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DEFICIT IRRIGATION OF SUNFLOWER
UNDER MEDITERRANEAN ENVIRONMENTAL CONDITIONS

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SUMMARY - This work aims at: analyzing response of sunflower crop to several irrigation water regimes and evaluating the suitability of sunflower to deficit irrigation strategies. An open-field trial on hybrid Sanbro_MR was carried out at experimental fields in Valenzano (Bari, Southern Italy), characterized by semi-arid Mediterranean climate and clay-loamy soil. The experiment includes five irrigation regimes: optimal water supply, application of 100% of water requirements up to flowering and 70% thereafter, application of 70% of water requirements through the whole season, application of 70% of water requirements up to flowering and rainfed conditions thereafter, and rainfed conditions during the whole season. Sunflower response to water supply and intensity, timing and duration of water stress was investigated by means of leaf area index (LAI), radiation interception, biomass production, water consumption, yield, water use efficiency (WUE) and radiation use efficiency (RUE). The overall results indicate deficit irrigation as an acceptable strategy for sunflower highlighting the importance of irrigation between flowering and maturity.

Key words: *Helianthus annuus*, deficit irrigation, water use efficiency, radiation use efficiency.

RESUME' – *Ce travail vise à analyser la réponse de la culture de tournesol à plusieurs régimes hydriques et évaluer l'aptitude du tournesol aux stratégies d'irrigation déficitaire. On a mené une expérimentation sur le terrain sur l'hybride Sanbro_MR cultivé dans les champs expérimentaux de Valenzano (Bari, Italie du Sud), dans un climat méditerranéen semi-aride et un sol argileux-moyen. L'expérience comprend cinq régimes d'irrigation: apport hydrique optimal, application de 100% des besoins en eau jusqu'à la floraison et 70% depuis, application de 70% des besoins en eau le long de toute la saison, application de 70% des besoins en eau jusqu'à la floraison et conditions en régime pluvieux depuis, et conditions en régime pluvieux le long de toute la saison. On a étudié la réponse du tournesol à l'apport hydrique et à l'intensité, l'époque et la durée de la contrainte hydrique au moyen de l'Indice de l'Aire Foliaire (LAI), l'interception du rayonnement, la production de biomasse, la consommation en eau, le rendement, l'efficience d'utilisation de l'eau (WUE) et l'efficience d'utilisation du rayonnement (RUE). Les résultats globaux indiquent que l'irrigation déficitaire est une stratégie acceptable pour le tournesol, ce qui souligne l'importance de l'irrigation entre la floraison et la maturité.*

Mots clés – *Helianthus annuus, irrigat*ion déficitaire, efficience d'utilisation de l'eau, efficience d'utilisation du rayonnement.

INTRODUCTION

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Large amounts of water are needed in agriculture, especially in the areas like the Mediterranean region, where evaporative demand is high and natural water resources are scarce. Production experiences have shown that irrigation scheduling done in the manner to fulfil crop water requirements is mostly desirable in order to achieve high yields and economically viable production. However, an increasing competition for water and environmental, economic and political pressures on agriculture, are contributing to change this attitude in many areas of the Mediterranean in the near future. In fact, when water is limited, alternative strategies must be sought to reduce irrigation water use and to improve its efficiency (Seckler, 1996; FAO, 2002). Among those strategies, deficit irrigation is getting particular importance during the last decades since it aims to optimise agricultural output while saving water for other purposes (Howell *et al.,* 1990; Seckler, 1996; English and Raja, 1996; FAO, 2002).

In a recent evaluation of deficit irrigation practices (FAO, 2002) over 20 authors from various countries described their experiences in a range of crops and under different environmental conditions. Most of presented works emphasized the importance of regulated deficit irrigation strategies that avoid severe water stress in the critical stages of crop development and yield formation. In order to "regulate" deficit irrigation, there is a need to sort out systematically the myriad of biophysical factors that affect the response of specific crops to limited water supply, such as stress timing, intensity, soil/rainfall/ET combinations, etc. Therefore, further field experimentations and measurements of crop response to water stress are indicated as the most appropriate tool to test the results of previous investigations and to improve water use in agriculture. Accordingly, several research projects are going on in the Mediterranean region and one of such initiatives is Specific Target Research Project DIMAS (Deficit Irrigation for Mediterranean Agricultural Systems) that is financed by European Commission 6th Framework Program.

