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An empirical framework for modelling transpiration use efficiency and radiation use efficiency of biomass sorghum in Mediterranean environment

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Abstract. In this experimental-modelling research, the potential biomass achievable by sorghum to be converted in bioethanol was assessed and then formalized into the radiation use efficiency (*RUE*) and transpiration use efficiency (*TUE*). Dry above-ground biomass (harvested at the flowering stage) ranged between 22.6 t ha^{-1} and 28.34 t ha^{-1} over two growing seasons with a total water consumption of 382 mm and 504 mm, respectively. Starting from sampling measurements, the empirical framework allowed to reproduce daily data of dry biomass, canopy development, intercepted photosynthetically active radiation and transpiration related efficiencies. *RUE* and *TUE* resulted 4.98 g MJ^{-1} and 7.45 kg m^{-3}, respectively. Their robustness (as stable parameters) was assessed through the validation process. Finally, the multiple linear regression approach, was applied to screen among limiting factors. It was pointed out that although sorghum was grown under irrigated regime, water demand resulted not fully fulfilled to achieve the full performance of the crop.

Keywords. Energy crop, crop modelling, bioethanol, biomass, water consumption.

INTRODUCTION

In the search for renewable energy sources, also promoted by the recent European directives (Renewable Energy Directive, RED I and RED II) sorghum (Sorghum bicolor L. (Moench) is seen as one of the main crops to produce bio (ethanol) energy.

Sorghum is highly efficient in using the available soil water, nitrogen and growing inputs. Indeed, in Mediterranean environment the crop showed higher efficiency respect to the agro-energy inputs, improving the energy performance and energy use efficiency of the bioethanol supply chain (Garofalo et al., 2015).

To assess the suitability of a crop for energy purpose, the potential biomass needs to be estimated, considering the consequences of the pedo-climatic context coupled to the soil-crop management on yield. This allows to screen and to rank the crops deputed to feed the energy supply chain and their requirements in water, solar radiation, nutrients.

Indeed, the growth and development of a crop is driven by several environmental components such as water availability, intercepted solar radiation and temperature. These factors affect all the hierarchically structured processes involved in the leaf gas exchange (CO_2 and H_2O), the storage of photosynthates, the accumulation of biomass and finally the yield (Garofalo and Rinaldi, 2015).

The strong relationship among crop water transpiration, solar radiation interception and biomass accumulation is made explicit by two empirical parameters: transpiration use efficiency (*TUE*) and radiation use efficiency (*RUE*). The photosynthetically active radiation (*PAR*; 400-700 nm waveband) is intercepted at canopy level to provide the radiant energy at chloroplast level to drive both CO_2 assimilation and H_2O transpiration processes.

The correlations between aboveground dry plant matter (*ADM*) and water used by the crop, as well as the radiation intercepted by the canopy, tend to remain linear in both well-watered and water deficit conditions (Hsiao, 1993; Hsiao and Bradford, 1983; Monteith, 1977; Tanner and Sinclair, 1983). The robustness of *RUE* and *TUE* resulted in their implementation (individually or both) in most of the crop simulation models as conservative parameters. A group of these models uses a crop growth module relying on *RUE* (*i.a.*, CERES, Ritchie et al. 1985; Jones and Kiniry 1986; Jones et al. 2003; EPIC, Jones et al. 1991; and STICS, Brisson et al. 2003).

TUE represents the driving parameter for another group of crop simulation models. It is the case of PARCH (Hess et al., 1997) and AquaCrop (Steduto et al., 2009). While CropSyst (Stöckle et al., 2003) estimates the crop biomass accumulation on the basis of both *TUE* and *RUE* parameters.

The estimation of *RUE* and *TUE* should be carried out under optimal-growing conditions, since their values are estimated based on the potential biomass accumulation and canopy development under a specific environment. Heat and/or water stresses that can occur during the growing period, negatively impact on the canopy development resulting in a reduction of the intercepted radiation, water transpired and anticipated senescence and as a result, on biomass.

Under Mediterranean environment, soil water shortage and high air temperature do occur during the spring-summer period, determining a high variability of estimated *RUE* and *TUE*.

Indeed, different values were reported for estimated *RUE* in Mediterranean environment, ranging from 3.4 g of *ADM* per MJ^{-1} of intercepted PAR (*iPar*; Mastrorilli et al., 1995) to 4.7 g MJ^{-1} (Perniola et al., 1996) or between 1.89 g MJ^{-1} and 3.81 g MJ^{-1} (Garofalo and Rinaldi, 2011).

On the other hand, further investigations on the water use efficiency in sorghum (*WUE*) reported values that ranged from 4.4 to 5.5 kg of *ADM* per m^{-3} of water used by the crop (Steduto and Albrizio, 2005) or from a minimum of 4.0 kg m^{-3} to a maximum 8.49 kg m^{-3} (Garofalo and Rinaldi, 2013).

In addition, uncertainty in *RUE* and *TUE* may arise according to the methods applied for their estimation.

Although *RUE* and *TUE* are commonly recognized as the slopes of the linear predictor function between the explanatory variable (*iPAR* or *Tr*) and the response variable (*ADM*), the extent of approximation is strictly dependent on the number of observations of such variables. The more data available, the better the estimate is.

In this context *ADM*, canopy cover (*CC*), *iPAR* and *Tr* collected on daily basis, would represent the optimal dataset, but technical, human or environmental constrains could not allow for daily sampling. In the light of that, most of the researches to estimate *RUE* and/or *TUE* relied on time-spaced samples or even on the data collected at harvest (Rinaldi and Garofalo, 2011; Kemanian et al., 2004; Kiniry et al., 2005, Garofalo and Rinaldi, 2015; Yimam et al., 2015; Liu and Stützel, 2004).

Dataset coming from samplings spared in time may not adequately draw the dynamics of growth, leading to an incorrect estimate of *RUE* and *TUE*.

However, empirical models can render a gradual transition from one phase of the growth to the next, at daily scale, by smoothing within a certain extent of approximation any sampling flaws (Yin et al., 2003).

