop and soil status at the initiation of the 18 day experimental period in each of the three experiments is reported in Table 2.

Table 2
Crop growth and soil water status at initiation of each experiment

Experiment initiation	Expt 1	Expt 2	Expt 3	
Days after sowing	33	21	23	
Heat units[a] (since sowing)	494	399	431	
			high	low
Plant density (m^{-2})	5.3	5.3	9.2	4.0
Leaf area index	1.1	0.7	1.3	0.7
Visible leaf number	14.6	11.0	13.3	13.4
Rooting depth (m)	1.0	0.7	0.7	0.7
Profile soil water[b] (mm)	165	150	181	175

[a] T_{max} = 38°C; T_{min} = 10°C; T_{opt} = 30°C.
[b] 0–120 cm.

Irrigation

Irrigation water averaged pH 7.2. Crops were irrigated to field capacity until 1–7 days after panicle initiation (21–33 days after sowing) and then irrigation was terminated on the drought plots (Table 2). The last day of irrigation on the henceforth non-irrigated plots is referred to as Day 0. Irrigation on the control plots continued on a 3–4 day schedule with applied water sufficient to replace water lost to atmospheric demand. Experiments were concluded 18 days (Day 18) after the last irrigation (Day 0).

Measurements

Environmental
Meteorological conditions were logged every 5 min and hourly averages were recorded (21X micrologger, Campbell Sci. Inc., Logan, UT). The sensors were approximately 10 m north of the plots. Temperature and relative humidity probes (Phys-Chem Sci. Corp., New York, NY) were located 1.5 m above the ground. Wind speed was measured with a three cup anemometer (Met One Inc., Grant's Pass, OR). These sensors were 2 m above the ground. Incoming solar radiation was measured with a silicon pyranometer (LI-200SZ, LI-COR, Inc., Lincoln, NE). Thermal units were calculated using a minimum (T_{min}) = 10°C, optimum (T_{opt}) = 30°C, and a maximum (T_{max}) = 38°C (Ong, 1983a,b,c; Mohamed et al., 1988; Monteith et al., 1989) temperature and linearly decreasing the daily thermal unit when mean daily temperature was above and below the optima.

Intercepted photosynthetically active radiation (PAR) was measured daily using a sunfleck ceptometer (Decagon Devices Inc., Pullman, WA) in Experiments 2 and 3. Six paired readings above and below the canopy were made in each plot between 12:00 and 14:00 h to estimate fractional interception. In Experiment 1, the ceptometer malfunctioned after 10 days. Thereafter, light interception was estimated from leaf area measurements. A Beer's Law analogy was used to predict leaf area per unit area of ground (LAI) from light interception data. The canopy extinction coefficient, k, was assigned a value of 0.6 after visual assessment of best fit of predicted and measured LAI. Measured values of k between 0.5 and 0.75 have been reported for temperate cereals (Hay and Walker, 1989).

Soil temperature was measured every 5 min with copper–constantan thermocouples coated with high temperature thermally conductive epoxy (Type TT-T-22 AWG teflon-coated wire and Omegabond 101, Omega Engineering Inc., Stamford, CT). In Experiment 1, hourly averages were recorded at 0.05, 0.30, and 1.0 m depths in each experimental plot (21X micrologger connected to AM32 multiplexer, Campbell Sci.). A similar procedure was followed in Experiment 2, but as a result of a programming error, data were incomplete in the irrigated plots. Soil temperatures were not recorded during Experiment 3.

Soil water

A neutron probe (Didcot Ltd., UK) was used to measure soil water every 15 cm through the profile until the ironstone layer was reached. Measurements were made daily between 07:00 and 11:00 h (details of calibration and measurement reported in McIntyre, 1992).

Soil profile (0–112.5 cm) volumetric water content at field capacity was determined 24 h after irrigation and measured 193 mm. The lower limit of plant available soil water (51 mm) was determined from probe measurements made 3–5 months after the last precipitation or irrigation event. This limit was used to calculate daily plant available water.

