Water and Radiation Effect on Sweet Sorghum Productivity

N. Dercas · A. Liakatas

Abstract Suitability of sweet sorghum in Greece, where irrigation supply during crop development is limited as rainfall is scarce and evapotranspiration loss is high, is examined in relation with radiation availability. A two-year field experiment was conducted, in central Greece, imposing four soil water regimes via different irrigation treatments: (1) Highly irrigated, (2) Highly irrigated till anthesis when irrigation stopped, (3) Medium irrigated, and (4) Low irrigated. It was found that above-ground dry biomass production from non-water-stressed sweet sorghum plants suggests a high productivity potential among C_4 crops. Under water shortage, radiation use efficiency may be significantly lower. Radiation use efficiency seems to be linearly related to water consumption. Stressed plants (probably except severely stressed) seem to use available water more efficiently than unstressed plants. The slope of the line relating dry matter produced and water evapotranspired increases the sooner the stress is sensed. Yield reduction resulting from post-anthesis irrigation stopage is very little. High water use efficiency values tend to be related with low radiation use efficiency values.

Key words sweet sorghum · radiation · water · efficiency · productivity

1 Introduction

In addition to being highly productive in terms of biomass, sweet sorghum is also known to show high draught and water logging resistance and salinity tolerance (Mastrorilli et al.

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1999; Berenguer and Faci 2001). For these reasons, among the biomass energy crops, it is considered as the "camel" (Li 1997).

To evaluate the risk deriving from the introduction of a crop to a new environment, its agronomical behavior should be analyzed. As plants rarely compete for light without simultaneously competing for water (Wallace 1995), radiation use efficiency (RUE) and water use efficiency (WUE) are two agronomic criteria used for performing the risk evaluation. Sweet sorghum is rather new to most European environments and has been the subject of agronomic studies. One of the major concerns was the adaptability of sweet sorghum to various climatic conditions (Petrini et al. 1993; Dalianis 1996) and its effect in using water, especially under Mediterranean conditions (Mastrorilli et al. 1995). Sweet sorghum efficiently (more than maize and other C_4 crops, Gosse 1996) transforms the intercepted radiation (RUE=3.7 gm^{-2} of dry matter per MJm^{-2} of absorbed photosynthetically active radiation) and the used water into dry matter (WUE=193 mm of water/kg of dry matter produced or 5.2 g of dry matter/kg of water consumed).

The risk involved in growing sweet sorghum in the Mediterranean region, in comparison with other crops (e.g., sunflowers, grain sorghum and soybean) traditionally cultivated in this region, seems to be very low (Petrini et al. 1993). The question that rises then is "are water needs of sweet sorghum consistent with the water resources of the region?." In South Europe, sweet sorghum potential productivity and water requirement were assessed under non-limiting (Mastrorilli et al. 1996) and limiting (Mastrorilli et al. 1999) conditions. To devise a strategy for optimizing the amount of water provided, the sensitivity of each growth stage to soil water depletion should be known and taken into account in setting up a rational irrigation planning (Mastrorilli et al. 1999). Due to climate, management and crop physiological characteristics, WUE (Asrar and Kanemasu 1984) and RUE (Curt et al. 1998) vary throughout the growing season. Before full ground coverage (leaf area index, $L<2.5$), more than 1000 mm of water are needed to produce 1 kg of above ground biomass, whereas under full-expanded canopy conditions the amount of water required decreases to a minimum, remaining constant until harvest (Mastrorilli et al. 1995). On the other hand, radiation interception also varies from seedling emergence to crop harvest (e.g., Watiki et al. 1993), largely depending on the canopy leaf area (Biscoe and Gallagher 1977). A general review of radiation interception and use has rather recently been made by Sinclair and Muchow (1999). In the absence of biotic or abiotic stresses, yield is related to the amount of radiation intercepted by the crop, affected by the timing of canopy closure (Ottman and Welch 1989). However, in recent research on RUE in South Europe, it is accepted that the limiting factor of sweet sorghum productivity potential is water (Curt et al. 1998).

Therefore, the suitability of sweet sorghum in marginal irrigated areas, where the irrigation supply is limited during crop development e.g., in SE Europe where rainfall is scarce and water loss via evapotranspiration is high, should be examined in relation with radiation availability.

2 Radiation and Water Use Efficiencies

2.1 Radiation Use Efficiency

Plant growth is a simple function of (a) the amount of radiation intercepted over the growing season; and (b) the amount of dry matter produced per unit of radiation intercepted (e). This latter quantity is often referred to as "radiation use efficiency" or as "biomass radiation coefficient" (Monteith 1993).

If $S(t)$ is solar irradiance on day t, $f(t)$ is the fraction of that energy intercepted by a canopy ($S_{\text{interc}}(t)/S(t)$) and $e(t)$ is the corresponding value of the biomass radiation coefficient, a general relation between standing biomass $W(D)$ on day D and radiation intercepted up to day D is

$$W(D) = \sum \{e(t), f(t), S(t)\} \tag{1}$$

where Σ represents summation from $t=1$ to $t=D$.

A mean value for e over D days can be defined by

$$e_m = W(D) \Big/ \sum \{f(D) \cdot S(D)\} \tag{2}$$

$$e_m = W(D) \Big/ \left\{ S_m \sum f(D) \right\} \tag{3}$$

Most stresses reduce both the available amount of radiation intercepted by foliage and the accumulation of dry matter per unit of intercepted radiation. However, the proportional change in e_m is usually smaller than the change in the seasonal total of intercepted radiation; this implies that the restricted supply of assimilate is not the only factor that inhibits leaf expansion (Monteith 1993). The dependence of e on biophysical factors has been clarified first by Monteith (1977), and later by Leuning et al. (1995). In order to compare values of e and f between treatments, it is essential to measure intercepted radiation as a function of time throughout growth (Monteith 1993).

