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Water-use efficiency of irrigated biomass sorghum in a Mediterranean environment

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Abstract

A large interest is currently addressed to the no-food crops as an alternative source of energy. One of these crops is the biomass sorghum (*Sorghum bicolor* L. Moench) thanks to its high biomass productivity and high use efficiency of solar radiation and water. Aim of the research is assess the biomass sorghum response to the water in the Mediterranean environment. Biomass sorghum was subjected to four irrigation regimes, at 50, 75, 100 and 125% of ET_c for three years (2008, 2009 and 2010). Water use efficiency (*WUE*), irrigation water use efficiency (*IWUE*) and water stress index (*WSI*) were calculated. Plant dry matter and green area index resulted different among the three years and the differences among irrigation treatments were more evident in 2009. The different soil water content at sowing among the three experimental years, affected the growth path during the growing crop cycle, explaining differences in term of biomass accumulation, leaf expansion and water consumption. *WUE* was higher in 2009 than in 2008 and 2010 with no differences among irrigation treatments for the first and third experimental year. *WU* ranged between 891 and 566 mm, the aboveground dry matter biomass between 4,097 and 1,825 g m^{-2} and *WUE* between 8.49 and 4.00 kg m^{-3}. *IWUE*, similarly to *WUE*, was higher in the second year than in the first and third year, but with differences among irrigation treatments in the 2008 and 2010. *WUE* calculated from *WU* normalized with *VPD* gave a more stable parameter in the three years. This research showed the suitability of biomass sorghum as energy crop in Mediterranean environment and its ability to use water efficiently.

Additional key words: *Sorghum bicolor;* irrigation water use efficiency; green area index; biomass yield; water stress index; actual transpiration.

Introduction

In the Mediterranean environment, where rainfall occurs mainly in winter, water is the crop yield limiting factor, especially for summer crops such as sorghum. An inadequate water supply in sorghum can also reduce the efficiency in the conversion of the intercepted radiation in dry biomass even though the solar radiation is an abundant factor in Mediterranean areas (Dercas & Liakatas, 2007; Garofalo *et al*., 2011; Rinaldi & Garofalo, 2011).

Several authors (Lewis *et al*., 1974; Sharma, 1985; Sharma & Alfonso Neto 1986; Omer *et al*., 1988) reported the response of sorghum (*Sorghum bicolor* L. Moench) to the timing and amount of irrigation water, with a clear reduction of growth and dry matter accumulation as a consequence of an increment of soil water deficit. Turner (1974) highlighted that soil water deficit reduced the stomatal conductance, transpiration, photosynthetic rate and dry matter accumulation. Moreover, Rosenthal *et al*. (1987) reported adverse effects on some crop variables such as leaf area, stem height and biomass production, with soil water decrements.

One of the most frequently used indices to evaluate the response of a crop in a specific pedo-climatic con-

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Abbreviations used: ADM (Aboveground Dry Matter); CAW (Crop Available Water); ET_c (Crop Evapotranspiration); ET_m (Maximum Evapotranspiration); ET_0 (Reference Evapotranspiration); GAI (Green Area Index); NPW (Not Productive Water); SWC (Soil Water Content); T_{act} (Actual Transpiration); T_p (Potential Transpiration); T_{pi} (Potential Transpiration at day *i*); VPD (Vapour Pressure Deficit); WSI (Water Stress Index); WU (Water Use); WUE (Water Use Efficiency); WUEvpd (Water Use Efficiency calculated with Water Use normalized with Vapour Pressure Deficit).

dition and water supply is the water use efficiency (*WUE*; de Wit, 1958; Tanner & Sinclair, 1983) that is strictly related to biomass accumulation and water used. Therefore, *WUE* can be an indicator to assess the best water irrigation strategy of biomass sorghum in Mediterranean environments as an alternative energy crop.

A large number of researches have been carried out on grain or sweet sorghum in Mediterranean environments, but only few studies on biomass sorghum are reported (*e.g.* Habyarimana *et al*., 2004). This lack of information can be attributed to recent interest of biomass sorghum as a resource of bio-energy crop; thanks to cellulose, hemicellulose and lignin content in stems and leaves, biomass sorghum could represent an alternative renewable resource to fossil fuels (Cosentino *et al*., 2008).

The estimation of *WUE* for biomass sorghum is also important for obtaining a useful crop parameter, especially for the crop growth models that estimate biomass accumulation from water use efficiency, such as CropSyst (Stöckle *et al*., 2003), Parch (Hess *et al*., 1997) and the recent AquaCrop (Steduto *et al*., 2009) models. In fact, as reported by Hsiao (1993) and Hsiao & Bradford (1983), a correlation between above ground dry plant matter (*ADM*) and water use (*WU*) tends to remain linear (and so, simple to be applied) in both well-watered and water deficit conditions. Moreover, *WUE* seems to be influenced only by plant water status regardless of soil nutrient status (Stanhill, 1986).

Different authors report that *WUE* in sorghum is not a stable parameter since it changes among years, environments, phenological stages, soil water and nitrogen plant availability (4.1-6.0 kg m^{-3}, Mastrorilli *et al*., 1999; 4.4-5.5 kg m^{-3}, Steduto & Albrizio, 2005; 6.5-8.6 kg m^{-3}, Saeed & El-Nadi, 1998). This *WUE* variability underlines a limitation of applicability of a "fixed" value of *WUE* in sorghum in different climatic and environmental conditions, and so there is the need to find alternative approaches in order to make more flexible the use of *WUE* calculated from different years and locations. Two possible approaches in *WUE* estimation are the use of *WU* normalized (de Wit, 1958; Tanner & Sinclair, 1983) by evaporative demand of the atmosphere (ET_0, mm; Steduto & Albrizio, 2005; Steduto *et al*., 2007) or by vapour pressure deficit (*VPD*, KPa, Stöckle *et al*., 2003).

One of the questions regarding *WUE* is that it does not provide constant indications on the effective use of water by the crop (transpiration) because it combines soil evaporation and crop transpiration in a single term. Moreover, *WUE* cannot be considered as an index of crop stress condition related to different water supplies. Water stress index (*WSI*; Idso *et al*., 1981), in fact, indicates the crop water availability level in relation to maximum evapotranspiration (ET_m). Furthermore, the gap between actual (T_{act}) and potential transpiration (T_p) gives the actual crop response to different water supply regimes, starting from reduction in canopy expansion to stomatal closure.

The aims of this work were to: i) determine the effects of four irrigation treatments on growth and yield of biomass sorghum, ii) assess several water use efficiency indices at different scales, taking into account soil evaporation, potential and actual transpiration, in order to evaluate the effective water crop demand, use and efficiency, and iii) furnish parameterized values of these indices in a Mediterranean environment also useful for the most common crop simulation models.

Material and methods

Experimental site

The field research was carried out at the experimental farm of Consiglio per la Ricerca e la Sperimentazione in Agricoltura-Unità di Ricerca per i sistemi colturali degli ambienti caldo-aridi, in Foggia (41° 8' 7" N; 15° 83' 5" E, 90 m a.s.l.), Southern Italy, over a three-year period (2008, 2009, 2010). The soil is a vertisol of alluvial origin, Typic Calcixeret (USDA 2010), silty-clay with the following characteristics: organic matter, 2.1%; total N, 0.122%; $NaHCO_3$ extractable P, 41 ppm; NH_4O Ac-extractable K_2O, 1,598 ppm; pH (water), 8.3; field capacity water content, 0.396 m^3 m^{-3}; permanent wilting point water content, 0.195 m^3 m^{-3}, available soil water, 202 mm m^{-1}.

The local climate is "accentuated thermo-Mediterranean" as classified by FAO-UNESCO (1963) Bioclimatic Maps, with daily temperatures below 0°C in the winter and above 40°C in the summer. Annual rainfall (average 550 mm) is mostly concentrated during the winter months, while only 101 mm of rainfall is recorded, on average, during sorghum crop cycle (1st May-15th August).