Daily actual transpiration was considered the daily water loss from the entire profile as measured with the neutron probe, e.g. [Day 2] – [Day 1] = actual transpiration on Day 1. The neutron probe was insensitive to soil evaporation 1–2 days after the last irrigation (McIntyre, 1992). Gravimetric measurements of soil water indicated that soil evaporation from the cropped plots was less than 1 mm after 2–4 days. To avoid confounding soil evaporation with transpiration, mean actual transpiration values for individual experiments are reported beginning with Day 3 (Table 1).

Physiological

Daily measurements were made of stem/leaf extension on seven plants in each plot (hereafter referred to as stem extension). Pegs were secured in the ground and a tape measure was hooked in the peg. This meant the height of the newest fully extended leaf was measured from the same point every day. A leaf was classified 'fully extended' when the ligules were visible. When a new leaf extended, measurements on the newly extended leaf and the previous leaf were both recorded to allow integration of plant height through time. When the panicle had fully emerged from the flag leaf, the flag leaf was measured until growth below the flag leaf ceased. Panicle shooting was not included in stem extension measurements. In each plot, the number of leaves fully extended and the number of leaves visible were recorded daily on the same seven plants measured for stem extension. A leaf was considered visible when the leaf tip had extended outside the whorl.

Above ground DM and leaf area were measured every 4–7 days. Four plants per plot were randomly harvested (cut level to the ground). All the leaves were removed and leaf area was measured (LI-3100 leaf area meter, LI-COR Inc.) while the samples were still fresh. RUE was obtained by regressing the net increase in stem and leaf weight over the sampling interval against intercepted solar radiation for the sampling interval.

Rooting depth was limited by ironstone between 100 and 120 cm. This laterite (plinthite) layer impedes root penetration (Eswaran et al., 1990). Water uptake beyond this layer in the profile was considered negligible. Pits were dug and rooting depth was noted on the last day of irrigation (Day 0) and at the conclusion of each experiment (Day 18).

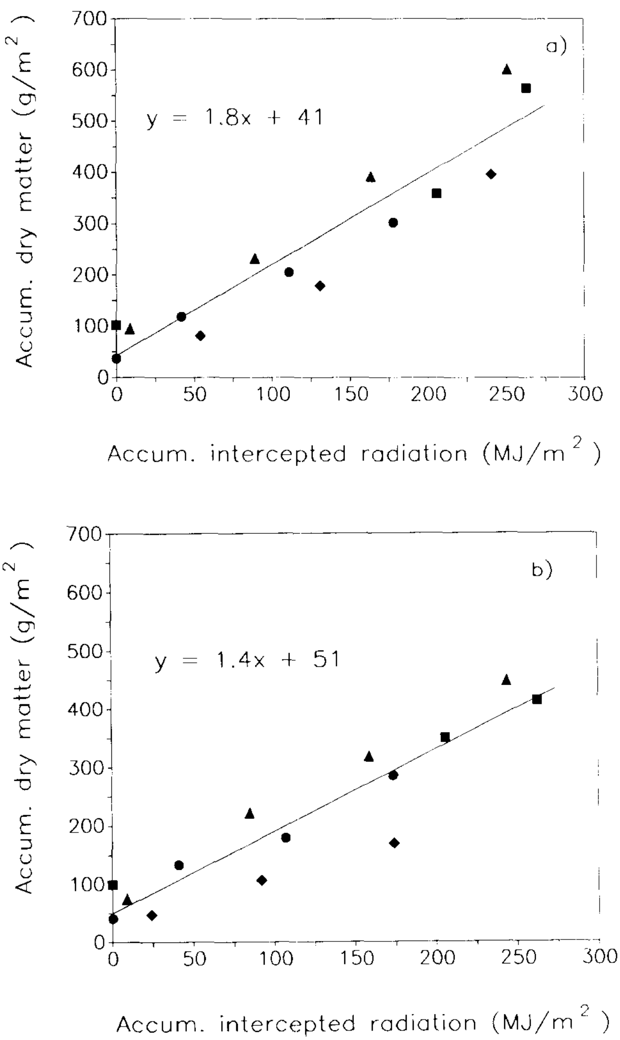


Fig. 1. Above ground dry weight as a function of accumulated intercepted radiation during Experiments 1 (■), 2 (◆), and 3 high (▲) and low (●) density in (a) irrigated and (b) non-irrigated treatments.