Thus, in this paper is reported an empirical approach to develop a framework to artificially reproduce daily data on growth and development of sorghum. The experimental dataset collected over two growing years was functional to both calibration and validation process of the algorithms provided for the empirical approach. The artificial data at daily scale shaped by the system, allowed us to estimate *RUE* and *TUE* of sorghum. Finally, the multiple linear regression statistics allowed to assess if solar radiation or soil water availability were the main constraint for achieving the potential crop performance.

MATERIALS AND METHODS.

Experimental site

The field experiment was carried out over 2-year period from 2013 to 2014 in Rutigliano (lat: 40° 59' N, long: 17° 01' E, alt: 147 m a.s.l.), Southern Italy, in the experimental farm belonging to the Council for Agricultural Research and Economics (CREA).

Soil texture was classified as clay-loam (USDA, 2010) with physical-chemical characteristics of soil were reported in Table 1. At 0.6 m in depth, the parent rock reduces the capacity of the root systems to expand beyond this layer and the capillary rise from deeper soil layers. As a consequence, the impact of the groundwater to the rooting zone is totally negligible.

The experimental site is under the Mediterranean climate (UNESCO-FAO classification, 1963), characterized by warm and dry summers, with daily minimum air temperature ranging from 0-5°C and daily maximum temperature from 32 to 43°C. Annual rainfall (average 535 mm) is mostly concentrated during the winter months and class 'A pan' evaporation exceeds 7.5 mm day^{-1} during the summer months. Daily meteorological data - temperatures, humidity, rainfall, wind velocity and solar radiation - were recorded by the local meteorological station.

Finally, initial soil water content at sowing time was of 0.324 m^3 m^{-3} and 0.312 m^3 m^{-3} (0-0.6 m depth) in the first year and second year, respectively.

Field experiment

Biomass sorghum (cv. Bulldozer) was sown at the beginning of June in 2013 and in late May in 2014, in rows 0.45 m apart and 0.1 m between seeds in each row (7 kg of seeds per hectare). Sorghum was harvested before heading (when the crop achieved the maximum dry matter yield) or the second half of September in both years. The experimental trial was arranged a single plot of 80 m^2 size, 14 rows per plot. Water distribution was supplied by drip irrigation system: one line for each plant row; 4 L h^{-1} per dripper; 0.3 m dripper spacing. Irrigation volumes were measured by flow meters (one per plot). Before sowing, 120 kg ha^{-1} of N and 90 kg ha^{-1} of P_2O_5 were supplied as diammonium phosphate. Mouldboard plow, disk harrow 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 chemicals when required.

Tab. 1. Main physical-chemical characteristics of soil of the experimental site.

Parameter	Unit	Average	Standard deviation (±)
Sand	g 100g^{-1}	21	0.6
Silt	g 100g^{-1}	37	2.9
Clay	g 100g^{-1}	42	3.6
Soil electrical conductivity 1:1	dS m^{-1}	0.6	0.05
Field Capacity	m3 m^{-3}	0.36	0.03
Wilting Point	m3 m^{-3}	0.22	0.02
Soil Organic Content	g kg^{-1}	14	1.1
Total Nitrogen	g kg^{-1}	1.5	0.2
Available Phosphorus	mg kg^{-1}	71	3.1
Exchangeable Potassium	mg kg^{-1}	540	61

During the experimental seasons, weather data were measured by means of a meteorological station located in the experimental farm. Maximum and minimum temperatures, global solar radiation (*Rg*), precipitation, wind speed and relative maximum and minimum air humidity were collected on a daily basis.

Growth analysis

Plants from 1- linear meter were sampled eight times during both sorghum seasons and each sample was replicated three times. The above ground biomass was obtained by adding stems and leaves. The plant material was dried at 80 °C until the weight was constant. At harvest, biomass samples covered a surface area of 2 m x 2 m and dry weight of stem and leaf determined accordingly.

To investigate the dynamic of the dry matter accumulated during the growing period, the sigmoid model

(Vannella, 1998) was calibrated on the observed data of the most favourable (in terms of accumulated biomass and canopy development) growing season (2014):

$$ADM_i = \frac{ADM_{\max}}{(1+e^{(t_i-t_h)/b})} \quad (1)$$

where ADM_i is the above dry biomass (t ha^{-1}) at day i, ADM_{max} the maximum achievable value of ADM, t_i the time expressed in days after sowing, t_h represents the time between sowing and time to reach 50% of the ADM_{max} and b the fitting parameter of the model.

The green leaf area index (GAI, m^2 m^{-2}) was measured at each sampling date with a LI-COR 2000 portable area meter (LI-COR Biosciences, Lincoln, NE, USA). For each sampling, figures were derived by the average of six measurements carried out below the plant canopy, during the 12:00 to 02:00 p.m. daytime and for each of the three replications within the main plot.

Daily green leaf area index (GAI_i) was estimated by fitting the field data with a beta function (Yin et al., 2003):

$$GAI_i = GAI_{\max} * (1+\frac{t_e-t_i}{t_e-t_m}) * (\frac{t_i}{t_e})^{\frac{t_e}{t_e-t_m}} \quad (2)$$

where GAI_{max} is the maximum GAI, t_m represents the time between sowing and time to achieve GAI_{max}, t_e the time at the end of canopy growth.

The values of the parameters involved in Eqs (1, 2) were achieved by iterative procedure implemented in Excel (Solver add-in program) using the Generalized Reduced Gradient (GRG) Nonlinear algorithm as solving method.

Daily canopy cover (CC_i; 0-1) was estimated with the equation:

$$CC_i = 1 - e^{(-k^*GAI_i{}^*cf)} \quad (3)$$

where k is the light extinction coefficient (-0.75; Rinaldi and Garofalo, 2013) and cf is the clumping factor (Nilson 1971; Lang 1986, 1987), as follow:

$$cf = 0.75 + (0.25) * (1 - e^{(-0.35^*GAI_i)}) \quad (4)$$

Intercepted radiation and radiation use efficiency

The fraction of PAR intercepted by the canopy at daily scale ($iPAR_i$; MJ m^{-2}) was estimated as:

$$iPAR_i = CC_i * Rg_i * 0.48 \quad (5)$$

where Rg_i (daily global radiation) was measured with a thermophile pyranometer (305–2800-nm wavelength range) and 0.48 the fraction of solar radiation photosynthetically active.