Biomass sorghum (cv. BIOMASS 133, Syngenta®) was sown on 9th, 12th and 4th May in the three years, respectively, in rows 0.5 m apart and 0.08 m between seeds in each row (250,000 seeds ha^{-1}). The crop was harvested before heading on 12th, 20th and 10th August in 2008, 2009 and 2010, respectively, at maximum dry matter accumulation, still rich in water and with simply glycosides composition (necessary for fermentative process in bio-ethanol production). The field experiments were carried out in a completely randomized block, setting four replications and elementary plots of 80 m^2 size, 16 rows per plot and 0.5 m apart. Water distribution was ensured by a drip irrigation system, with one line for each plant row and 4 L h^{-1} drippers and with one flow meter for each plot. As pre-sowing fertilization, 72 kg ha^{-1} of N and 87 kg ha^{-1} of P_2O_5 as diammonium phosphate were supplied. Moldboard plow, disk arrow and rotary tiller were used to prepare the soil for the sowing, similarly to local farmer practices. Weeds were controlled by herbicides before sowing and by hand-hoeing during the first part of growing cycle. The health of the plants was ensured by fungicides and insecticides when required.

Irrigation and water use

Crop evapotranspiration (ET_c, in mm) was measured in 2008 by means of two weighted lysimeters and crop coefficients (K_c) were estimated as ratio between ET_c and the reference evapotranspiration (ET_0, in mm), the latter was calculated using the FAO-Penman-Monteith model (Allen *et al.*, 1998). K_c derived from the first experimental year (Rinaldi & Garofalo, 2011) were used in 2009 and 2010 to calculate ET_c, as follows:

$$ET_c = ET_0 * K_c \quad [1]$$

Irrigation scheduling was set on the ET_c basis, restoring the water used by the crop whenever the ET_c reached 60 mm (subtracting rainfall), in order to compare four irrigation regimes: *I_125* = 125% ET_c, with each irrigation of 75 mm; *I_100* = 100% ET_c, with each irrigation of 60 mm; *I_75* = 75% ET_c, with each irrigation of 45 mm; and *I_50* = 50% ET_c, with each irrigation of 30 mm.

Growth analysis

Growth analysis was carried out at five sampling dates every two weeks from June to August: *ADM* was measured by taking a 0.5 linear meter sample from each plot and separated into stems, green and dead leaves. The plant material was dried at 80°C until the weight was constant. At harvest, the fresh biomass weight was determined on whole plot and the dry matter percentage on a 0.5 m linear meter sample.

To analyze the evolution of dry matter cumulated during crop growth cycle and compare the path of *ADM* among treatments and years, a sigmoid model (Vannella, 1998) was used:

$$ADM = \frac{ADM_{\max}}{(1+e^{-(t-t_0)/b})} \quad [2]$$

where ADM_{max} is the maximal value of *ADM*, *t* the time expressed in days after sowing, t_0 represents the period between sowing and time to reach 50% of the final maximal value and *b* the fitting parameter of the model.

Green leaf area index (*GAI*) —with a destructive method— was determined using the Delta T Devices (Decagon Devices Inc., WA, USA) leaf area meter. Daily green area index (GAI_i) was obtained from the five values recoded at sampling dates according to Mailhol *et al.* (1997), as follows:

$$GAI_i = GAI_{\max} * \left(\frac{\sum_{k-1}^{i} t_i - t_e}{t_m}\right)^2 * \exp\left(\frac{2}{\alpha} * \left(1 - \left(\frac{\sum_{k-1}^{i} t_i - t_e}{t_m}\right)^a\right)\right) \quad [3]$$

where GAI_{max} is the maximum *GAI*, t_i is the time at day *i*, t_e is the time at crop emergence, t_m is the time at GAI_{max} and α has a physical significance governing the *GAI* shape. GAI_{max}, t_m and *a* were the calculated values to fit the experimental data.

Daily potential transpiration (T_{pi}) was calculated starting from:

$$T_{pi} = (1 - e^{(k * GAIi * Cf)}) * (ET_0 * K_{cmid}) \quad [4]$$

where *k* (–0.7524) is the light extinction coefficient, calculated as the slope of regression line between the natural logarithm of diffuse non-intercepted sky radiation and *GAI*, both measured with a LI-COR 2000 portable area meter at sampling time, and K_{cmid} is the K_c measured at maximum canopy development. For each plot, the data derived from the average of six measurements carried out below the plant canopy during the middle of the day from 12:00 noon to 02:00 p.m., at each growing sample. GAI_i is the green leaf area at day *i* and *Cf* is the clumping factor (Nilson, 1971; Lang, 1986, 1987), calculated with the following equation:

$$Cf = 0.75 + (0.25) * (1 - e^{(-0.35 * LAId)}) \quad [5]$$

where GAI_i is the green leaf area index estimated with Eq. [3].

Irrigation and water use efficiencies

Gravimetric soil water measurements were carried out at 0.2, 0.4, 0.6, 0.8 and 1.2 m depths at sowing, harvest and growth analysis sampling dates, and soil moisture was expressed in volumetric content.

Seasonal water use (*WU,* in mm) was calculated according to the following simplified water balance equation:

$$WU = \pm \Delta SWC + R + I \quad [6]$$

where ΔSWC is the variation, between seeding and harvest dates, of the volumetric soil water content in the 0-1.2 m depth layer, *R* is the rainfall and *I* the irrigations; all variable parameters are expressed in mm.

Usually, *WUE* and *IWUE* (kg m^{-3}) are calculated applying the formula proposed by Tanner & Sinclair (1983), taking into account only the final value of *ADM* and the cumulated value of water used for irrigation or the water used by crops. In this work, *WUE* and *IWUE* were calculated as the slope of the linear regression between *ADM* (dependent variable) and *WU* (*WUE*) and between *ADM* and irrigation (*IWUE*). All the variables were measured at each sampling data (*i*).

$$ADM_i = IWUE * \sum_{i=sowing}^{i=harvest} Irrigation \pm b$$
$$ADM_i = WUE * \sum_{i=sowing}^{i=harvest} WaterUse \pm b \quad [7]$$

The alternative approach to calculate *WUE* was with *WU* normalized by vapour pressure deficit (*VPD*, in kPa). For linear regression between *ADM* and irrigation, the intercept (*b*) was forced to zero, whereas in the regression between *ADM* and *WU* or *WUvpd*, the values of intercept on X axis (*–b/a*) provided an indication on water lost by soil evaporation (Passioura, 1977).

$$ADM_i = WUEvpd * \sum_{i=sowing}^{i=harvest} (WaterUse / VPD) \pm b \quad [8]$$

VPD (kPa; Murray, 1967) was calculated from daily maximum and minimum temperature and maximum and minimum relative humidity.

Water stress analysis

Plant efficiency to convert water in biomass was assessed with different indicators of water stress. One of these, the water stress index (*WSI*; Idso *et al*., 1981), was calculated as slope of linear regression, at intercept forced to zero, between cumulated maximum evapotranspiration (ET_m) and *WU*.

ET_m in 2008 was measured by means of weighted lysimeters, whereas in 2009 and 2010 ET_m was calculated by multiplying ET_0 by Kc_{max}. This latter derived from K_c estimated in 2008, but correcting K_{cmid} with climatic conditions and plant height (Allen *et al*., 1998).

In particular:

$$K_{cb} = K_{cmid} + \left(0.04 * (u_2 - 2) - 0.004 * (RH_{min} - 45)\right) * \left(\frac{h}{3}\right)^{0.3} \quad [9]$$

where K_{cb} is K_{cmid} corrected, u_2 is the wind speed (m^2 s^{-1}) and *h* is the maximum plant height (m).

Since *WSI* considers also the water lost by soil evaporation, it does not involve the water effectively transpired by the crop. Therefore, a correct evaluation of water stress index could be done using the relationship between potential (T_p) and actual transpiration (T_{act}). T_{act} was estimated with Eq. [6], but starting from GAI_i greater than 3.0 m^2 m^{-2}, assuming that after this value, the soil is completely shaded by canopy and so evaporation is negligible (Ritchie, 1972).