Results and discussion

Radiation use efficiency

RUE was not significantly different ($P = 0.05$) among the irrigated treatments (Fig. 1(a); Table 3). A regression of DM production vs. intercepted radiation in our study produced a RUE of 1.78 g MJ^{-1} ($r^2 = 0.88$) for all the irrigated plots. RUEs calculated for individual experiments (Table 3) were in the range of values reported in the literature of 1.3–2.5 g MJ^{-1} (Reddy and Willey, 1981; Azam-Ali et al., 1984; Squire et al., 1984; Squire, 1990; Begue et al., 1991). However, the higher efficiencies are for millet grown under smaller atmospheric saturation vapor pressure deficits (less than 3 kPa) than our experimental conditions (3.7–5.2 kPa). For example, Squire (1990) reports RUE ranging from 1.4 to 2.5 g MJ^{-1} when daily maximum saturation vapor pressure deficits did not exceed 3 kPa. Where daily maximum saturation vapor pressure deficits were between 3 and 5 kPa, he reported lower RUEs (0.3 and 0.8 g MJ^{-1}) than we found.

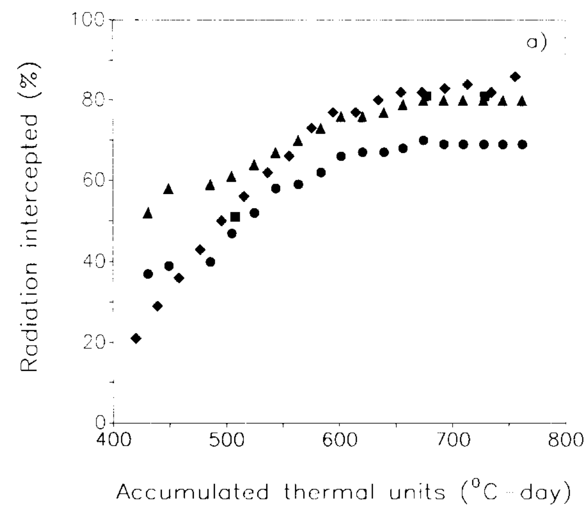
RUEs for the non-irrigated treatments were not significantly different ($P = 0.05$) from each other if Experiment 2 was excluded. A combined RUE of 1.40 g MJ^{-1} ($r^2 = 0.95$) was obtained for Experiments 1 and 3. Experiment 2 had a significantly lower efficiency (Fig. 1(b); Table 3). When data from Experiment 2 were excluded from the analysis there was no significant difference between irrigated and non-irrigated treatments in RUE (RUE = 1.62 g MJ^{-1}, $P = 0.05$). Though RUEs in non-irrigated millet for Experiments 1 and 3 were not significantly different from the irrigated plots, they were lower. These lower values of RUE for non-irrigated millet coupled with a decline in non-irrigated DM production (observed toward the end of the experimental period in both Experiments 1 and 3) suggest that if the experimental period had extended beyond 18 days, a more pronounced decline in RUE would have been observed in all the non-irrigated plots.

Table 3
Mean radiation use efficiency (RUE) in irrigated and non-irrigated millet during the 18 day measurement periods of Experiments 1, 2, and 3

Experiment	RUE (g MJ^{-1})	
	Irrigated	Non-irrigated
1	1.62	1.20
2	1.70	0.81
3 low density	1.45	1.31
3 high density	2.10	1.56

Radiation interception

Radiation interception peaked at approximately the same thermal time in irrigated plots (Fig. 2(a)) of all the experiments; 600–650 accumulated thermal units after sowing. This peak occurred close to the time of flag leaf appearance. In the irrigated plots, light interception reached similar values for all experiments except for the low density treatment of Experiment 3. Leaf area per plant was greatest in the low density plot, but the plant population in low density millet was apparently too sparse to intercept a similar percentage of radiation compared with the higher density plots by the time of flag leaf