2.1.1 Radiation Interception

Strictly, the process of photosynthesis responds not to energy in the photosynthetically active radiation (PAR) waveband but to the number of quanta received per unit area and per unit time (Monteith 1993). There is a tight correlation between the interception of total energy and the interception of quanta (Green 1987). This is a consequence of the validity, in most uniform plant stands, of the Beer's law relation between the transmission of radiation τ in a specified waveband and the leaf area of foliage above the level of measurement, i.e.,

$$\tau = \exp(-kL) \tag{4}$$

where k is an extinction coefficient depending on wavelength and on the optical and geometrical properties of leaves and L is the leaf area index involved.

To estimate quantum transmission using solarimeters, the value of k for the total radiation (k_T) is found by measuring the mean fraction of incident total radiation below L {i.e., $\tau_T = S_T$ (below)$/S_T$ (above)} and inverting Eq. 4 to give

$$k_T = -\ln(\tau_T)/L \tag{5}$$

A useful practical approximation is that the ratio of k for PAR (or quanta) (k_q) to k for the whole solar spectrum (k_T) is given by the square root of the corresponding absorption coefficients for leaves, a_q and a_T (Monteith and Unsworth 1990):

$$k_q \Big/ k_T = a_q^{1/2} \Big/ a_T^{1/2} \tag{6}$$

The fractional transmission of quanta is then given by

$$\tau_q = \exp\left\{-\left(\frac{a_q^{1/2}}{a_T^{1/2}}\right)k_T \cdot L\right\} \tag{7}$$

$$\tau_q = \tau_T^{\left(a_q^{1/2}\middle/a_T^{1/2}\right)} \tag{8}$$

Strictly, it is the fraction of incident quanta absorbed by foliage that determines rates of photosynthesis rather than the fraction intercepted. This is the complement of absorbed plus reflected radiation and $(1-\tau_q)$ is therefore an overestimate of absorbed quanta. However, the fraction of quanta reflected by a closed canopy is usually only 5 to 10% of incident radiation so that differences between fractional interception and fractional absorption are small (Monteith and Unsworth 1990; Campbell and van Evert 1993).

Defining then the mean PAR interception efficiency, f_q, as the ratio $[\sum \mathrm{PAR}_{\mathrm{int\,erc}}(D)/\sum \mathrm{PAR}(D)]$, the extinction coefficient to PAR, k_q, (in analogy to Eq. 5 for total solar radiation) takes the form

$$k_q = -\ln\left(\tau_q\right)/L = -\ln\left(1-f_q\right)/L \tag{9}$$

and the energy efficiency is the ratio $\sum \mathrm{PAR}_{\mathrm{int\,erc}}(D)/\sum S(D)$.

2.2 Water Use Efficiency

The relationship between crop production and water loss allows to estimate the water use efficiency (WUE) or "biomass water ratio," as proposed by Monteith (1993). WUE is defined as mm of water evapotranspired (ET) by the crop per kg of above-ground dry biomass (W) or the biomass (g) produced per unit of water (kg) consumed. ET may be estimated, on an appropriate time scale basis, by using the soil water balance equation. WUE, supposed as the linear relationship between ET and W (Stanhill 1986), provides a mean value as

$$\mathrm{WUE}_m = W(D)\Big/\sum \mathrm{ET}(D) \tag{10}$$

indicating that crops lose water at the same rate from emergence to day D.

3 Materials and Methods

A two year (1994–1995) field experiment was conducted with sweet sorghum (variety Keller), on a deep, well-drained soil in Central Greece. The soil was clay loam down to 0.7 m and sand clay loam throughout the deep (up to 1.8 m) profile. Organic matter content of the 0.5 m upper layer was 1.0%, whereas for the underlying layer it was 0.5%. Soil bulk density averaged 1.55, and the profile water storage at the water potentials of 0.03 and 1.5 MPa was 0.32 and 0.15 $\mathrm{m^3 m^{-3}}$, respectively.

Crops were sown on 10 May in the first year and a weak earlier in the second year, with a plant density of ∼138,900 plants/ha in 15 m × 7.5 m plots with spacing 72 cm between and
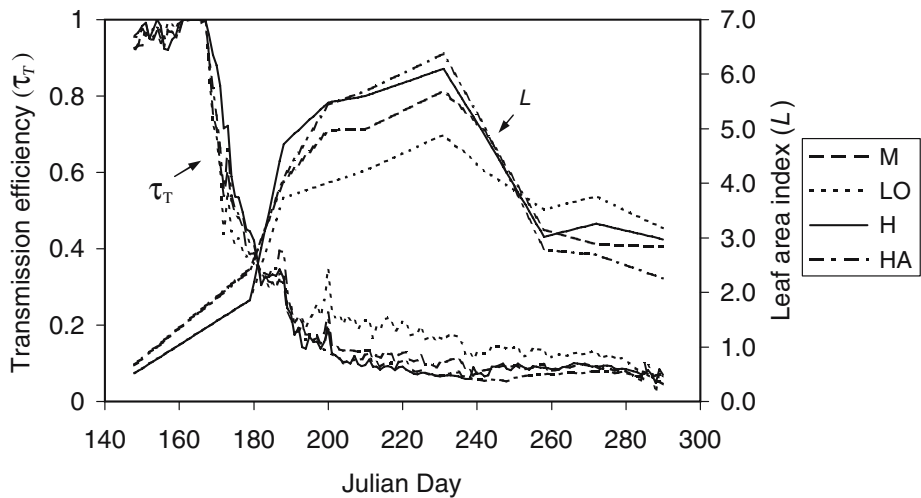
Figure 1 Season variation of the canopy transmission efficiency to total solar radiation, as affected by the irrigation treatment and related to the leaf area index.