RUE (g MJ^{-1}) was calculated as the slope of the linear regression between the cumulated daily values of ADM and $iPAR$ by forcing the intercept (b) to zero:

$$RUE = \frac{ADM_{i\,par}}{\sum_{i=sowing}^{i=harvest} iPAR_i} \quad (6)$$

Irrigation, transpiration and transpiration use efficiency

The reference evapotranspiration (ET_0, in mm), was calculated using the FAO-Penman-Monteith model (Allen et al., 1998).

Irrigations were scheduled according the crop evapotranspiration (ETc, mm), restoring the water used by sorghum whenever the 30 mm threshold was reached (subtracting rainfall).

ETc was calculated as follow:

$$ET_c = ET_0 * Kc \quad (7)$$

where Kc is the crop coefficient as reported by Rinaldi and Garofalo (2011) and ET_0, the reference evapotranspiration

Daily transpiration at day i (Tr_i) was calculated as:

$$Tr_i = CC_i * (Kc * ET_0) \quad (8)$$

Finally, TUE (kg m^{-3}) was calculated as the slope of the linear regression between cumulative ADM and water consumed by transpiration (Eq. (9):

$$TUE = \frac{ADM_{itr}}{\sum_{i=sowing}^{i=harvest} Tr_i} \quad (9)$$

with b (intercept) forced to 0.

Temperature limitation on growth

To account for the effect of temperature on growth and canopy development, the "T_{lim}" factor was calculated which describes the effect of daily average temperature T_m on biomass accumulation, as reported by Montieth (1977). T_{lim} was assessed as follow:

$$
\begin{aligned}
&T_{\lim} = 0 \;\; when \;\; \begin{matrix} T_m < T_b; \\ T_m > T_x \end{matrix} \\
&T_{\lim} = 1 \;\; when \;\; T_m = T_{opt} \\
&T_{\lim} = \frac{T_m - T_b}{T_{opt} - T_b} \;\; when \;\; T_b \le T_m \le T_{opt} \\
&T_{\lim} = \frac{T_{opt} - T_b}{T_m - T_b} \;\; when \;\; T_{opt} \le T_m \le T_x
\end{aligned}
\qquad (10)
$$

where T_b is the base temperature (8 °C), T_{opt} the optimal temperature for growth (25 °C) and T_x the maximum temperature threshold for growth (33 °C; Alagarswamy and Ritchie 1991; Hammer et al. 1993; Rinaldi and Garofalo, 2011; Djanaguiraman et al., 2014).

Thus, the fitting of the parameters reported in Eq (1) occurred in two steps. The first one, involved a preliminary estimate of ADM_{max}, t_m and b on observed data, after which ADM_i and GAI_i resulting from Eqs. (1-2) were recalculated multiplying their values by T_{lim}. Finally, a second fitting procedure of parameters was carried out based on daily ADM_i and GAI_i corrected for T_{lim} to refit their figures to the values observed at sampling date.

The plant development rate was expressed by the growing degree days, GDD (°C) which measures that measured the heat accumulation calculated as the difference between the daily mean temperature and $T_{b.}$

Validation of the framework

To check the robustness of the framework, Eqs. (1) and (2) were replicated on the 2013 growing season, keeping the values of their parameters, unchanged. The outcomes were adjusted by T_{lim} calculated based on the climatic pattern of 2013 and compared with the observed data.

Finally, for 2013 $iPAR_i$ was estimated with Eqs. (3-5) and Tr_i with Eqs. (8) and (9) to validate *ADM* radiation-dependent and *ADM* transpiration-dependent adjusted by T_{lim} by means of *RUE* and *TUE* values assessed in the calibration step, when the 2014 data-set was used.

Biomass-*RUE* dependent and biomass-*TUE* simulated with this approach, were compared with the 2013 observed data to validate the reliability of *RUE* and *TUE* computed with the calibration step.

RESULTS

Meteorological patterns

In 2013, during the first part of growing period, climate was characterized by peaks of maximum temperature (*Tmax*) up to 33 °C, up to 19 °C for minimum temperature (*Tmin*). Cooler temperatures characterized the period from late June until the third decade of July, where *Tmax* remained below 28 °C and *Tmin* below 18 °C (Fig. 1).

Except for some very hot days (daytime temperature up to 37 °C), the second part of the growing peri-

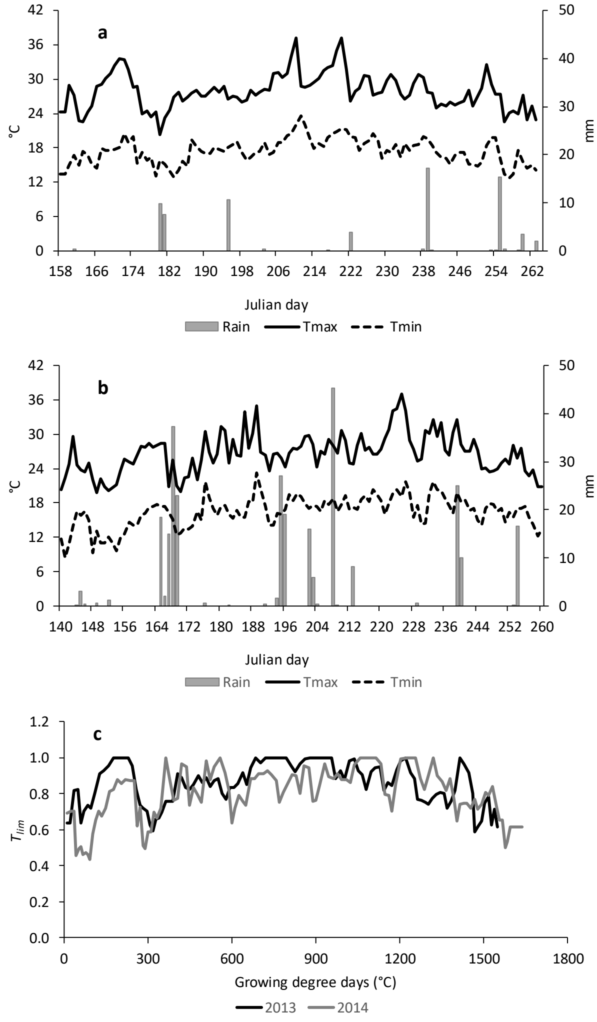

Fig. 1. Maximum temperature (Tmax; continuous line), minimum temperature (Tmin; dashed line), rain (grey columns) recorded in 2013 (a) and 2014 (b) growing season and Tlim (see text) behaviour.

od recorded temperature below 30 °C (*Tmax*) and 19 °C (*Tmin*) in August, to remain below 25 °C and 18 °C in September (hotter temperature in some days at the beginning of September, were observed).