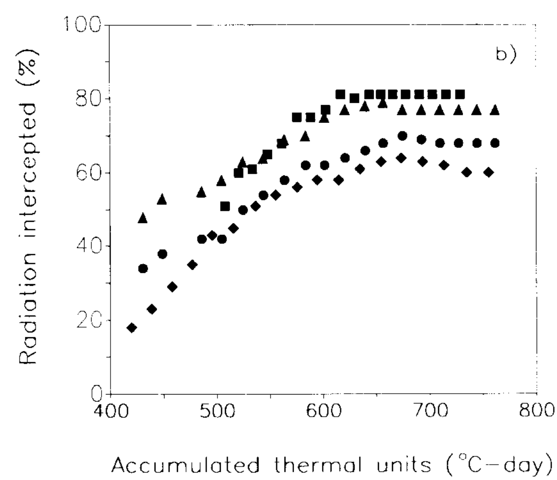


Fig. 2. Intercepted radiation as a function of thermal time accumulated after sowing for Experiments 1 (■), 2 (◆), and 3 high (▲) and low (●) density in (a) irrigated and (b) non-irrigated treatments.

appearance (Fig. 2(a)). Interception in the non-irrigated plots of Experiments 1 and 3 (high and low density) peaked at a similar thermal time and at similar values compared with the irrigated controls (Fig. 2(a, b)). However, maximum radiation interception in non-irrigated millet in Experiment 2 was below that of the irrigated plots in Experiment 2.

Leaf area ratio (LAR, m^2 leaf g $plant^{-1}$) decreased with increasing thermal time (Fig. 3(a)) in all experiments and treatments. LAR of irrigated and non-irrigated millet was similar in a given experiment, but LAR of both the

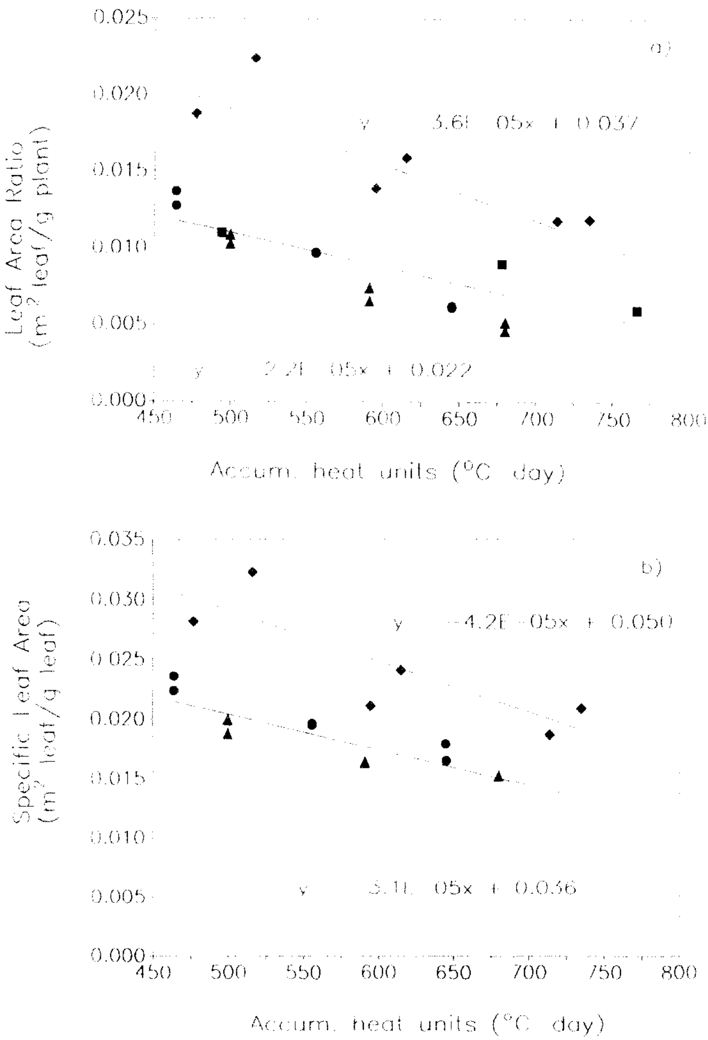


Fig. 3. (a) Leaf Area Ratio and (b) Specific Leaf Area as a function of thermal time accumulated after sowing for Experiments 1 (■), 2 (◆), and 3 high (▲) and low (●) density in irrigated and non-irrigated treatments.