At this point, the water stress index due to gap between cumulative T_p and T_{act} for each sampling date was calculated as slope of linear regression, with intercept forced to zero, as follows:

$$WSI_t = \frac{\sum_{d=GAI>3}^{b=harvest} T_{act}}{\sum_{d=GAI>3}^{d=harvest} T_p} \quad [10]$$

From T_p cumulated between two sampling times was derived daily T_{act} (T_{acti}):

$$T_{acti} = T_p * \left(1 - \frac{\left(\left(\exp\left((D_{rel} * f\right) - 1\right)\right)}{\exp(f) - 1}\right) \quad [11]$$

where D_{rel} and *f* are parameters to fit cumulative T_{acti} with T_p. D_{rel} can be considered as the fraction of total crop available water (*CAW*, mm) at which T_p is reduced to T_{act} through stomatal closure and *f* represents the effect of water depletion on stomatal closure; at higher values of *f* correspond low values of water stress. To assess accurately the D_{rel} as a reference value for stomatal closure in biomass sorghum, it is necessary to relate

D_{rel} to *CAW*, the latter calculated as the sum of soil water content variation, rain and irrigation, taking as starting point the time when *GAI* is greater than 3.0 m^2 m^{-2}.

Analysis of variance of the data was carried out using a "randomized block" design model, and least significant difference (LSD) was used to compare mean values.

Results

Climatic behaviours

In Suppl. Table 1 [pdf online] are reported the climatic data recorded during the years of experiment and the average values recorded at Foggia in a long term period (1952-2007). The maximum (T_{max}) and minimum (T_{min}) temperatures were different over the three years from the first part of growing cycle. May 2009 was characterized by T_{max} and T_{min} greater than those of 2008 and 2010, with T_{max} characterized by values greater than 10°C compared with long term averages. However, 2010 was characterized by slightly lower *T* compared to 2008 and 2009 in the second part of growing cycle or from July to harvest time.

The same consideration can be made for daily global radiation (R_g), with greater differences found in May 2009 than in 2008 and 2010. In the first two weeks of June, R_g was lower in 2008 than in the other two years, but globally, had no influence on crop growth (sowing dates: 9th, 12th and 4th May; emergence dates: 20th, 25th and 13th May, in 2008, 2009 and 2010, respectively). The first and the third year were similar in terms of cumulated rainfall, 67 mm and 76 mm respectively, whereas in 2009, 92 mm were recorded. But a very large difference has been attributed to rainfall cumulated from 1st January to the sowing date, equal to 168 mm, 418 mm and 255 mm for 2008, 2009 and 2010, respectively. Comparable averages were observed in the three years as regards daily reference evapotranspiration (ET_0), but these were slightly greater than long-term values. A detailed description of climatic behaviours is reported by Rinaldi & Garofalo (2011).

Irrigation and water use

In Table 1, the number of irrigations, the amount of water applied, Δ*SWC* and the seasonal water use (*WU*) are reported. In the first and third year the greatest

Table 1. Main information about irrigation of biomass sorghum during the three experimental years

Year	Water regimes	Number of irrigations	Irrigation water aplied (mm)	ΔSWC (mm)	Water use (mm)
2008	*I_125*	8	550	148^{bc}	791^{a}
	I_100	8	460	110^{c}	633^{bc}
	I_750	8	370	178^{b}	611^{bc}
	I_500	8	280	223^{a}	566^{c}
Average			*415*	172^{b}	650^{a}
2009	*I_125*	6	365	434^{a}	891^{a}
	I_100	6	305	371^{a}	768^{b}
	I_750	6	245	365^{ab}	702^{c}
	I_500	6	185	317^{b}	594^{d}
Average			*275*	372^{a}	739^{a}
2010	*I_125*	8	565	211^{a}	852^{a}
	I_100	8	452	178^{a}	706^{b}
	I_750	8	339	122^{c}	537^{c}
	I_500	8	226	152^{bc}	454^{d}
Average			*396*	166^{b}	637^{a}
2008-10 *Avg.*		*7*	*362*	*237*	*675*

Different letters indicate significant differences between means at $p < 0.05$ level (LSD test).

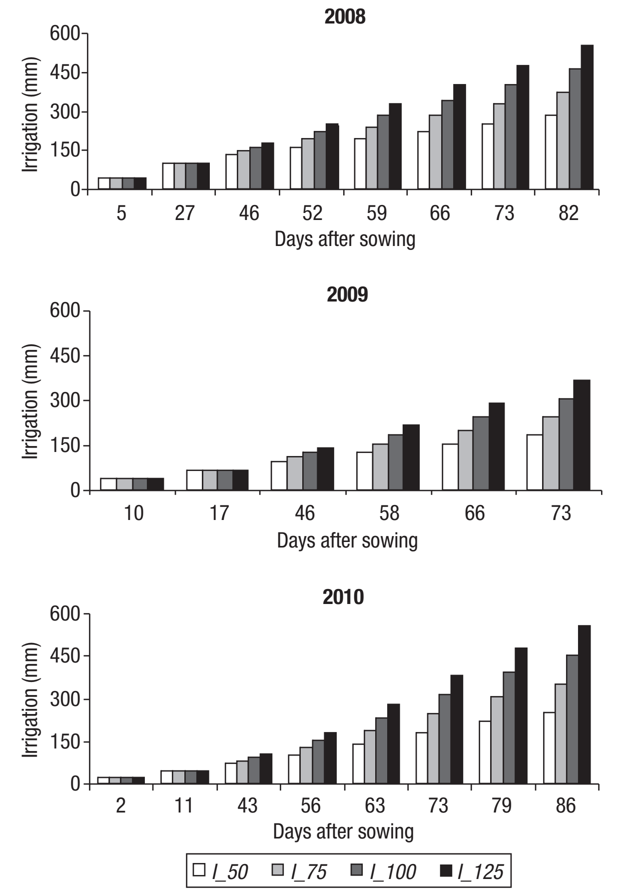

Figure 1. Times and cumulated amounts of water applied with irrigation for the four irrigation treatments and in the three years.

component of *WU* (Eq. [6]) was irrigation (*I*), while in the second year was ΔSWC, the latter representing the water stored in the soil layers trough rainfall before sowing and subsequently used by crop during the growing cycle. This difference in water accumulated into soil during the winter and spring months could explain the increase in irrigation water supply (Fig. 1) in the first and in the third year of experiment (415 mm in 2008 and 396 mm in 2010) compared with the second one (275 mm in 2009).

The crop *WU* ranges between minimum and maximum of irrigation treatments and is greater in the first and third year than in the second one (Table 1).

Growth analysis

The main parameters (ADM_{max}, t_o and b) of sigmoid function (Eq. [2]) used to fit the function with the observed *ADM* data are reported in Table 2. The coefficient of determination (R^2) was always high, especially in 2009 and 2010, but also in 2008 it was near to 0.90. The goodness of parameterization is shown by the curve of evolution of dry biomass (Fig. 2) where the fitted line is always close to mean of experimental data and its standard deviation. From emergence to maximum, *ADM* showed an exponential increase, even if some differences emerged among years. In fact, in 2008 the exponential phase is more pronounced, but within a shorter period and lower absolute values than 2009 and 2010. Moreover, *ADM* stopped earlier in 2008 than in the other two years. The final crop yield in terms of *ADM* was significantly different between *I_125* and *I_50*. The exponential phase of crop growth in 2009 was more smoothed and delayed in time, reaching the maximum value of this phase at about 90 days after sowing; differences in *ADM* were observed already at 60 days and kept until harvest, with a clear separation between *I_125* and *I_100* compared to *I_75* and *I_50*. The third year had an intermediate pattern between 2008 and 2009. Exponential crop growth phase stopped at about 80 days after sowing for *I_125*, *I_100* and *I_75*, while *I_50* showed a faster development but a lower dry matter accumulation up to the harvest. As shown in Fig. 2, in 2009 the harvest occurred about 20 days after compared to the other years, since the plant delayed the flowering stage, fixed as harvest time. Indeed, in 2009 was recorded (not shown) mean temperature, from the end of July to the first decade of August, lower compared to 2008 and 2010, lengthening the crop growing cycle and allowing global increment in dry matter accumulation of 32% higher than 2008 and 2010. Probably in 2008 and 2010, the shortening of the growing cycle, did not lead to the full exploitation the water availability for the sorghum, especially in the hottest period of growth, on the contrary assessed in 2009, that coupled with similar climatic behaviour, established a smaller differentiation in term of *ADM* accumulation within and between years and treatments, compared to 2009.