10 cm within the rows. The experiment consisted of irrigation treatments, imposing four soil water regimes: (1) highly irrigated (I_H), (2) highly irrigated till anthesis when irrigation stopped (I_{HA}), aiming to evaluate the effect of late irrigation shortage on sorghum yield, (3) medium irrigated (I_M), and (4) low irrigated (I_{LO}). Soil water regimes under the I_M and I_{LO} treatments were, respectively, $0.56I_H$ and $0.34I_H$ in 1994 and $0.64I_H$ and $0.46I_H$ in 1995. I_H and I_{HA} cumulative irrigations were, respectively, 458 mm and 364 mm in the first and 512 mm and 432 mm in the second year of experimentation (Dercas and Liakatas 1999). Complete soil coverage occurred about 3 weeks and anthesis was completed 100 days after emergence.

Soil water content was measured gravimetrically in the depth of 0.0–0.2 m and with a Neutron probe in the depth of 0.2 to 1.8 m (the maximum actual root depth) on a weekly basis as well as the day before the irrigation and 2 days after the irrigation or after a rainfall event. Nitrogen fertilizer was applied at the rate of 40 kg/ha.

Growth and biomass production of plants raised under the four soil water regimes were recorded throughout the cultivating period by nine consecutive harvestings, the final on 25 October in 1994 and 2 weeks earlier in 1995. At each harvest, a 4.0 m row length of crop was randomly chosen from each plot. Fresh weights of whole plants and separately of stems, leaves and panicles were measured. A representative sub-sample from each plant part was then used to determine dry matter. The leaves of 1.0 m row plants were used for L evaluation with the help of a leaf area meter.

In the experimental site, various meteorological parameters were recorded every 10 seconds and averaged or summed every 15 mins namely wind speed, air temperature and relative humidity at 2.0 m above soil surface, solar, photosynthetically active and net radiation above the crop canopy, as well as in canopy solar radiation (just below the top and at the middle of the canopy, as well as just above the ground) using tube solarimeters. These data were supplemented by measurements of rainfall. Actual meteorological data for both crop cycles are provided in a previous paper (Dercas and Liakatas 1999).
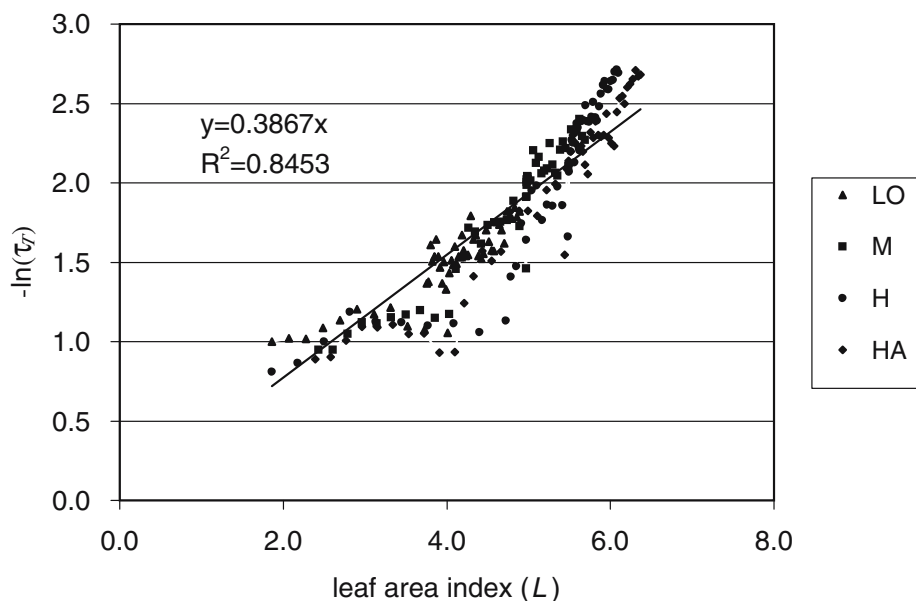
Figure 2 Relation between the negative logarithm of the canopy transmission efficiency and the leaf area index (1994 data).

4 Results and Discussion

4.1 Transmission and Interception Efficiencies

The season variation of the canopy transmission to total solar radiation (τ_T), as affected by the irrigation treatment, largely depends on the rate of leaf area development (Figure 1). Generally, the canopy penetrating relative to the incident radiation flux starts declining rather exponentially, since approximately a month after emergence, following a rapid increase in the green leaf area index (L), with τ_T tending to a constant value (<0.1) soon after L becomes a maximum, probably coinciding with maximum stem elongation.

The canopy radiation interception characteristics up to anthesis completion are better demonstrated when plotting $-\ln(\tau_T)$ against L (Figure 2). The determined extinction coefficient k_T (Eq. 5) varied from 0.37 (r^2=0.70) in the less watered treatment (I_{LO}) to 0.40 (r^2=0.78) in the non-water stressed treatment (I_H) for the 1994 crop. Corresponding 1995 values were lower (0.24 (r^2=0.65) and 0.33 (r^2=0.76)). Although analysis of variance revealed significant differences between the two crop cycles, the unique value of 0.34 representative for sweet sorghum (cv. Keller), may be addressed to k_T.