Total rainfall in 2013 growing season was 72.4 mm, spaced over time, with two fairly rainy events, one at the end of August and the other in mid-September (Fig. 1).

The crop growing period of 2014 was warmer than in 2013, especially from 16th to 51st day after sowing (from June 4th to July 10th) with peaks of *Tmax* that exceeded 31 °C for several days and some events of *Tmin* above 20 °C.

Conversely, the middle part of the growing period was cooler in 2014 than in 2013, with *Tmax* rarely above 30 °C as well as Tmin which remained below 18 °C.

However, for the most of the second part of the growing season, temperature reached maximum peaks of 2-3 degrees above 30 °C, whereas *Tmin* was cooler than the first period of the growing period; the last part of the growing cycle in 2014, was slightly hotter than 2013, with *Tmax* that ranged from 23 to 27 °C and *Tmin* below 15 °C.

Rainfall in 2014 cultivation time frame was much higher than 2013 (157 mm vs 72 mm) with 96 mm falling on four consecutive days in June and 76 mm recorded from from 21st July to 1st.

Two following events for a total of 35 mm of rainfall characterized the end of August, whereas a single event of 17 mm concluded the growing period in 2014.

Crop growth and development analysis

The daily growth and canopy development curves of the 2014 growing season, resulting from the calibration of Eq. (1) and Eq. (2), were well fitted to the observed values of *ADM* ($R^2 = 0.976$) and *GAI (*$R^2 = 0.97$*;* fig. 2). It should be pointed out that the values of parameters of both models were preliminary calibrated to fit the estimated *ADM* and *GAI* to the observed values and recalibrated on daily values of *ADM* and *GAI* corrected by T_{lim}. In this way, parameters of Eq. (1) and (2) were predicted net of the effect of temperature on growth.

Over the 2014 growing season (year used for the calibration of the empirical models), the average temperature rarely achieved optimal values and T_{lim} was close to 1.

This trend was particularly noticeable from the middle to the final part of the growing season, where T_{lim} showed values between 0.9 and 0.7 or even below 0.7, mainly due to mean temperatures which remained below the optimal value (25 °C) rather than above the maximum threshold (33°C).

From 300 GDD to 1000 GDD, was observed a first growing phase characterized by an exponential convex growth, followed by a second phase (between 1000 GDD and 1500 GDD) identified by a concave senescent growth. The inflection point (transaction between the first and second growing phase) at which the development rate reached its maximum value (t_h) was formalized 78 days after sowing. Finally, the potential dry biomass achievable at harvest (net of limitations due to temperatures not optimal for the crop) was estimated as 32 t ha^{-1}, whereas the actual *ADM* at harvest was 28.32 t ha^{-1}. Such figure is consistent with the yield values reported in the international literature: in Greece (from 17 t ha^{-1} to 31 t ha^{-1}; Dercas and Liakatas, 2007), in Spain (18.38 t ha^{-1}, Farrè and Faci, 2006), in Italy (from 40.97 t ha^{-1} to 23.22 t ha^{-1}, Rinaldi and Garofalo, 2011)

As regards the development of canopy (*GAI*), the beta function curve highlighted the highest expansion rate in the first period of growing season (from 300 GDD to 700 GDD) with *tm* achieved at 65 days after sowing. After that, followed a near-linear development of the canopy (from 700 GDD to 1050 GDD) to reach the maximum value of 6.8 m^2 m^{-2} (5.2 m^2 m^{-2} when accounting for T_{lim} during the growing cycle) at 92 days after sowing (*te*), time to end the plant growth.

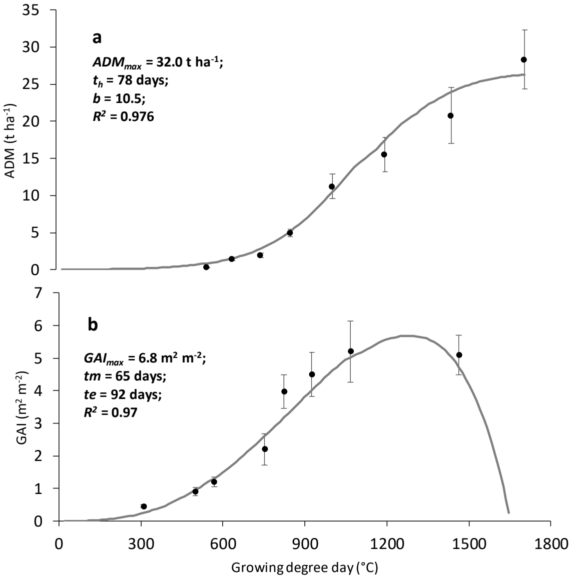

Fig. 2. Dynamic of total above dry matter (ADM a; line), green area index (GAI b; line) and experimental data (circle) observed during 2014 growing season. Vertical bars indicate ± standard deviation. The values of parameters of the empirical models are shown (see text).

Canopy radiation interception and radiation use efficiency

Sorghum reached a high value of *CC* (0.9) quite rapidly, or 64 days after sowing.

Basically, this value was reached with *GAI* of 3.34 m^2 m^{-2} keeping a high efficiency in radiation interception for more than 50% of its growing cycle (Fig. 3**a**) with performance in line with Fletcher et al. (2013) but slightly lower than Rinaldi and Garofalo (2013).