Values for GAI_{max}, t_m, a and R^2 are reported in Table 2. The lowest R^2 value was observed in 2009 but, globally, the sigmoid function curves were within the standard deviation in all the treatments in the three years (Fig. 2). As for *ADM*, in 2008 biomass sorghum had GAI_{max} values lower than 2009 and 2010. The differences among irrigation treatments were noticeable after the second irrigation (Fig. 2) and kept until harvest, when *I_125* and *I_100* had similar *GAI* values and greater

Table 2. Parameters for the *ADM* and *GAI* sigmoid functions (Eq. [2] and [3]), and coefficient of determination from linear regression (forced to 0), considering values from all crop growing cycle

Year	Water regime	ADM_{max}	Parameters			GAI_{max}	Parameters		
			t_o	b	R^2		t_m	a	R^2
2008	*I_125*	2,900^a	50^a	6.3^a	0.85	8.00^a	64^a	3.4^b	0.72
	I_100	2,450^a	49^a	7.1^a	0.92	7.34^a	63^a	2.8^{bc}	0.94
	I_750	2,100^{ab}	47^a	5.1^b	0.85	6.53^b	61^a	3.7^a	0.97
	I_500	1,800^b	47^a	4.9^b	0.94	6.18^b	63^a	4.1^a	0.93
Average		*2,313^a*	*48^b*	*5.9^c*	*0.89*	*7.01^b*	*63^a*	*3.5^b*	*0.89*
2009	*I_125*	4,167^a	63^a	15.1^a	0.96	11.17^a	66^a	4.5^a	0.79
	I_100	3,700^{ab}	61^a	12.2^b	0.99	10.82^a	70^a	4.7^a	0.78
	I_750	2,450^b	64^a	15.6^a	0.87	8.98^{ab}	65^a	3.5^b	0.75
	I_500	1,900^c	62^a	13.4^{ab}	0.98	7.00^b	64^a	3.4^b	0.87
Average		*3,054^a*	*63^a*	*14.1^a*	*0.97*	*9.49^a*	*67^a*	*4.0^b*	*0.80*
2010	*I_125*	3,048^a	62^a	8.6^a	0.93	9.89^a	78^a	9.9^{ab}	0.96
	I_100	2,962^{ab}	63^a	8.7^a	0.95	10.50^a	83^a	13.3^a	0.92
	I_750	2,800^b	58^a	6.6^b	0.91	9.51^{ab}	84^a	8.8^b	0.98
	I_500	2,299^c	53^b	5.9^b	0.86	8.00^b	76^a	7.0^c	0.99
Average		*2,777^a*	*59^{ab}*	*7.5^b*	*0.99*	*9.48^a*	*80^b*	*9.8^a*	*0.96*
2008-10 *Avg.*		*2,715*	*57*	*9.1*	*0.93*	*8.66*	*70*	*5.8*	*0.88*

ADM_{max}: maximum above dry matter (in g m^{-2}); t_0: period between sowing and time to reach 50% of the final maximum value; b: fitted parameter; GAI_{max}: maximum green area index (in m^2 m^{-2}); t_m: time to reach GAI_{max}; a: fitted parameter. Different letters indicate significant differences between means at $p < 0.05$ level (LSD test).

than *I_75* and *I_50*. In 2009, the canopy expansion was very rapid especially compared to 2008 and 2010, but the canopy decline was fast as well. A high soil water content at sowing allowed *I_125*, *I_100* and *I_75* treatments to obtain similar *GAI* values regardless of different irrigation water supplies until 65 days after sowing; but after this point, *I_75* showed a fast leaves senescence and at harvest was closer to *I_50*. The behaviour of *GAI* in 2010 was more diluted over time with the maximum *GAI* value reached later than in the previous two years. *I_125* showed higher values than the other irrigation treatments during exponential canopy expansion (from 50 to 70 days after sowing). More detailed results about *GAI* and *ADM* were reported by Rinaldi & Garofalo (2011).

Irrigation and water use efficiencies

In the first year, reduction in water supply favoured an increment of *IWUE,* with the highest value in *I_50* treatment (5.66 kg m^{-3}), supplying 280 mm of water, followed by *I_75*, *I_100* and *I_125* treatments (Table 3). On the contrary, in the second year of experiment, no statistically significant differences between irrigation treatments were evident in *IWUE*, with an average value equal to 11.33 kg m^{-3}, more than double the average value recorded in 2008. In 2010, *IWUE* increased with decreasing irrigation water supply, making *I_50* the treatment with the absolute highest value (12.42 kg m^{-3}). Dercas & Liakatas (2007) reported that *IWUE* does not change with irrigation, and they found a value (4.45 kg m^{-3}) closer to the first experimental year than the second and third one.

The slopes of regression lines between *ADM* and water used by the crop at each sampling (Table 4) correspond to the *WUE* (kg m^{-3}). In the first and third year, an average value of 4.16 kg m^{-3} was statistically lower than *WUE* obtained in the second year (7.36 kg m^{-3}). It was statistically similar among treatments in 2008 and 2009, while in 2010, *I_125* and *I_100* differed from *I_75* and *I_50*. This large variability in *WUE* of sorghum as consequence of different water supplies is confirmed by different authors.

The not productive water, or the water lost by soil evaporation (Passioura, 1977), estimated as the ratio

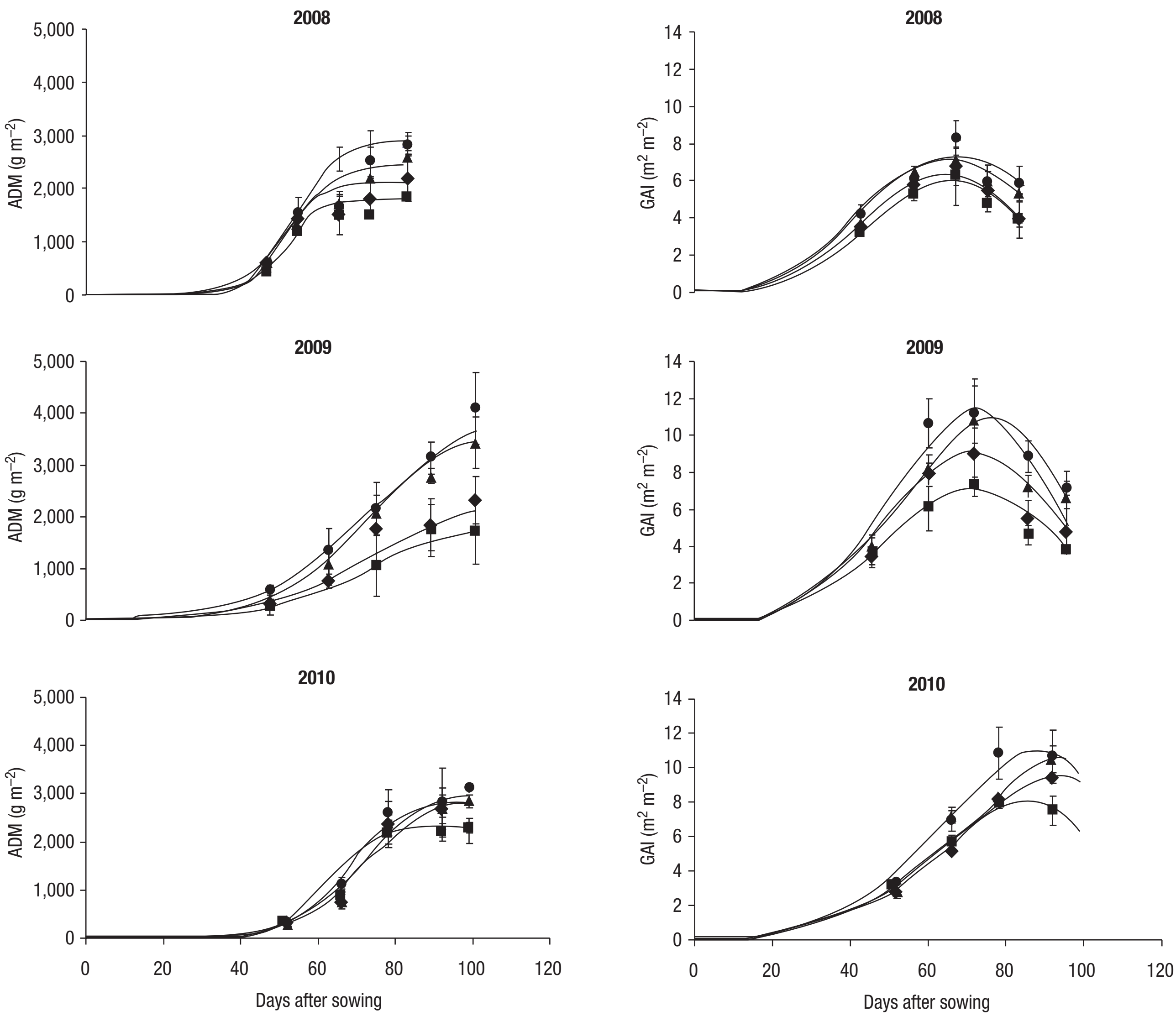

Figure 2. Dynamic of total above dry matter (*ADM*; line) and green area index (*GAI*; line) and experimental data observed during sorghum growing cycle. For treatments: *I_125* circle; *I_100* triangle; *I_75* rhombus; *I_50* square. Vertical bars indicate ± standard deviation of means.