Based on data provided by Ross (1975), Eq. 8 relating the transmissions to whole solar spectrum (τ_T) and to PAR (τ_q) was solved, implying that $\left(\alpha_q^{1/2} \big/ \alpha_T^{1/2} \right) = 1.92$ and according to (Eq. 6) $k_q=1.92k_T=0.65$.

In spite of different cultural practices and methodologies applied in previous experimental efforts elsewhere, this k_q value is rather close to the values estimated by Ripa 1992 (k_q=0.6), also by Varlet-Grancher et al. 1992 (k_q=0.59), by Perniola et al. 1996 (k_q=0.62) and by Curt et al. 1998 (k_q=0.57). Taken into account that k_q for grain sorghum
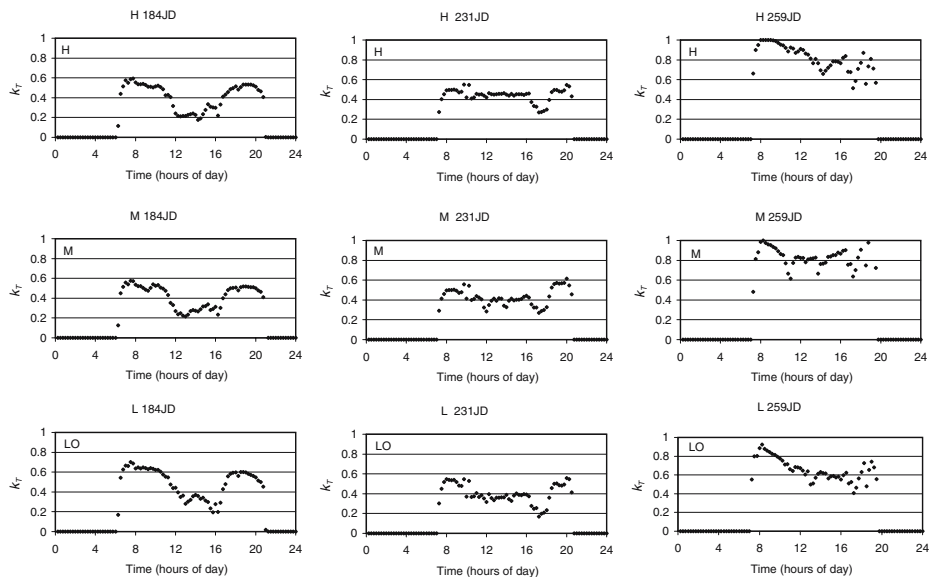
Figure 3 k_T diurnal variation as affected by irrigation treatment at various development stages.

was addressed an average value of 0.51 (Rosenthal et al. 1993), a higher capacity for radiation interception by sweet sorghum is inferred.

Considering in Eq. 5 a constant L value during a diurnal cycle, the corresponding k_T variation may be obtained for certain developmental stages (Figure 3). k_T, being rather stable and minimum around noon (at maximum solar height), increases towards either morning or evening (J.D. 184), also reflecting the foliage development variation among treatments. This early season distinct contrast between hours of different solar elevation, becomes less pronounced as L increases (J.D. 231 and 259) and there is less chance for the incident radiation to reach the ground. To allow for diurnal changes in τ_T due to variation in solar angle (α), k_T can be expressed as $k_T = k_{Tmin}/\sin(a)$, where k_{Tmin} is the minimum value of the attenuation coefficient at solar noon ($\alpha = 90°$) (Ozier-Lafontaine et al. 1997).