irrigated and non-irrigated treatments was significantly higher in Experiment 2 than in the other experiments (Fig. 3(a)). Specific leaf area (SLA, m^2 leaf g $leaf^{-1}$) also decreased with time. SLA did not vary significantly between irrigated and non-irrigated millet, but was higher in Experiment 2 than Experiment 3 (Fig. 3(b); data only available from Experiments 2 and 3). SLA varied positively with the mean maximum temperature for the 18 day experimental period in the irrigated treatments ($r^2 = 0.73$) and to a lesser degree ($r^2 = 0.58$) in the non-irrigated treatments (3–4 points used for regression). Charles-Edwards et al. (1986) also report that SLA is temperature dependent with increasing temperatures resulting in an increase in SLA. Monteith et al. (1989) define SLA for millet as a constant in their RESCAP model and assign it a value of 33.0 m^2 kg^{-1}. This value does not appear suitable for our experimental conditions.

Dry matter production

In the irrigated treatments, DM production per unit ground area as a function of accumulated heat units was not significantly different ($P = 0.05$) among experiments. However, DM accumulation in the irrigated treatments of Experiment 2 and the low density plots of Experiment 3 were beginning to decline relative to the irrigated plots in Experiment 1 and the high density plots of Experiment 3 toward the end of the experimental period.

By the end of the experiments, DM in all the non-irrigated plots was lower than DM measured in corresponding irrigated plots (e.g. 27% reduction in Experiment 1, and 26% in Experiment 3 high density). By this time, RUE was likely declining in response to water stress. DM production in the non-irrigated plots as a function of thermal time was significantly lower in Experiment 2 than DM production in the other non-irrigated treatments ($P = 0.05$). In Experiment 3, though differences were not significant, it appeared that the high density treatment resulted in more dry matter accumulation than the low density treatment. This was because RUEs were similar for both densities whereas intercepted radiation was greater in the high density treatments.

Stem extension

Maximum above ground growth for pearl millet is reported to occur between 28 and 32°C and to decrease linearly with lower temperatures to a minimum base temperature of 10–12°C (Garcia-Huidobro et al., 1982; Ong, 1983a; Mohamed et al., 1988). In this study, daily stem extension rates were highest at a mean daily temperature of 28–29°C and appeared to decline above and below this value (Fig. 4). Ong (1983c) reports maximum hourly leaf extension rates in pearl millet (7 mm h^{-1}) occur at 30°C and decline linearly at temperatures both above and below this value. Most optimal

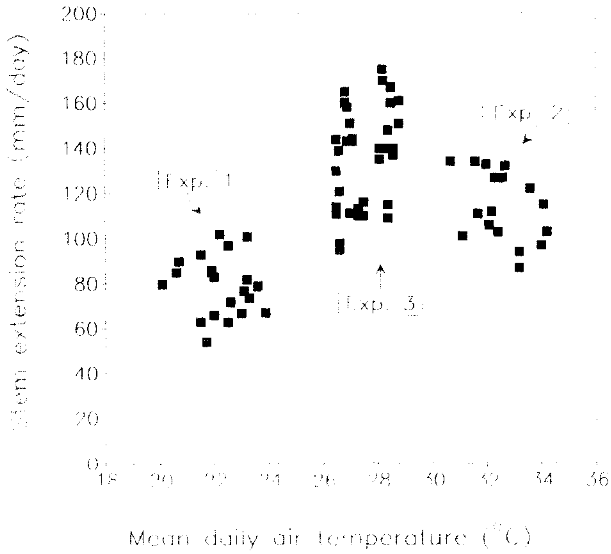


Fig. 4. Stem extension in irrigated millet as a function of mean daily air temperature.

temperature studies have been carried out in glasshouses with temperature fluctuations of no more than ± 5°C. In our field experiments there was a much greater amplitude in diurnal temperature. Suspecting that this wider amplitude was partially responsible for our observed optimal range being somewhat lower than that observed by Ong (1983c), we used hourly air temperature to look at optimal temperature for extension. When daily stem extension rates were regressed against daily heat units derived from hourly temperature data, some of the variability in stem extension in irrigated millet could be attributed to air temperature ($r^2 = 0.63$ excluding Experiment 2, $r^2 = 0.38$ for all experiments).