At the end of growing season, cumulative *iPAR* was of 568 MJ m^{-2}, with a linear increment of intercepted radiation from emergence to harvest (Fig. 3**b**), consistent with the value indicated by Narayanan et al. (2013) but less than that reported by Ceotto et al. (2013).

The strong correlation between dry biomass accumulated during the growing season and the radiation intercepted by the canopy is drawn by figure 3**c**. The slope of the linear regression between *iPAR* and *ADM* was equal to 0.0481, confirming the sorghum high efficiency (4.81 g MJ^{-1}) in converting the intercepted solar energy in photosynthates.

Our results pointed out a higher *RUE* compared to recent studies (e.g. 3.48 g MJ^{-1} reported by Ceotto et al., 2013; 3.23 g MJ^{-1} found out by Garofalo et al., 2011) but consistent with previous investigations (4.7 g MJ^{-1}, Perniola et al., 1995).

Obviously, the forcing to reproduce a logistic growth pattern through a linear regression model produces bias. A polynomial fitting would have matched the growth curve more accurately but would not have led to the formalization of a single parameter (*RUE*) of quick understanding and easy application.

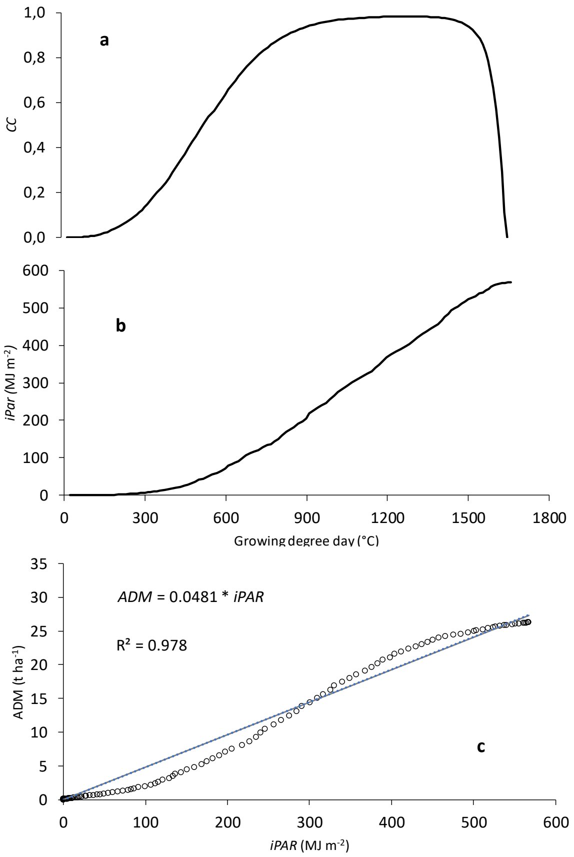

Fig. 3. Trend of the intercepted radiation (iPAR; a), canopy cover (CC; b) during the 2014 growing season and linear regression between iPAR and aboveground dry matter (ADM; c).

Plant transpiration and transpiration use efficiency

Total water supplied with irrigation in 2014 amounted to 225 mm, split in one application (15 mm) before sowing to restore the water field capacity and seven applications (30 mm each) over the 2014 growing season.

Rainfall plus water supply indicated a total water consumption (soil evaporation, drainage and crop, drainage and crop transpiration) equal to 475 mm (Fig. 4 a), in line with the finding (489 mm-517 mm) reported by Hao et al. (2014), or (446 mm-683 mm) indicated by Yimam et al. (2015) both calculated under well-watered regimes. It should be pointed out that to account for the effect of closed canopy on rainfall interception, a 22% reduction of water amount from precipitation in calculating *WU* (Kozak et al., 2007) was applied after *CC* reached 0.9.

The water daily transpired by the crop raised rapidly from 28 days after sowing to reach peaks of 7-10 mm between 80 and 100 days after sowing (Fig. 3**a**). The reported value of Tr_i was due to combined effect of the rapid expansion of canopy (in the early phenological stages) and the evaporative demand of the atmosphere (Fig 3**a**). On the other hand, the cumulative water transpired by the crop (see Eq. (8)) was 399 mm, with a trend synchronized with the canopy development (Fig. 3**b**). The discrepancy between *Tr* and the total water consumption represented the loss of water by evaporation and drainage, otherwise called not productive water, which was estimated to range between 61 mm and 280 mm in sorghum (Garofalo and Rinaldi, 2013).

Most of the abovementioned difference was accounted in the first part of the growing season, due to the evaporation from bare soil or partially covered by the canopy other than the crop transpiration. Once achieving *GAI* of 3.0 m^2 m^{-2} or a *CC* close to 0.9, *WU* was due to the plant transpiration, if the soil was completely shaded by canopy and so evaporation was negligible (Ritchie, 1972).

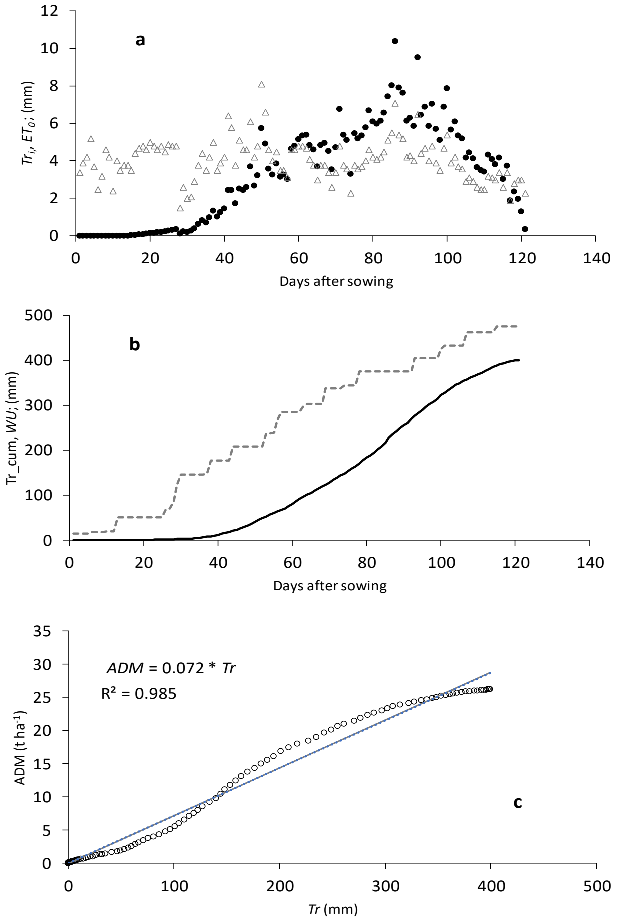

Fig. 4. Daily transpiration and reference evapotranspiration (Tri, ET0 a), cumulative transpiration (Tr_cum, continuous line) vs total water consumption (WU, dashed line; b) and linear regression between Tr and aboveground dry matter (ADM; c), in 2014 growing season.