4.2 Radiation Use Efficiency

Plotting for all treatments dry matter produced from successive cuttings of above-ground biomass (W) against cumulative intercepted photosynthetically active radiation (PAR) up to the end of anthesis on the I_H-treatment (J.D. 178–240 in 1994 and J.D. 182–229 in 1995), the maximum value of the biomass radiation coefficient (e) may be determined (Figure 4). On average 3.55 g MJ^{-1} were produced when plants were fully watered (I_H-treatment). Water stress, apart from reducing the available amount of radiation intercepted due to slower leaf development observed in Figure 1, also reduces the accumulation of dry matter per unit of intercepted radiation. Under water shortage, RUE$_{max}$ was reduced by up to 40% in the I_{LO}-treatment, as RUE depends on leaf photosynthetic activity (Sinclair and Muchow 1999), much reduced in water stressed crops (Gallagher and Biscoe 1978). When the S_T up to the end of anthesis instead of the PAR was taken into account, the 1994-RUE value for the low-water treatment (I_{LO}) was equal to 1.30 g MJ^{-1} compared to 1.65 for the I_M-
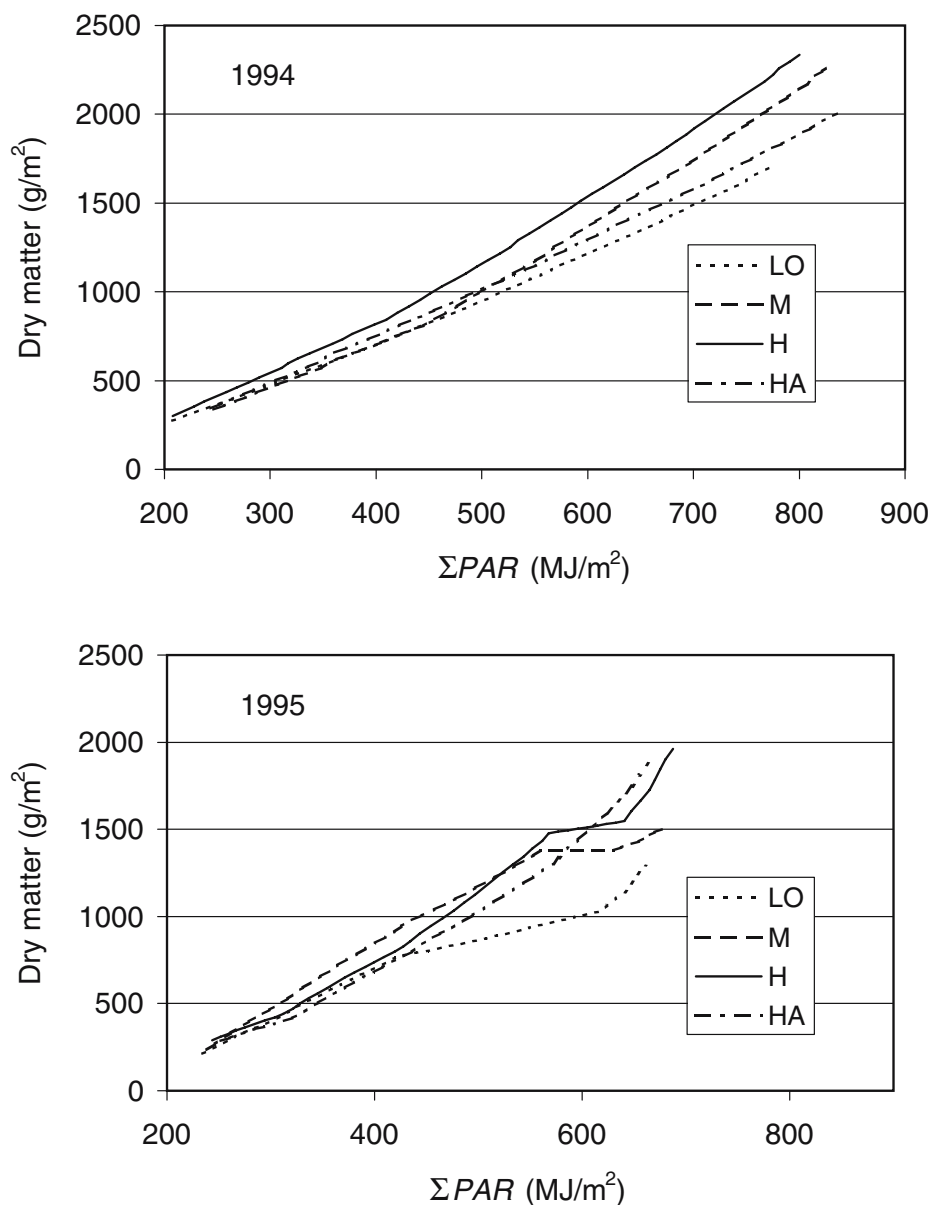
Figure 4 Dependence of dry matter production on cumulative intercepted PAR and irrigation treatment on both crop cycles.

treatment and 1.67 for the I_H-treatment ($r^2 > 0.99$). RUE treatment-differences were more pronounced in 1995 with corresponding values 1.10, 1.33 and 1.73 ($r^2 > 0.94$).

RUE was found to decrease as the vapour pressure deficit (*VPD*) increases (Kiniry et al. 1989), a case characteristic of drought progressing conditions with reduced CO_2 exchange rates (Kawamitsu et al. 1993). On the other hand, the difference between crop canopy
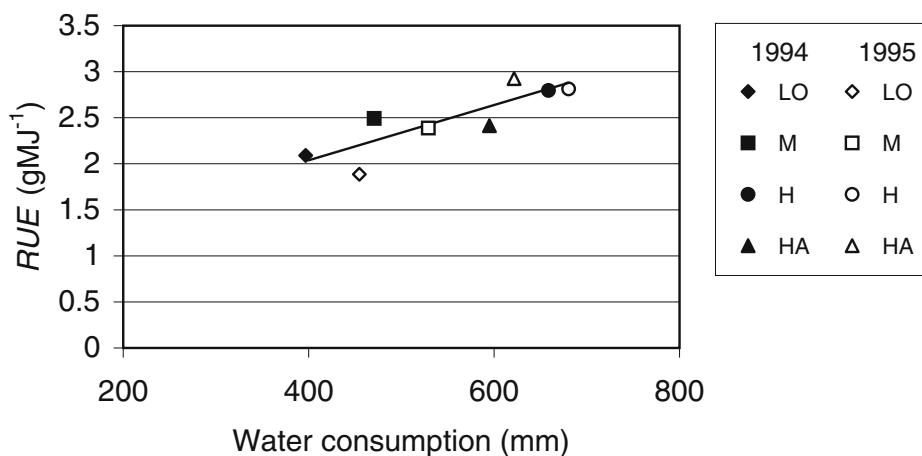
Figure 5 Relation between RUE and water consumption from all irrigation treatments of both crop cycles (up to JD 270).