Squire and Ong (1983) and Ong (1983c) found that saturation vapor pressure deficits less than 3 kPa had little or no effect on leaf extension rates in pearl millet. Similar rates of stem extension were observed in our study, where average daily mean saturation vapor pressure deficits were greater than 3 kPa in all three experiments (Table 1). This suggests that stem extension in millet may not be sensitive to a broad range of saturation vapor pressure deficits, including high saturation vapor pressure deficits.

In Experiments 1 and 3, stem extension rates in the non-irrigated treatment did not differ from those in the irrigated treatment (Fig. 5(a)) despite the decrease in plant available water (PAW) occurring over the course of the experiments (Fig. 5(b)). In contrast, stem extension rates in the non-irrigated treatment of Experiment 2 began declining immediately relative to irrigated values (Fig. 5(a)). Although PAW was lower at the initiation of Experiment 2 than at the beginning of the other two experiments, the PAW values in the

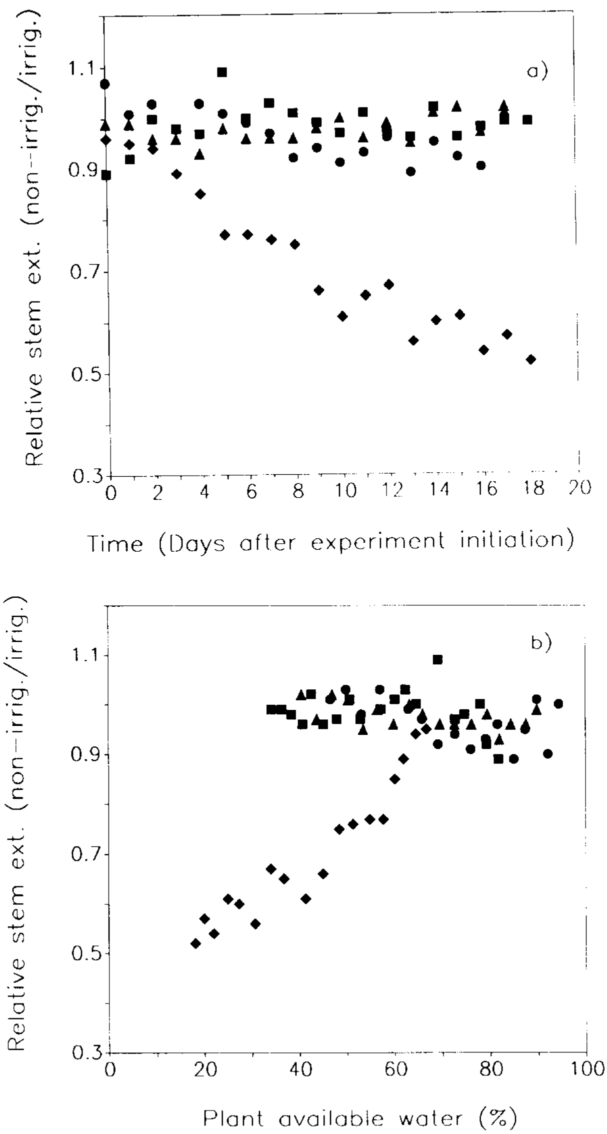


Fig. 5. Ratio of non-irrigated to irrigated stem extension rates in Experiments 1 (■), 2 (◆), and 3 high (▲) and low (●) density as a function of (a) time after experiment initiation and (b) plant available water.

latter period of these experiments were similar to PAW values during the first part of Experiment 2 (Fig. 5(b)). Additionally, actual transpiration was similar in all three non-irrigated experiments (Table 1). This was because of the fact that, though potential evapotranspiration was higher in Experiment 2, radiation interception in the non-irrigated treatment of this experiment was reduced relative to the non-irrigated treatments of Experiments 1 and 3 (Fig. 2). In all three experiments, the soil water content of the upper 38 cm of the soil profile decreased over the 18 day period to a volumetric water content of about 0.05 m^3 m^{-3}, which in the soil of the study area represents a water potential of - 0.3 MPa or less. In addition, McIntyre (1992) did not find a relation between decline in relative stem extension rates and other indicators of water stress, such as changes in predawn leaf water potential and/or stomatal conductance (data not presented).