between the intercept (*b*) and the slope (*WUE*) of the linear regression between *WU* and *ADM* (Eq. [7]) is reported in Table 4. In 2008, it was 124 mm (22% of seasonal *WU)*, 266 mm in 2009 (44%) and 63 mm (10%) in 2010. This so large difference between years can be explained by the different rainfall patterns before sowing and the subsequently soil water stored in 2009; moreover when the canopy did not completely cover the soil surface (May), in 2009 were recorded high mean temperature, ET_0 and R_g, climatic factors influencing the water lost by soil evaporation.

Moreover, some of not productive water might come from the saturation of vapour-pressure deficit (*VPD*), since the *VPD* decreases leaf conductance and photosynthesis, and also trough stomatal closure at high leaf water-potential (Bunce, 1985, 1988).

As mentioned above, *WUE* in 2009 was about 75% greater than in 2008 and 2010. This gap was considerably reduced when the comparison was made with *WUvpd* (Table 5). In fact, despite 2009 showed the highest value (19.80 kg m^{-3} kPa^{-1}) and 2008 and 2010 the lowest ones (14.36 and 12.99 kg m^{-3} kPa^{-1}, respectively), the gap was reduced to 27% in 2008 and 34% in 2010, compared with 2009.

We can observe that the not productive water was substantially similar among years (46, 76 and 64 mm),

Table 3. Coefficient of determination (R^2), slope (a or *IWUE,* kg m^{-3}), standard error for the slope (*SE*) and significance probability (p), for the linear regression (intercept forced to 0, according to Eq. [7]), between sorghum aboveground dry biomass (g m^{-2}) and irrigation (mm)

Year	Water regimes	R^2	*a* or *IWUE*	SE	*p*
2008	*I_125*	0.78	4.38[c]	0.28	< 0.001
	I_100	0.80	4.81[bc]	0.27	< 0.001
	I_75	0.66	5.12[ab]	0.39	< 0.001
	I_50	0.68	5.66[a]	0.37	< 0.001
Average		*0.72*	*4.79[c]*	*0.16*	*< 0.001*
2009	*I_125*	0.62	10.65	0.86	< 0.001
	I_100	0.66	12.04	0.91	< 0.001
	I_75	0.58	11.65	1.00	< 0.001
	I_50	0.50	11.41	1.08	< 0.001
Average		*0.65*	*11.33[a]*	*0.46*	*< 0.001*
2010	*I_125*	0.73	6.65[d]	0.48	< 0.001
	I_100	0.78	7.66[c]	0.48	< 0.001
	I_75	0.81	9.60[b]	0.58	< 0.001
	I_50	0.71	12.42[a]	0.87	< 0.001
Average		*0.61*	*7.90[b]*	*0.34*	*< 0.001*
2008-10 *Avg.*		*0.31*	*7.68*	*0.29*	*< 0.001*

The average values of the three years and, for each year, among irrigation treatments, followed by different letters, are different at $p = 0.05$ (LSD test).

which disagrees with the observed results of *WUE.* This points out that normalization of *WU* with *VPD* takes into account the not productive water from canopy rather than from soil, since *VPD* between sub-stomatal cavity and outside air resulted in loss of water from leaf surface.

Although differences between the three years diminished if we consider the *WUEvpd* rather than *WUE*, differences among treatments and years remained, underlining as other factors (for example, radiation interception and radiation use efficiency) linked to water use are involved in crop growth (Rinaldi & Garofalo, 2011).

Water stress analysis

The linear regression (intercept forced to 0) between *WU* and ET_m is reported in Fig. 3, where the slope coefficient (*WSI*) can be considered as an indicator of crop water status.

In 2008, *WSI* was equal to 1 in *I_50* and *I_75*, with no evidence in water stress status, despite their water supply was reduced to 50% and 25%, respectively, compared with *I_100*. This is probably due to a great capacity of deficit irrigated sorghum to extract efficiently water from soil, especially in the deeper soil layers. Also in 2009, *WSI* was equal or higher than 1.0 in *I_50* and *I_75*, and this shows as biomass sorghum is a crop with an elevated capacity to adapt itself to water stress conditions. On the contrary, observing the path in 2010, *WSI* was in agreement with the irrigation water supply.

An alternative method to estimate the water stress, which excluded the soil evaporative component, was assessed through the comparison between T_p and T_{act}. It can be considered the response of crop to reduction in water availability; in fact, the plant reduces leaves growth in order to adapt the transpiration process to soil water availability (T_p) and closes the stomata (T_{act}) in water stress condition. Daily T_p for all years and all water (irrigation) treatments are reported in Fig. 4. Of course, the dynamic of T_p is influenced by *GAI*, but differences in plant T_p among treatments and years are highly reduced, especially at the maximum crop canopy expansion. As expected, T_p in sorghum reached very high values (up to 6 mm), starting from 40 days after sowing to GAI_{max} (up to 10 mm).

The regression lines between cumulative T_{act} and T_p are reported in Fig. 5, and the slopes represent WSI_t. These values were similar in 2008 and 2010 for *I_125*

Table 4. Coefficient of determination (R^2), slope (*a* or *WUE,* kg m^{-3}), intercept (*b*), standard error for the slope (*SE*), significance probability (*p*) and not productive water (*NPW*, mm) as *–b/a* of Eq. [7], between sorghum aboveground dry biomass (g m^{-2}) and water use (mm)

Year	Water regimes	R^2	*a* or *WUE*	*b*	SE	*p*(*a*)	*p*(*b*)	*NPW*
2008	*I_125*	0.84	4.41^{a}	–795	0.62	< 0.001	n.s.	180^{a}
	I_100	0.87	4.40^{a}	–432	0.62	< 0.001	n.s	98^{b}
	I_75	0.70	4.08^{a}	–380	0.95	< 0.001	n.s	93^{b}
	I_50	0.81	4.00^{a}	–497	0.68	< 0.001	n.s	124^{b}
Average		*0.80*	*4.09^{b}*	*–453*	*0.33*	*< 0.001*	*< 0.05*	*124^{b}*
2009	*I_125*	0.75	7.41^{a}	–2,190	1.19	< 0.001	< 0.05	296^{a}
	I_100	0.81	8.49^{a}	–2,378	1.16	< 0.001	< 0.01	280^{a}
	I_75	0.64	7.13^{a}	–1,840	1.49	< 0.001	< 0.05	258^{ab}
	I_50	0.63	6.90^{a}	–1,666	1.47	< 0.001	< 0.05	241^{b}
Average		*0.75*	*7.36^{a}*	*–1,923*	*0.56*	*< 0.001*	*< 0.001*	*269^{a}*
2010	*I_125*	0.87	4.02^{b}	–195	0.43	< 0.001	n.s.	49^{b}
	I_100	0.90	4.68^{b}	–285	0.44	< 0.001	n.s	61^{b}
	I_75	0.87	6.49^{a}	–619	0.68	< 0.001	< 0.05	95^{a}
	I_50	0.85	6.16^{a}	–287	0.73	< 0.001	n.s	47^{b}
Average		*0.78*	*4.22^{b}*	*30*	*0.29*	*< 0.001*	*n.s*	*63^{c}*
2008-10 *Avg.*		*0.69*	*5.07*	*–561*	*0.27*	*< 0.001*	*< 0.001*	*152*

The average values of the three years and, for each year, among irrigation treatments, followed by different letters, are different at $p = 0.05$ (LSD test).