temperature and air temperature becomes maximum at high VPD values under dry conditions and therefore it is used, along with VPD, as "base line" in the determination of a crop water stress indicator (Olufayo et al. 1996). In agreement for non-stressed plants, Varlet-Grancher et al. (1992) addressed to RUE values between 3.1 and 3.6 g MJ^{-1} (k_q= 0.61) and Mastrorilli et al. (1995) the value 3.71 g MJ^{-1} (k_q=0.6). However, Curt et al. (1998) provided for RUE the value 4.96 g MJ^{-1}. This value seems to be higher than the estimates of RUE for C_4 species (<4.0 g MJ^{-1}) by Sinclair and Muchow (1999), using Murata's (1981) results with a more realistic conversion coefficient from CO_2 to plant dry matter, and even higher than the Loomis and Williams' (1963) theoretical estimate (4.68 g MJ^{-1} on a PAR basis) of the maximum limit to RUE. On the other hand, this high RUE value is difficult to be explained by a temperature influence on leaf photosynthetic rate at the warmer southern (in comparison with northern) Europe, as claimed by Curt et al. (1998), because little variation in RUE over a wide range of latitudes was observed by Goudriaan (1982) and in warmer climates there is less sensitivity of potential maximum RUE of C_4 crops to total irradiance (higher in low and thus warmer latitudes) as the quantum efficiency of photosynthesis by leaves is independent of temperature (Choudhury 2001). Besides, respiration, determining daily carbon accumulation, increases with temperature.

Other C_4 crops, like grain sorghum (Kiniry et al. 1989: 2.4–3.2 g MJ^{-1}; Rosenthal et al. 1993: 3.46 g MJ^{-1} and Mastrorilli et al. 1995: 3.39 g MJ^{-1}), sudan-grass (Varlet-Grancher et al. 1992: 2.5–2.9 g MJ^{-1}), maize (Bonhomme et al. 1982: 2.1–3.2 g MJ^{-1}; Kiniry et al. 1989: 3.5 g MJ^{-1} and Tollenaar and Aguilera 1992: 2.38–3.02 g MJ^{-1}) and miscanthus (Tayot et al. 1994; Clifton-Brown et al. 1996 and Dercas et al. 1996a: 2.4–4.09 g MJ^{-1}) usually exhibit RUE values lower than sweet sorghum, suggesting a usually higher productivity potential of the latter.

The significant dependence of RUE on irrigation treatment led to the idea of plotting RUE against water consumption (Figure 5). RUE values for all treatments and crop cycles seem to follow a straight line (r^2=0.72) with RUE improving with increasing water input at a rate 0.003 g MJ^{-1} mm^{-1}, in the water consumption range of approximately 400–700 mm.

Table I Season-average WUE values, seasonal consumptive water uses and final yields, as affected by irrigation treatment

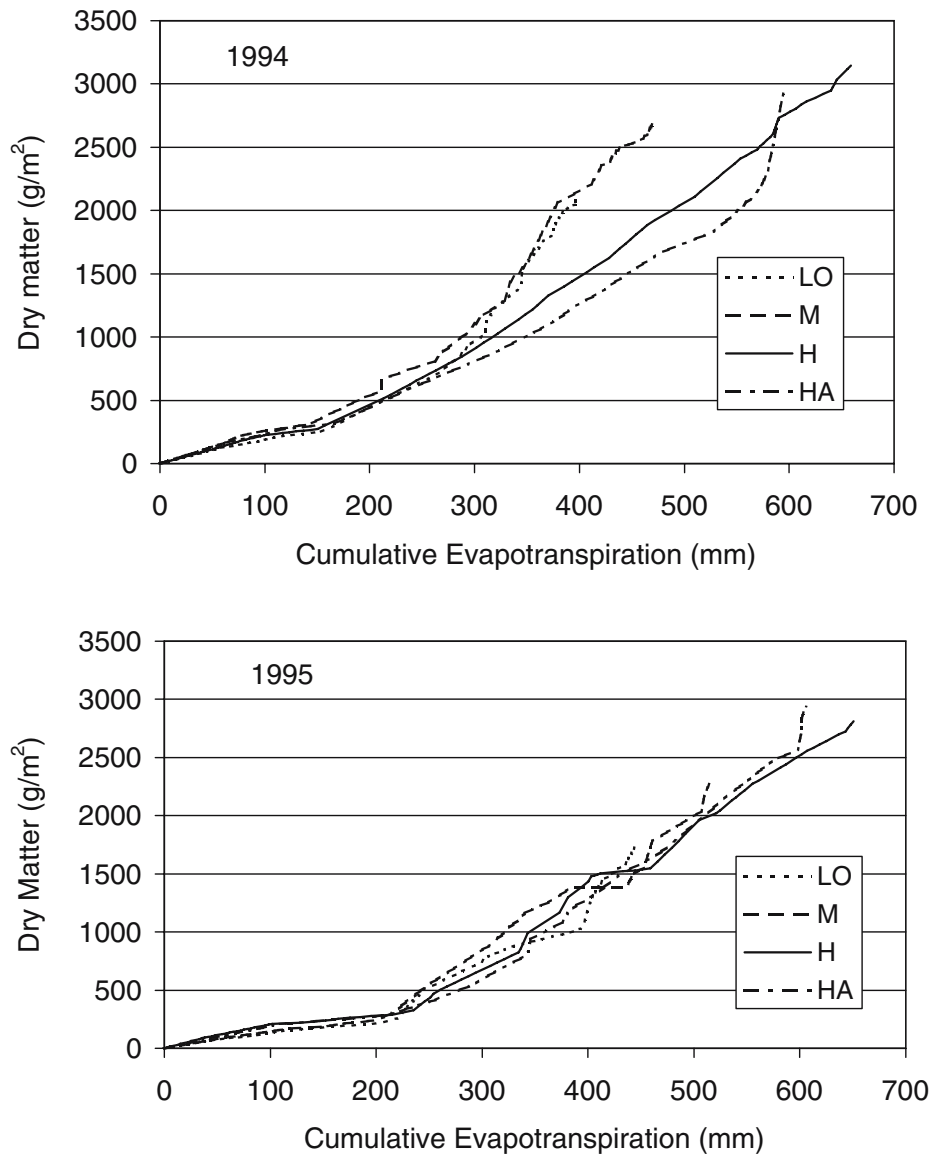| | Non-stressed (H) | | | Stressed throughout the cycle | | | | | | Stressed after anthesis (HA) | | |
| | | | | Medium (M) | | | Severe (LO) | | | | | |
	WUE (gm⁻² mm⁻¹)	Final yield (gm⁻²)	Water consumption (mm)	WUE (gm⁻² mm⁻¹)	Final yield (gm⁻²)	Water consumption (mm)	WUE (gm⁻² mm⁻¹)	Final yield (gm⁻²)	Water consumption (mm)	WUE (gm⁻² mm⁻¹)	Final yield (gm⁻²)	Water consumption (mm)
1994	4.8	3147	662	5.7	2686	472	5.3	2111	397	5.0	2957	596
1995	4.3	2811	651	4.4	2267	515	3.9	1716	444	4.8	2934	606
Aver.	4.6	2979	657	5.1	2477	494	4.6	1914	421	4.9	2946	601
% loss		0	0		17	25		36	36		1	9