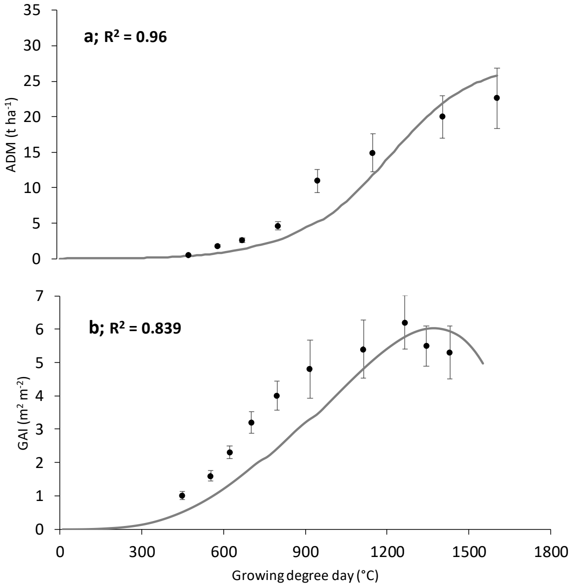

Fig. 5. Dynamic of total above dry matter (ADM a; line), green area index (GAI b; line) and experimental data (circle) observed during the growing season. Vertical bars indicate ± standard deviation.

At the end of the growing period the gap between the total water consumption and water transpired by the canopy was 76 mm.

The slope between the transpiration (net of water loss by evaporation or drainage) and cumulative dry biomass on daily basis was of 0.072 t mm^{-1} or 7.2 kg m^{-3} (Fig. 3**c**) a value higher than those reported by other researches (Thapa et al., 2017; Reddy and Angira, 2015) but consistent with other investigations (Garofalo and Rinaldi, 2013).

Validation of the empirical framework

To check the robustness of this framework, from the formalization of biomass accumulation and canopy development to the accuracy of the estimated *RUE* and *WUE*, the empirical structure was verified on experimental data collected over the 2013 growing season.

Basically, the parameters of Eqs. (1-5) and Eqs. (7-8) remained unchanged excepting for *Rg* and ET_0, as well as T_{lim}, that varied according to 2013 climate trend.

Validation process pointed out a satisfying matching between the experimental data of *ADM* and *GAI* with figures replicated by the empirical model (R^2 = 0.96 for *ADM*, Fig. 5**a**; R^2 = 0.839 for *GAI*; Fig 5**b**).

Water transpired by the crop in 2013 had a pattern close to that computed in 2014; indeed, the daily transpiration grew up rapidly from 30 to 80 days after sowing, passing from 1 mm to 6 mm and then settle between 6-8 mm at maximum canopy expansion and decline rapidly once reached the reproductive phase (Fig. 6**a**).

Cumulative *Tr* in 2013 was slightly lower than 2014 (- 29 mm), but *WU* was 22% lesser compared to the first growing season (Fig. 6**b**). A shorter distance between *WU* and *Tr* in 2013 was due to a lower amount of rainfall in this year compared to 2014 (reduced water loss by drainage) and lower evaporative demand of the environment (ET_0; Fig. 6**a**).

Once it was established that the framework was suitable to replicate the growth of the crop and development of the canopy, *ADM* of 2013 was estimated on the basis of computed *Tr* and *iPAR* (2013) and *TUE* and *RUE* of 2014.

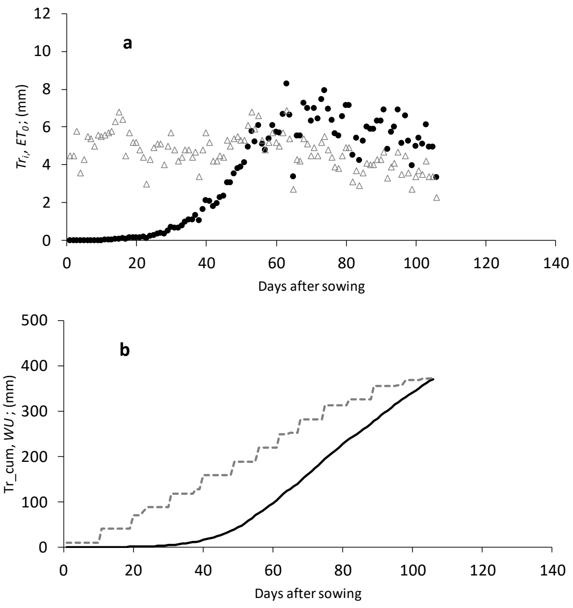

Fig. 6. Daily transpiration and reference evapotranspiration (Tri, ET0 a), cumulative transpiration (Tr_cum, continuous line) vs total water consumption (WU, dashed line; b) in 2013 growing season.

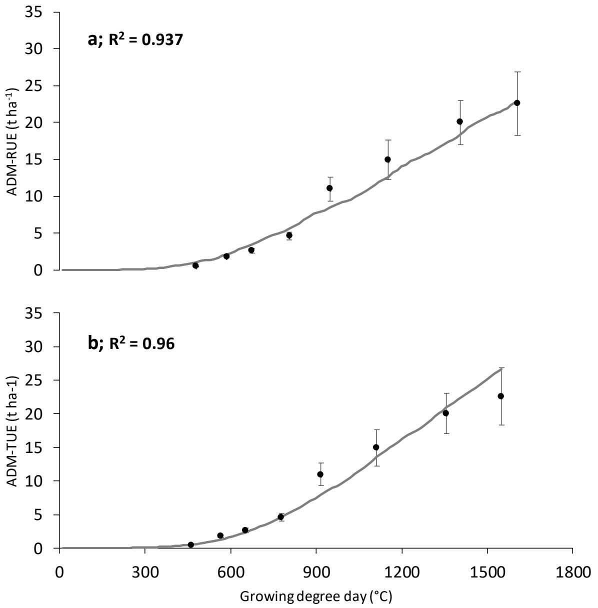

Fig. 7. Comparison between the trend of observed (full circle) aboveground dry matter (ADM) and ADM dependent on RUE (ADM-RUE; grey line, a) and ADM dependent on TUE (ADM-TUE, b) in 2013 growing season.