Table 5. Coefficient of determination (R^2), slope (*a* or *WUEvpd,* kg m^{-3} kPa^{-1}), intercept (*b*), standard error for the slope (*SE*), significance probability (*p*) and not productive water (*NPW*, mm) as *–b/a* of Eq. [8], between sorghum aboveground dry biomass (g m^{-2}) and water use (mm)

Year	Water regimes	R^2	*a* or WUE_{vpd}	*b*	SE	*p*(*a*)	*p*(*b*)	*NPW*
2008	*I_125*	0.88	16.68^{a}	–1,181	2.13	< 0.001	< 0.05	71^{a}
	I_100	0.92	17.76^{a}	–802	1.86	< 0.001	< 0.05	45^{b}
	I_75	0.72	14.30^{a}	–597	3.17	< 0.001	n.s.	42^{b}
	I_50	0.70	11.46^{b}	–316	4.29	< 0.001	n.s.	28^{c}
Average		*0.77*	*14.36^{b}*	*–602*	*1.28*	*< 0.001*	*< 0.01*	*46^{b}*
2009	*I_125*	0.90	20.59^{a}	–1,833	1.92	< 0.001	< 0.01	89^{a}
	I_100	0.91	22.43^{a}	–1,816	1.92	< 0.001	< 0.001	81^{a}
	I_75	0.69	16.98^{b}	–1,161	3.13	< 0.001	n.s.	68^{b}
	I_50	0.70	15.24^{b}	–1,006	2.80	< 0.001	n.s.	66^{b}
Average		*0.82*	*19.80^{a}*	*–1,619*	*1.21*	*< 0.001*	*< 0.001*	*76^{a}*
2010	*I_125*	0.82	13.38^{c}	–823	1.56	< 0.001	< 0.05	62^{ab}
	I_100	0.86	13.62^{bc}	–962	1.54	< 0.001	< 0.01	71^{a}
	I_75	0.85	17.38^{a}	–1,490	2.02	< 0.001	< 0.001	86^{a}
	I_50	0.77	15.15^{ab}	–854	2.29	< 0.001	< 0.05	56^{b}
Average		*0.79*	*12.99^{b}*	*–745*	*0.88*	*< 0.001*	*< 0.001*	*69^{a}*
2008-10 *Avg.*		*0.76*	*15.87*	*–997*	*0.70*	*< 0.001*	*< 0.001*	*64*

The average values of the three years and, for each year, among irrigation treatments, followed by different letters, are different at $p = 0.05$ (LSD test).

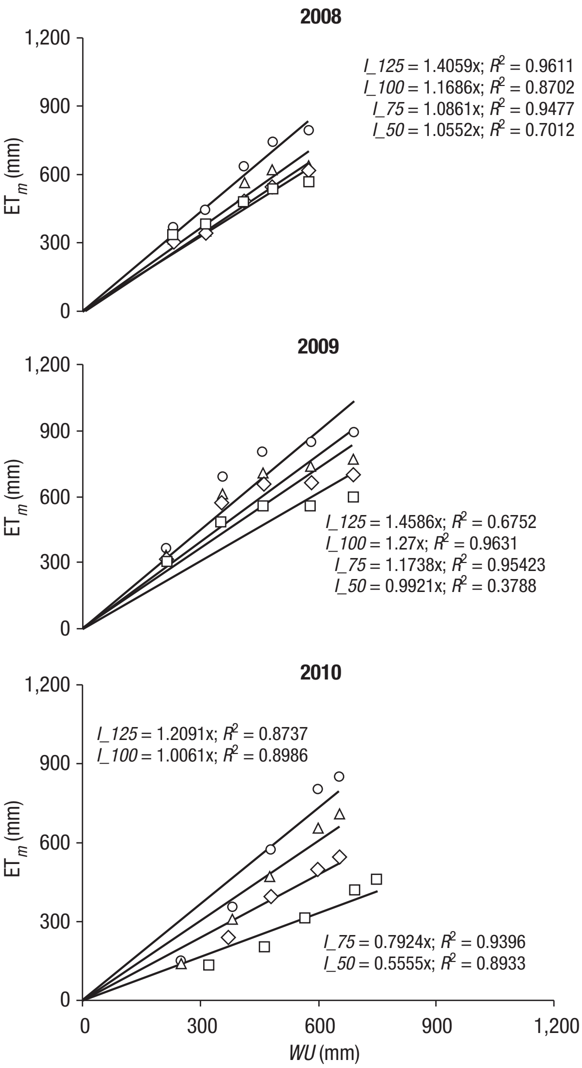

Figure 3. Linear regression between water used by biomass sorghum (*WU*, mm) and maximum evapotranspiration (ET_m, mm) during growing cycle. For treatments: *I_125* circle; *I_100* triangle; *I_75* rhombus; *I_50* square. The equation slopes represent *WSI* (see text).

treatment and slightly higher in 2009. Similar WSI_t was found in *I_100* treatment in the 3 years, but 2010 showed more stressed plants for *I_75* and *I_50* water regimes compared to 2008 and 2009. From these results, it is evident that *I_125* and *I_100* treatments also suffered from water stress condition, probably due to the time elapsed between the irrigation events.

WSI_t is an indicator of the water stress magnitude: coupling it with the time when the stress occurs, further information can be obtained on plant drought resistance or when stomata begin to be closed.

In Table 6, the fitted values for Eq. [11] are reported: they represent the fraction of *CAW* at which begins the gap between T_p and T_{act} (D_{rel}) and its inverse magnitude, *f*. From these values, T_{act} was estimated as shown in Fig. 4. Unlike T_p, a gap among treatments was observed for T_{act}: *I_125* and *I_100* showed better performance than *I_75* and *I_50*, especially in 2008 and 2009, while in 2010 a large superiority of *I_125* was observed. D_{rel} values increased with water supply in all the three years. The same behaviour for *f* value indicated a better adaptation to water stress in well watered regimes. Since *CAW* was different among years and irrigation treatments, to obtain a reference value of water availability threshold for a significant stomatal closure, *CAW* for each treatment was multiplied by D_{rel} (Table 6). This threshold for plant water stress was similar for all treatments within each year, with a mean of 187, 234 and 253 mm for the first, second and third experimental year, respectively. These values indicate the minimum water supply (soil water content, rain and irrigation) that biomass sorghum needs not to reduce significantly actual transpiration (stomatal closure). Furthermore, this threshold represents a basal water requirement of sorghum and confirms as sorghum is a drought resistant crop also for a prolonged period of time.

Discussion

This research was conducted to assess the feasibility to introduce the biomass sorghum in Mediterranean environment as a renewable energy source, evaluating the productivity in terms of biomass produced and the capability to obtain the best water use efficiency. Biomass produced and water used by crop cannot be evaluated separately and the parameter that relates these two factors should be stable and representative for the widest range of climatic management and soil conditions. Moreover, the knowledge of tolerance and/or the impact of water stress coupled to the soil water threshold at which sorghum suffers from water stress allow a more accurate irrigation management.

Irrigation and water use

Seasonal *WU* was different among years and these differences can be ascribed to the capability of sorghum to extract water from the deeper soil layers which were surely wetter in 2009 than in 2008 and 2010 because a lot of the rain fell before sowing date. *WU* in sorghum,