Figure 6 Dry matter produced in relation to cumulative evapotranspiration and irrigation treatment of both crop cycles.

4.3 Water Use Efficiency

The relationship between evapotranspiration water loss and total above-ground dry matter production provides an estimation of the season-average WUE values. These values are given in Table I for non-stressed (I_H) and stressed, either throughout the cycle (I_M and I_{LO}) or only at the post-anthesis stage (I_{HA}) crops, along with corresponding final yields and seasonal consumptive water uses.
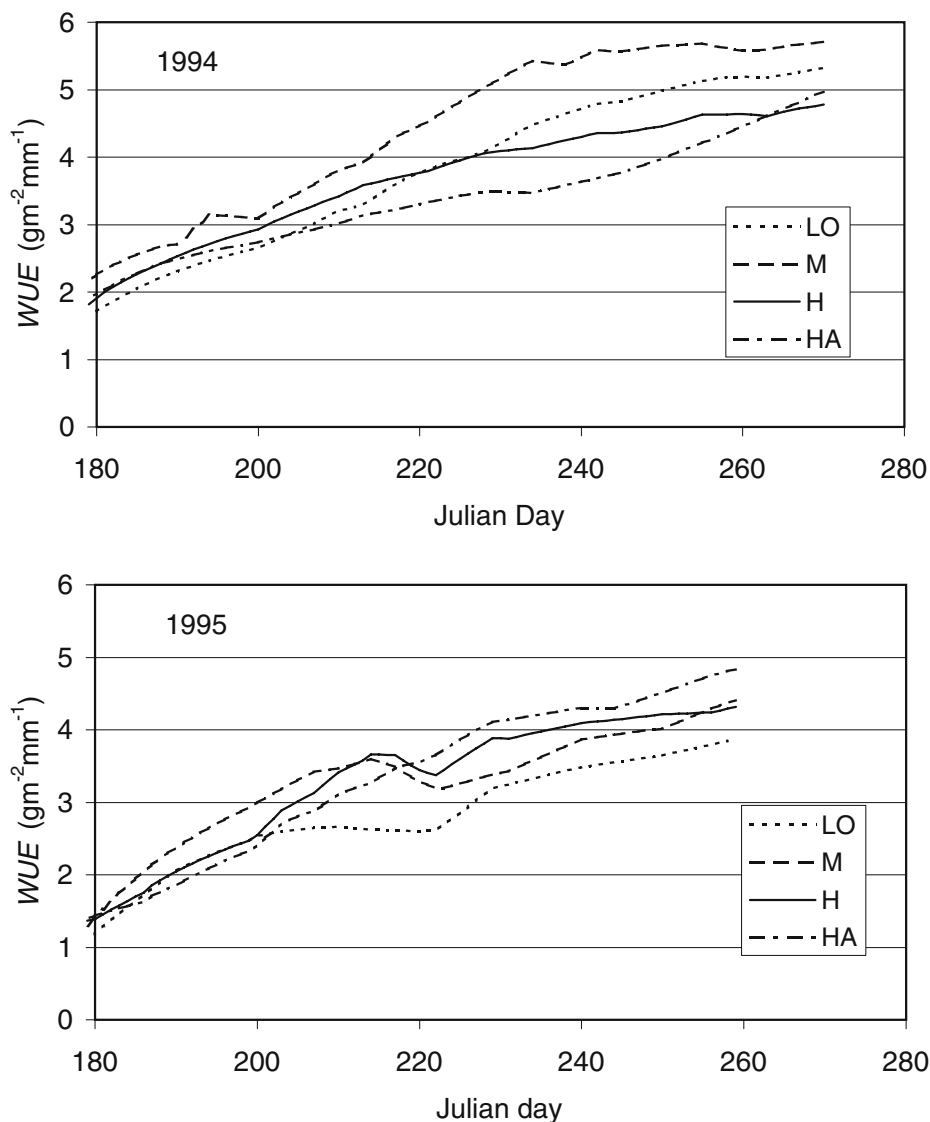
Figure 7 Treatment dependence of the in-season variation of the mean up to a certain JD value of WUE for both crop cycles.