This work, a part of research activities carried out within DIMAS project, investigates deficit irrigation of sunflower grown under Mediterranean environmental conditions. Sunflower crop is chosen due to its well-known adaptability to water stress conditions and relatively high water demand. This work aims to: (i) analyse sunflower growth under five water regimes including optimal water supply, rainfed conditions and three deficit irrigation scenarios; (ii) determine critical stages of crop growth for water deficit; (iii) quantify the impact of water stress duration and intensity on sunflower.

MATERIALS AND METHODS

Experimental layout

The experiment has been conducted at the experimental fields of Mediterranean Agronomic Institute of Bari (Valenzano - BA, Southern Italy; 41°03'N, 16°52'E, 72 m a.s.l) in year 2005 as a part of CIHEAM-IAMB Master of Science Program (Zivotic, 2005). The area is characterized by typical Mediterranean climate, with average annual rainfall of about 530 mm, distributed mostly during autumn and winter, and with hot and dry summer season.

Weather data, including daily values of air temperature and humidity, windspeed and incoming solar radiation and precipitation, were collected at the agro-meteorological station of CIHEAM – Bari Institute, located about 350 m far from experimental field.

The soil was of clay-loam texture, of 70 cm depth and soil water holding capacity of about 150 mm/m. Soil hydraulic properties were derived from soil sampling at different depths and pedo-transfer functions.

The sunflower hybrid SANBRO_MR, characterized with early flowering and maturity and high yield potential, was sown on April 8th on a total surface area of about 1600 m^2 of a rectangular shape (40x40m). The plant density was of 5.56 plants per m^2. The crop was maintained in healty conditions during the whole season. The fertilizers were not applied during the growing cycle since soil analyses done before sowing showed a high content of N-P-K.

The emergence of sunflower plants was on 19th of April and the head visible stage was around 1st of June. The hybrid was characterized with early flowering and about 80% of plants appeared to flower on 20th of June. Sunflower plants entered into maturity stage one month later, on 24th of July and harvesting was done on 6th of August for rainfed and strong water stress treatments and on 8th of August for other three treatments. Total precipitation during the growing season was 111 mm distributed in 17 rainy days. The most important rainfalls occurred in July (DAS 94-96) with a total amount in three days of 51.8 mm, and few days before harvesting (DAS 118) with 21.8 mm.

The experiment included five irrigation regimes: optimal water supply (treatment A), application of 100% of water requirements up to flowering and 70% thereafter (treatment B), application of 70% of water requirements through the whole season (treatment C), application of 70% of water requirements up to flowering and rainfed conditions thereafter (treatment D), and rainfed conditions during the whole season (treatment E).

The crop measurements (leaf area index, dry biomass) and intercepted solar radiation have been done every two weeks. The plants were randomly sampled by collecting five representative plants from each plot. The leaf area was measured by LI-COR, 310, 11 times during the season. Dry biomass was measured after drying in an oven (75°C), until biomass has reached the constant weight. The intercepted solar radiation was measured by light bar (LICOR 1000), six times during the growing season at midday (solar time) in days when sky was clear.

Soil water balance and irrigation scheduling

The irrigation was managed by using the Excel-based soil water balance tool (Todorovic, 2006). Two tensiometers were installed at each plot at the depths of 25 and 45 cm in order to monitor the variation of soil water potential. The Excel-based tool for real time irrigation management was based on the estimation of the soil water balance in the effective root zone and meteorological, soil and crop data. The soil water balance (Fig. 1) was expressed in terms of water depletion in the effective root zone Dr,i (mm) at the end of each day through the following equation:

$$D_{r,1} = D_{r,i-1} - P_i - IR_i - CR_i + ET_{c,i} + RO_i + DP_i \tag{1}$$

where: Dr,i-1 represents the root zone depletion at the end of the previous day i-1 (mm), Pi is the effective precipitation on day i (mm), IRi is the net irrigation supply on day i (mm), CRi is the capillary rise on day i (assumed to zero), ETc,i is the crop evapotranspiration (mm), ROi is the runoff on day i (mm) and DPi is the deep percolation on the same day (mm).
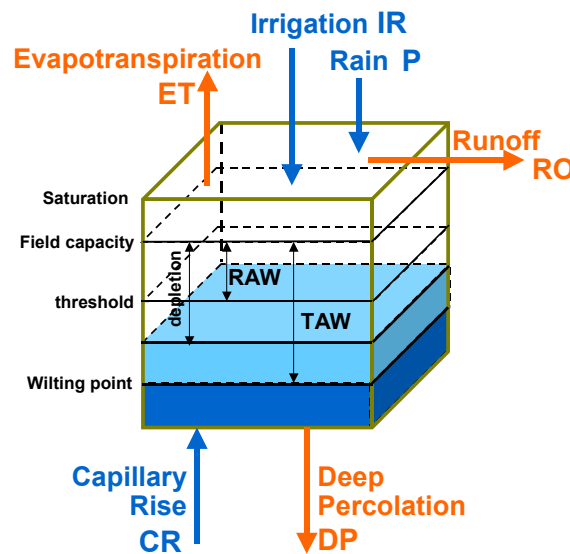