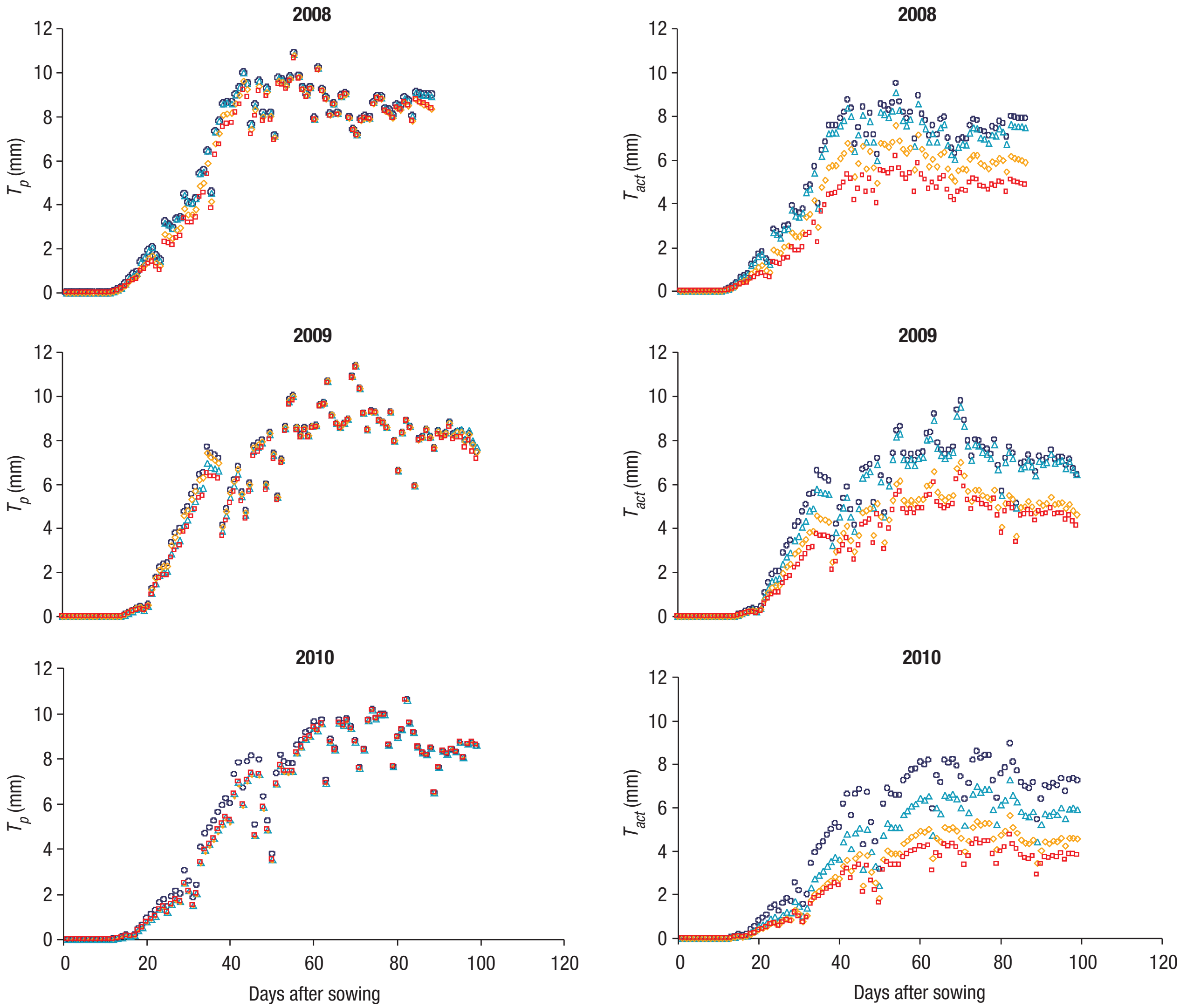

Figure 4. Daily potential transpiration (T_p; left) and actual transpiration (T_{act}; right) estimated during sorghum growing cycle. For treatments: *I_125* circle; *I_100* triangle; *I_75* rhombus; *I_50* square.

as reported by other authors, varies with irrigation regime; Dercas & Liakatas (2007) in Greece indicate how water use in sweet sorghum passes from 662 mm to 397 mm with 512 and 175 mm of irrigation, respectively. Farrè & Faci (2006) observed a reduction equal to 314 mm in seasonal crop evapotranspiration, passing from 500 to 100 mm of water applied with irrigation in Spain.

Growth analysis

Sorghum ADM_{max} attainable resulted influenced not only by irrigation treatment, but also by other factors. Indeed, although irrigation led to significant differences in term of ADM_{max} with the highest values for the well irrigated regimes within years, among years the crop response did not result univocal, indicating a strong interaction between year and irrigation. Similar results were obtained by Farah *et al*. (1997) in grain sorghum, with values of *ADM* oscillating between 3,050 and 2,210 g m^{-2}, passing from 627 to 498 mm of water supplied in Sudan; lowest *ADM* was obtained by Farrè & Faci (2006) in Northern Spain, with values of 1,838 g m^{-2} for 588 mm of evapotranspiration and 522 g m^{-2} for 274 mm of water used.

In limited water supply conditions, typical of Mediterranean environment, biomass sorghum showed a similar or slightly better performance and stability for dry matter accumulation compared with sweet sorghum.

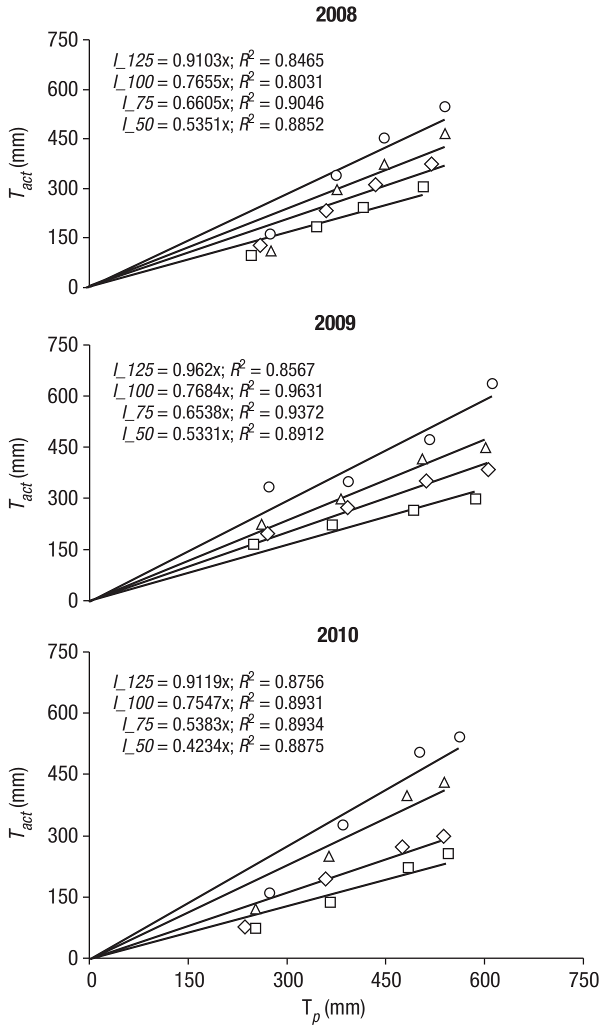

Figure 5. Linear regression between potential transpiration (T_p, mm) and actual transpiration (T_{act}, mm) during sorghum growing cycle. For treatments: *I_125* circle; *I_100* triangle; *I_75* rhombus; *I_50* square. The equation slopes represent WSI_t (see text).

Curt *et al*. (1995), reported as in central Spain, in sweet sorghum cultivated in low watered regime, the *ADM* at harvest ranged between 1,200 and 2,300 g m^{-2}, whereas in our field experiments, the ADM_{max} values (*I_50*) were between 1,800 and 2,299 g m^{-2}. In well irrigated conditions, the productive results were similar for biomass and sweet sorghum, about 3,200 g m^{-2} in Mastrorilli *et al*. (1995) *vs* 3,300 g m^{-2} in our experiment (*I_125*).

A greater advantage in term of dry matter accumulation of biomass sorghum in drougth conditions, emerged strongly if compared with the data reported by Berenguer & Faci (2001) on grain sorghum. Indeed, in grain sorghum, at water consumption comparable with *WU* in *I_50* treatment, the authors indicated values of aerial dry matter ranging between 1,026 and 1,249 g m^{-2} and so almost halved if compared to the results obtained for biomass sorghum in this research.

Reduction of *GAI* in sweet sorghum, as a consequence of reduction in water supply, is reported by Dercas & Liakatas (1999) who observed that by halving the water regime the peak of *GAI* was reduced by ~33%.

Irrigation and water use efficiencies

This interaction between year and irrigation could explain the differences in *IWUE* recorded for the three experimental years. Also in literature, the path of *IWUE* can change as consequence of irrigation management. Tolk & Howell (2003) showed *IWUE* decline at increasing irrigation, whereas Farrè & Faci (2006) gave an opposite indication on maize crop and reported a decrease in *IWUE* as consequence of increase of irrigation water supply going from 3.57 kg m^{-3} with 100 mm to 2.89 kg m^{-3} with 380 mm of irrigation water.