Although water consumption did determine final yield, a stage-stress dependent yield reduction may be observed. When irrigation stopped after anthesis, implying a 9% less water application on average, final yield reduction was very little (1%). Plants irrigated throughout the season at a reduced rate (by 25% in the I_M and 36% in the I_{LO} plots) produced increasingly less (by 17% and 36%, respectively). However, it seems that stressed plants (probably except severely stressed) use available water more efficiently. When there is practically no water shortage, the dry matter produced per mm of water evapotranspired after 150–200 mm were lost (Figure 6) remains almost constant (5.38 gm^{-2} mm^{-1}, r^2=
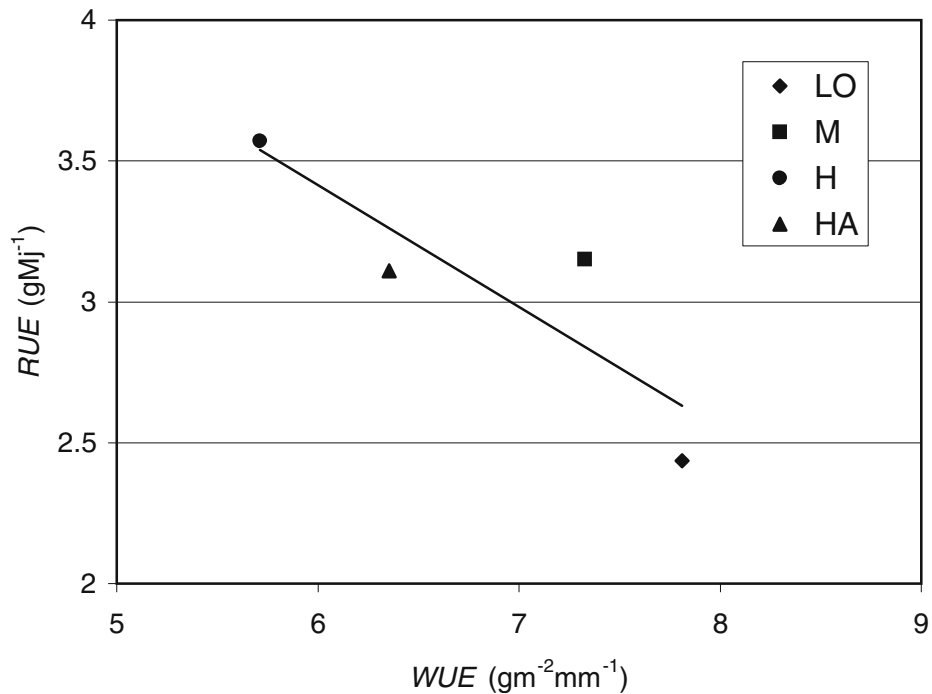
Figure 8 Relation between RUE and WUE values from all treatments of the 1994 crop cycle (regression slope for the period JD 178–270).

0.995 in 1994 and 5.94 $gm^{-2} mm^{-1}$, $r^2=0.983$ in 1995). When water shortage onsets, the slope of the line relating dry matter and water consumption increases the sooner the stress is sensed by the plants (JD 210, a month before anthesis in the least watered plots). Slope increase is steepest in the case of plants stressed post-anthesis (I_{HA}). The post anthesis line slope implies a production as high as 8.6 $gm^{-2}mm^{-1}$. Under well-watered conditions, WUE values are similar to those already reported (Mastrorilli et al. 1995; Dercas et al. 1996b; Cosentino et al. 1997). Singh and Singh (1995) found that WUE was highest under moderately stressed conditions in sorghum, unlikely maize (under wet conditions) and pearl millet (under severely stressed conditions). Photosynthetic water-use efficiency of leaves was suggested by Steduto et al. (1997) to be inversely proportional to VPD, normally high under water-stress conditions. However, Berenguer and Faci (2001) observed important yield compensation of sorghum when grown under limited irrigation. Mastrorilli et al. (1999) determined WUE of stressed crops lower for stress during the "leaf stage" (4.76 $gm^{-2}mm^{-1}$) but higher for stress during the (pre-anthesis) stem stage (6.04 $gm^{-2}mm^{-1}$) in comparison to non stressed crops (5.71 $gm^{-2}mm^{-1}$). WUE values were higher also in drier years.

In-season variations of the mean up to a certain JD value of WUE are illustrated in Figure 7. Although increasing with time, *mean*-WUE increase diminishes, especially after anthesis (unless plants were stressed), WUE tending to a constant value. Mastrorilli et al. (1995) also found that, under full expanded canopy conditions ($L>2.5$), the amount of water required to produce a unit of dry matter decreases to a minimum and then remains constant until harvest.

High WUE values tend to be related with low RUE values (Figure 8), as water shortage leads to less expanded foliage unable to make maximum use of radiation availability.

5 Conclusions

Quanta interception capacity of sweet sorghum, becoming maximum when green leaf area index (*L*) also becomes a maximum, is higher compared with grain sorghum. Early-season dependence of interception efficiency on solar elevation becomes less pronounced as *L* increases.

From practically non-water-stressed sweet sorghum plants, the above-ground dry biomass produced by the photosynthetically active radiation intercepted during the fast growing stage (RUE$_{max}$), suggests a high productivity potential for sweet sorghum among C$_4$ plants. Under water shortage, RUE becomes lower and seems to be linearly related to water consumption, improving with increasing water input. Soon after crop establishment, WUE of unstressed plants is rather constant. Stressed plants (probably except severely stressed) seem to use available water more efficiently. The slope of the line relating dry matter produced and water evapotranspired increases the sooner the stress is sensed. Slope increase is steepest when irrigation completely stops post-anthesis. However, this results in very little yield reduction. High WUE values tend to be related with low RUE values, as the less expanded foliage under water shortage is unable to make maximum use of radiation availability.

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