Air temperature and saturation vapor pressure deficit were presumably similar in the irrigated and non-irrigated treatments of Experiment 2. Among factors measured, the irrigated and non-irrigated treatments of Experiment 2 differed in soil water status and soil temperature. In the non-irrigated plots, average daily mean and maximum temperatures at 5 cm were higher than in the irrigated plots (Table 4). Even in the irrigated plots, rising soil temperatures at the end of the irrigation cycle could have had a deleterious effect on stem extension and account for the observed periodicity in relative stem extension decline (Fig. 5(a)). Studies by other researchers have indicated that it is important to consider soil as well as air temperatures in growth and development studies (Lal, 1978; Ong, 1983a,b,c; Bristow and Abrecht, 1991). For example, Ong (1983c) reported that leaf extension rate was linearly related to meristem temperature up to approximately 30°C and noted that the meristem temperature most closely resembled the mean of air and soil temperature (Ong, 1983b). The higher soil temperatures observed in this experiment may be superoptimal and therefore associated with declining stem extension rates.

There is an ontogenic effect on leaf stem extension rate, i.e. different leaves will elongate at different rates (Ong, 1983c). Leaf number in the non-irrigated and irrigated plots within an experiment were the same when measurements began. However, by the end of Experiment 2 a difference in leaf number was

Table 4
Mean, mean maximum, and mean minimum soil temperature for 18 day experimental periods at 5, 30, and 100 cm during Experiments 1 and 2

	5 cm				30 cm				100 cm			
	Expt 1		Expt 2[a]		Expt 1		Expt 2[a]		Expt 1		Expt 2[a]	
	Dry	Wet	Dry	Wet	Dry	Wet	Dry	Wet	Dry	Wet	Dry	Wet
Mean	23.3	20.9	35.2	31.7	24.0	22.1	33.5	31.5	25.7	25.4	30.5	29.8
Max	29.2	26.3	40.9	35.5	25.3	23.7	35.2	33.0	26.0	25.6	31.0	30.6
Min	18.6	16.7	30.9	28.4	22.6	20.5	32.1	30.6	25.5	25.1	30.2	28.9

[a] Three day mean of Days 4–6 (non-irrigated plots did not differ significantly from 18 day mean as reported in Table 1).

apparent which could have partially contributed to the difference in extension rates.

Conclusions

The RESCAP model proposed by Monteith et al. (1989) is a useful tool for predicting DM production and for analyzing conditions under which DM production is suboptimal. In the RESCAP model, DM production is a product of the daily light interception and RUE. Light interception is predicted knowing SLA, LAR, and a canopy extinction coefficient. LAR and SLA data from our experiments with irrigated millet suggest these values may not be sufficiently conservative to use as constants in a model to predict canopy development. Although our results suggest SLA and LAR are not influenced by soil water status during GS 2, both these plant parameters appeared to increase with increasing air temperature. This would contribute to radiation interception as a function of thermal time in the irrigated treatment of Experiment 2 being similar to the other medium to high density treatments despite the reduced time for growth. It suggests that radiation interception as a function of thermal time at medium to high planting densities (i.e. 53 000 to 92 000 plants ha^{-1}) may fluctuate less with environmental parameters than SLA or LAR.

Our experimentally determined values indicate RUE is relatively conservative during GS 2 in millet, even under conditions of high saturation vapor pressure deficits and decreasing soil water status. However, RUE may be significantly affected by high soil temperatures. This dependency should be further explored and considered when predicting and managing DM production in areas of the SAT where soil temperatures become quite high, especially during periods of drought.

Even though millet was grown on stored soil water for an 18 day period under high saturation vapor pressure deficits, there was little impact on RUE, light interception, stem extension and DM production for most of this period, when surface soil temperatures remained below 34°C (daily mean at 5 cm). Our results suggest that timing of irrigation or precipitation events could be quite widely spaced during this period without a severe impact on dry matter production so long as soil surface temperatures were controlled.

Acknowledgements

This research was funded in part through the Title XII Collaborative Support Program Subgrant SM-CRSP-012 from North Carolina State University. The authors would like to thank Dr Peter Craufurd and Dr Ken Fischer of IITA for their generous support and assistance.

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