Other studies, however, reported contrasting results about sorghum. Amaducci *et al*. (2000) reported that fibre sorghum did not take advantage of irrigation in a well-watered environment of Northern Italy and this was also confirmed by Monti *et al*. (2002), with positive but not significant relationships of irrigation on *IWUE*. From these authors and from this research, it appears clear as in sorghum the *IWUE* is a parameter that is influenced by some other conditions which make this parameter not very reliable in different agricultural conditions.

One of these conditions could be the soil water content at sowing time. In barley, this is a crucial point for roots lengths and density and consequently for *ADM* as reported by Sahnoune *et al*. (2004). In addition, early water status seems to influence the number of tillers in cereals (Baldy, 1986; Guedira *et al*., 1997; Volkmar, 1997). Considering the average value recorded during all crop cycles, the number of tillers per plant in 2009 was 1.54, greater than in the other two years (1.22, on average).

The difference in soil water content among the three years of experiment was due to rain fell before sowing date; *IWUE* does not take into account this "aspect" that we consider, instead, very important when we need to parameterize above ground biomass and the available water for crop. This limitation can be overcome using *WUE*.

Table 6. Parameters for T_{act} function (Eq. [11]) and coefficient of determination from linear regression (forced to 0) considering values from all crop growing cycle, total crop available water (*CAW*, in mm) from *GAI*> 3.0 m² m⁻² and threshold for stomatal closure ($CAW*D_{rel}$, in mm)

Year	Treatment	Parameters				
		D_{rel}	*f*	R^2	*CAW*	$CAW*D_{rel}$
2008	*I_125*	0.29	2.04	0.62	639	188
	I_100	0.36	2.02	0.54	575	205
	I_75	0.40	0.91	0.81	429	172
	I_50	0.50	0.66	0.75	361	182
Average		*0.39*	*1.41*	*0.73*	*501*	*187*
2009	*I_125*	0.34	2.15	0.87	659	231
	I_100	0.38	2.15	0.97	587	221
	I_75	0.44	1.27	0.96	496	218
	I_50	0.54	0.92	0.93	400	216
Average		*0.43*	*1.62*	*0.87*	*536*	*234*
2010	*I_125*	0.34	1.35	0.83	697	237
	I_100	0.47	1.32	0.78	587	276
	I_75	0.62	1.30	0.79	385	240
	I_50	0.70	1.29	0.76	373	260
Average		*0.53*	*1.32*	*0.86*	*511*	*253*
2008-10 *Avg*		*0.42*	*1.49*	*0.82*	*516*	*225*

The first correlation between water used by crops and biomass was developed by de Wit (1958). Afterwards, several works are reported about the relationship between *WU* by the crops and the crop production parameters (Hanks, 1974; Stanhill, 1986; Monteith, 1993). As reported by Lindroth *et al*. (1994) and Beale *et al*. (1999), *WUE,* based on harvestable biomass and total annual evapotranspiration from the field, could be a useful tool to identify crops suitable for energy purpose. Mastrorilli *et al.* (1999), in a Mediterranean environment, reported values of *WUE* in sweet sorghum in well watered regimes, ranging between 5.6 and 4.1 kg m⁻³ despite small differences in water consumption (580 and 552 mm). In this research, at water stress condition for biomass sorghum (*I_50*), the water consumption was of 538 mm (three years average), comparable with the water use of sweet sorghum in optimal water supply (Mastrorilli *et al.*, 1995) showing better water extraction from the soil and appreciable use efficiency to convert water in biomass (5.7 kg m⁻³ for *I_50 vs* 5.3 kg m⁻³ for sweet sorghum) in Mediterranean environment. Reduction in *WUE* as a consequence of a decline of water used is also reported in grain sorghum: Steduto & Albrizio (2005), in Southern Italy, found *WUE* equal to 5.7 kg m⁻³ with 510 mm of water supply, but this value decreased by 23% when the *WU* decreased by only 5%. Values of *WUE* observed in 2009 are close to those reported in forage sorghum by Saeed & El-Nadi (1998), in Sudan, with a variation from 8.6 to 6.9 kg m⁻³, using a fixed level of water amount (700 mm), but varying the time between irrigation events and the relative amount of water. According to these assumptions, the values of *WUE* present in this research show sorghum as a valid energy crop in Mediterranean environment. In fact, considering an average value of *WUE* for the three years equal to 5.07 kg m⁻³, it results comparable with other values reported for different energy crops such as *Cynara* (between 3.1 and 5.5 kg m⁻³) reported by Fernandez & Curt (1996), *Spartina* (between 5.1 and 8.2 kg m⁻³), and *Miscanthus* (between 7.8 and 9.5 kg m⁻³) observed by Beale & Long (1997).

WUE seems to indicate a conservative behaviour of this parameter on water productivity in sorghum with small fluctuations among treatments within year (Table 5). *WUE* is a more conservative indicator compared tothe *IWUE* within year, but it shows weakness if we use it among years. In fact, values of *WUE* equal to 4.09 kg m⁻³ in 2008, 4.22 kg m⁻³ in 2010 and 7.36 kg m⁻³ in 2009, which are statistically different, suggest that probably different climatic conditions do not allow considering this parameter as representative in crop water productivity.

Many researches were carried out to identify which climatic variables could influence or drive plant transpiration and soil evaporation and to link the water productivity to climatic variables. In many of these studies, the vapour pressure gradient between leaf and air (Δe) is considered main engine in canopy transpiration (Norman, 1979). Tanner & Sinclair (1983) reported that "normalization" of transpiration by flux gradient (Δe, between leaf and air saturation vapour pressures) allows obtaining the best estimation of biomass as a function of water used. Since vapour pressures are temperature dependent, it is necessary to measure leaf temperature as much as above air temperature; if it is not possible, it is necessary to introduce simplification in gradient-flux calculation. This simplification can be obtained using evapotranspiration from water balance and *VPD* as reported in this paper. Paw & Gao (1988) and Asseng & Hsiao (2000) showed some weakness when *VPD* is used in substitution of leaf-to-air water vapour pressure difference (Δe), when canopy temperature is cooler or hotter than air temperature that causes a value of Δe substantially lower or higher, respectively. In crops such as sorghum, in which *LAI* overcomes quickly 3.0 m^2 m^{-2}, the shaded leaves are the most representative portion of the canopy, and thus, it is reasonable the assumption that all canopy leaves are at air temperature. *WUEvpd* was more efficient than *IWUE* and *WUE*, and the response of dry matter accumulation as a result of the water availability among years indicates that *WUEvpd* is more suitable to different climatic conditions.

An average value of *WUEvpd* equal to 15.9 kg m^{-3} kPa^{-1} let us to assess biomass sorghum as a high energy biomass crop, similar to or better than other crops such as *Miscanthus* for which Beale *et al.* (1999) reported values of *WUEvpd* equal to 10.7 kg m^{-3} kPa^{-1}.

Water stress analysis

WUE and *WUEvpd* provided a global judgement on sorghum water productivity. Reducing irrigation water supply, sorghum kept an appropriate canopy development among treatments without reducing the potential transpiration. But differences emerged when the actual versus potential transpiration was evaluated, with an average difference of only 23 mm in the most irrigated treatment and of 270 mm in the least irrigated one. The threshold of *CAW* to avoid physiological water stress was estimated about 225 mm; this threshold was similar for all treatments, although the sorghum in well watered regimes showed a better adaptation to water stress time, as highlighted by the higher value for *f* (adaptation to stomatal closure).

Conclusions

These results suggest that biomass sorghum has a high potential productivity (3-4,000 g m^{-2}) of dry matter in Mediterranean environments if it is supplied with an adequate seasonal water amount, not less than 300 mm. However, sorghum showed a good adaptation to water stress; on average, it shows a reduction of potential transpiration only below 225 mm of *CAW*.

The suitability of biomass sorghum as bioenergy crop in Mediterranean environment is underlined by similar or higher values of *WUE* and *ADM* if compared with sweet and grain sorghum, when the water supply is reduced. Moreover, the *WU* comparable with other sorghum cultivars in water stress conditions, in a shorter growing cycle, indicates as the biomass sorghum has a better capacity to extract water from deeper soil layers, avoiding prolonged water stress condition.

For this reason, by exploiting crop characteristics, it is possible to schedule deficit irrigation, obtaining good biomass yield, but saving water resources.

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