This procedure (validation step) allowed us to assess the stability and effectiveness of these parameters (*RUE* and *TUE*) as well as the empirical approach here proposed, in estimating the potential productivity of sorghum.

Formalization of *ADM* dependent on *RUE* (*ADM-RUE*) as well as *ADM* dependant on *TUE* (*ADM-TUE*) and T_{lim} acting on potential *ADM*, was congruent with the experimental data collected in 2013 (Fig. 7).

Effect of available water and radiation on plant performance

A sensitivity analysis was aimed at assessing whether the biomass accumulation was mainly affected by the intercepted radiation or by transpiration or by both drivers interacting each other, or again, if both parameters had the same weight. Specifically, the standardized multiple linear regression (Myers, 1990) was applied, with cumulative ADM_i as dependent response variable and cumulative Tr_i and cumulative $iPar_i$ as predictors for both years, as single factors and in interaction. In this way, it was assessed whether the daily increase in biomass was more sensitive to the daily amount of water used by the crop or to the intercepted radiation or, in other words, which was the limiting factor (if any).

The standardized regression coefficients (β) pointed out that transpiration was the main driver in regulating the accumulation of biomass and that interaction between *Tr* and *iPar* was not significant (Fig. 8).

DISCUSSION

Our experimental data confirmed the high capability of sorghum to produce high amount of biomass under well-watered irrigation regime, as reported in other investigations (Zegada-Lizarazu and Monti, 2012). However, the ability of this crop to thrive also under suboptimal conditions is well documented (Garofalo and Rinaldi, 2013) where other crops would struggle (Woods, 2001).

In addition, sorghum is known for being a low demanding N crop, even compared to other C4 crops. For example, it was highlighted that sorghum requires up to 40% less nitrogen fertilization than maize (Smith and Buxton, 1993), whereas Garofalo et al. (2015) pointed out the lack of statistical differences between the biomass productivity of sorghum under well-fertilized regime compared to halved N doses (150 kg N ha^{-}1 vs 75 kg N ha^{-1}) or even no N fertilization. The same authors also indicated comparable performance between sor-

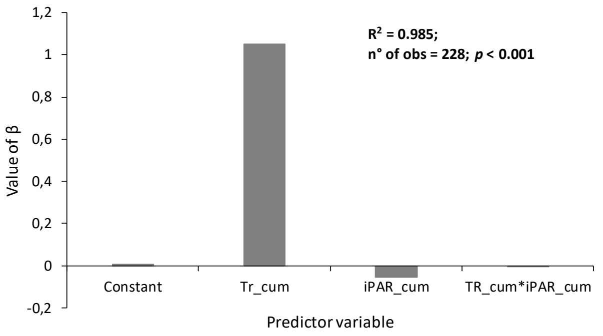

Fig. 8. Standardized regression coefficients (β) of cumulative transpiration (Tr_cum), cumulative intercepted solar radiation (iPAR_cum) and the combined effect on biomass accumulation. The higher the value, the higher their contribution.

ghum cultivated under conventional soil practices compared with no-tillage soil management.

High biomass productivity even with reduced agro-inputs result in a high energy efficiency and energy performance of a specific energy crop, which are the key points to make the sorghum suitable for energy purposes (Garofalo et al., 2018).

However, the assessment of the performance (e.g. biomass, yield or energy harvest) of a crop using only the "productivity" (biomass or yield) parameter, net of the environmental impacts that lead to its value, may determine assessment bias.

Radiation, available water and air temperature are the main weather-related variables affecting the bio-physical processes related to the growth and development of a crop. If these processes are recognized as a hierarchical pyramid structure in which the complexity is reduced as we move from the base to the tip, *RUE* and *TUE* are located at top, including and integrating the mechanisms and climatic constrains for plant growth and development (Garofalo and Rinaldi, 2015).

Although, *RUE* and *TUE* are known to be crop-specific parameters (Hughes et al., 1987; Russell et al., 1989; Monteith, 1994), other studies pointed out as these variables can vary according to environmental factors and management (i.e. nitrogen and water supply, plant density, cultivars; Sinclair and Horie, 1989; Rosenthal and Gerik, 1991; Cosentino et al., 2016).

However, here we assume that *RUE* and *TUE* should be easy to read and quick to understand and maintain their robustness and effectiveness inside the modelling frameworks or modelling solutions as stable parameters.

This implies the calculation of *TUE* and *RUE* as fixed indices of the potential crop performance, on which "limiting factors" afterwards act.

In the Mediterranean environment the factors constraining the plant growth are the water scarcity and heat waves, especially in spring-summer cropping systems, not the solar radiation.

Thus, in this experimental-modelling research drought conditions were mitigated through irrigation; as for temperature, the T_{lim} correction allowed to separate its effect when *RUE* and *TUE* were estimated.

As previously stated, in other investigations, the data of biomass used for the estimation of *RUE* or water use efficiencies were collected from sampling during the growing season; out-of-scale values could lead to overestimation or underestimation of these parameters.

Thus, in this research the empirical framework was set up to replicate daily biomass accumulation of sorghum, starting from sampling data. Although flaws in sampling may occur, the proposed approach is adequate to dampen such biases, since it models the growth dynamics between two figures through a curvilinear instead of a linear transition.

The approach proposed in this research led to results that can also be considered valid in other pedo-climatic and management contexts comparable to those from which the data for this research were obtained. Significant variations in terms of canopy development and/or biomass accumulation, intercepted radiation and transpiration can occur with crop and soil management substantially different from our field trials (i.e. sub-optimum fertilization, sprinkler system instead of drip irrigation, no-tillage instead of conventional tillage, etc.)

In other researches, the efficiency to convert water in biomass was estimated without partitioning the water consumption in soil evaporation and crop transpiration or accounting for the rainwater intercepted by the closed canopy, whose amount is not gathered from soil and not available for the transpiration process (Moroke et al., 2011; Hao et al., 2014; Chimonyo et al., 2016). Water loss by evaporation as well as rainfall intercepted by closed canopy and not available for the water requirement of the crop are not involved in the bio-physical processes of the plant and their inclusion in water use efficiency may lead to underestimation of this parameter.

In this paper is indicated a procedure that reproduce the daily canopy development (Eqs. (2-4)) and the water daily transpired by the canopy itself (Eqs. (7-8)) taking into account the effect of closed canopy on rainfall interception. Thus, water transpired by the crop fitted linearly with daily biomass accumulation, led to the estimation of *TUE*.

The replicability of this empirical structure has proved feasible through the validation step and *RUE* and *TUE* calibrated in 2014 accurately formalized the biomass accumulation observed in 2013 (validation year).

This let us to discuss on the most suitable index (*RUE* or *TUE*) to replicate the growth of the crop as a function of intercepted radiation or water transpired by the canopy.

If the available water or radiation are alternatively the limiting factors, the choice of the parameter to simulate the plant growth should be linked to the limiting factor itself; *RUE* if radiation is limiting for the optimal growth or *TUE* if the crop is under sub-optimal watered regime.

In the experimental trials carried out for this investigation, the water management was aimed at maintaining the crop under well-watered condition to avoid possible water stresses. On the other hand, in the Mediterranean environment, solar radiation did meet the energy demand for photosynthesis.

Results from the standardized multiple linear regression suggested that the accumulation of crop biomass over the two growing seasons, was mainly driven or affected by the water used by the sorghum rather than by the intercepted radiation as a single factor or in interaction with transpiration. Such result paves the way to three hypothesises: i) solar radiation was not a limiting factor; ii) during the two growing seasons, the sorghum crop experienced the soil water shortage; iii) all the biophysical processes are water-dependent. For the latter, some authors reported that *RUE* was strongly correlated to the water consumed by the crop (Derkas and Liacatas, 2007; Rinaldi and Garofalo, 2011). However, we assumed that *RUE* (as well as *TUE*) should be a stable parameter as a predictor of potential sorghum performance and that limiting factors (such as the water availability) should act in reducing the potential biomass computed by *RUE* and/or *TUE*. This assumption is further evidenced by the surface response plot (Fig. 9) which pointed out that the accumulation of biomass occurred mainly in response to *Tr*_cum rather than *iPar*_cum.

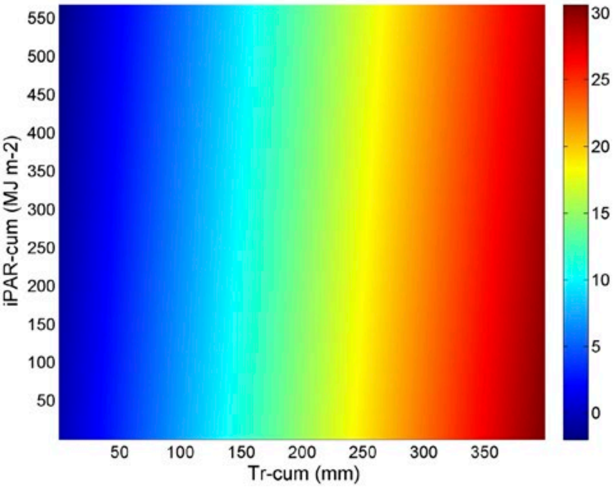

Fig. 9. Interaction response surface of the cumulative ADM (right bar) as it depends on cumulative intercepted solar radiation (iPAR-cum) and cumulative transpiration (Tr-cum).

CONCLUSIONS

Our experimental-modelling research proposes an empirical framework to formalize the daily growth and development of sorghum as well as *RUE* and *TUE* as a function of intercepted radiation and transpiration on daily basis. Under well-watered regime and in Mediterranean pedo-climatic conditions (as in our experimental trials), sorghum proved to be high performant in biomass yielding even with less water requirements respect to other energy crops (Triana et al., 2014), such as giant reed (1161 mm) or miscanthus (991 mm). This turned in the capability of sorghum to fully take advantage fromsolar radiation and water supply, providing high values of *RUE* and *TUE*, thus making this crop suitable for energy purposes (high energy yield in response to the agro-inputs management).

The estimate of *RUE* and *TUE* was the conclusive step in the whole empirical procedure, which starting from sampling carried out over the growing season, led to the projection of data at daily scale involved in the estimation of the efficiency of the plant to convert radiation and water into biomass.

This framework is easy to replicate also in other pedo-climatic contexts and for other crops , since few inputs are required for specification and parametrization (i.e. weather data and crop coefficient of the species under investigation).

The modelling approach used for this research was empirical and all the relationship among the analysed parameters (biomass and canopy development as a function of temperature, and intercepted radiation and transpiration) were quantified by means of regression models. Therefore, this approach excluded any process-based analysis underlying these relationships which could be deepened through mechanistic crop simulation models.

In addition, for the experimental trials the crop was grown under optimal level of nitrogen fertilizer as well as conventional soil tillage; by varying these two conditions the results and discussions reported so far could also undergo significant changes. Changes that could also be induced by climate change scenarios, where prolonged or repeated drought or heat waves conditions could undermine the crop growth-water or the crop growth-radiation dependence, which in turn are *TUE* and *RUE*.

Although the water supply was aimed at satisfying the water demand of sorghum, the regression analysis highlighted that the water requirement was likely not fully met.

This leads to the final considerations: i) in our experimental trials, sorghum did not reach its full performance and that; ii) other irrigation scheduling and distribution methods in addition with investigations on different soil tillage schemes, different nitrogen doses, plant densities or sowing times should be assessed to attain also at the farm scale the findings collected so far.

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