Fig. 1. Schematic presentation of the soil water balance components used in the estimation of root zone water depletion (RAW – readily available water; TAW – total available water)

The effective rainfall was estimated using a simple rainfall coefficient approach with value of 0.8 during the whole season. The application efficiency used for estimation of net irrigation supply was assumed to be variable (for applied drip irrigation method between 90 and 95%) depending on the time of irrigation, crop cover, etc… The crop evapotranspiration was calculated from reference evapotranspiration (ETo) through the single crop coefficient approach:

$$ET_c = K_c ET_o \tag{2}$$

where: effects of both crop transpiration and soil evaporation are integrated in a single crop coefficient Kc. Tha Kc values are assumed on the basis of the FAO 56 data (Allen et al., 1998) checked for the

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Apulia region from other sources as 0.35 during the initial growing stage and at the time of harvesting and 1.15 during the mid-season (the period from flowering to maturity). Reference evapotranspiration was calculated on a daily basis by using the FAO Penman-Monteith equation (Allen et al., 1998) in the following form:

$$ET_o = \frac{0.408\Delta(R_n - G) + \gamma\frac{900}{T+273}U_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34U_2)}$$

(3)

where ET_o is the reference evapotranspiration ($mm\,day^{-1}$), R_n is the net radiation ($MJm^{-2}day^{-1}$); G is the soil heat flux density ($MJm^{-2}day^{-1}$); T is the mean daily air temperature at 2 m height, (^oC), Δ is the slope of the saturated vapour pressure curve (kPa^oC^{-1}); γ is the psychrometric constant ($0.066\ kPa^oC^{-1}$); e_s is the saturated vapor pressure at air temperature (kPa); e_a is the prevailing vapour pressure (kPa), and U_2 is the wind speed measured at 2 m height (ms^{-1}).

The management allowable depletion was assumed to 0.45 of total available water ($p=0.45$) during the whole growing cycle as suggested in FAO 56 (Allen *et al.,* 1998). However, when the root zone soil water content drops below the predefined threshold, the crop evapotranspiration was adjusted as:

$$ET_{c,adj} = K_s K_c ET_o$$

(4)

where: ETc,adj is the crop evapotranspiration adjusted for water stress, Ks is a dimensionless reduction coefficient (0-1) dependant on available soil water content and given by:

$$K_s = \frac{TAW - D_r}{TAW - RAW} = \frac{TAW - D_r}{(1-p)TAW}$$

(5)

where TAW is total available water, RAW is readily available water (45% of total), D_r is the root zone soil water depletion and *p* is the fraction of total available water (0.45).

In the soil water balance calculation, runoff and capillary rise are assumed to be zero while deep percolation was calculated as the surplus of water in the root zone caused by excessive precipitation and/or irrigation. Accordingly, the net irrigation amounts applied to different irrigation treatments are given in *Table 1*.

Table 1. Net irrigation supply for four different irrigation treatments

Irrigation date	DAS	Net irrigation supply (mm)			
		Treatment A	Treatment B	Treatment C	Treatment D
15-Apr-05	7	16.6	16.6	16.6	16.6
28-Apr-05	20	29.1	29.1	20.6	20.6
06-May-05	28	11.6	11.6	8.1	8.1
16-May-05	38	19.3	19.3	9.9	9.9
21-May-05	43	23.3	23.3	18.6	18.6
31-May-05	53	36.6	36.6	25.5	25.5
14-Jun-00	67	55.3	55.3	38.8	38.8
22-Jun-05	75	49.5	34.9	34.9	-
29-Jun-05	82	40.7	29.1	29.1	-
05-Jul-05	88	49.5	34.6	34.6	-
19-Jul-05	102	43.7	30.6	30.6	-
28-Jul-05	111	43.7	30.6	30.6	-
TOTAL (mm)	122	418.9	351.6	298.0	138.2

RESULTS AND DISCUSSION

Soil water content variation and crop evapotranspiration

The results of soil water balance are obtained on a daily basis and are given by means of the root zone soil water depletion as illustrated in Figures 2, 3, 4, 5 and 6 for the treatments A, B, C, D and E, respectively. The intensity of water stress for different treatments is monitored by means of Ks coefficient, used for reduction of ETc and calculated by Eq. 5.
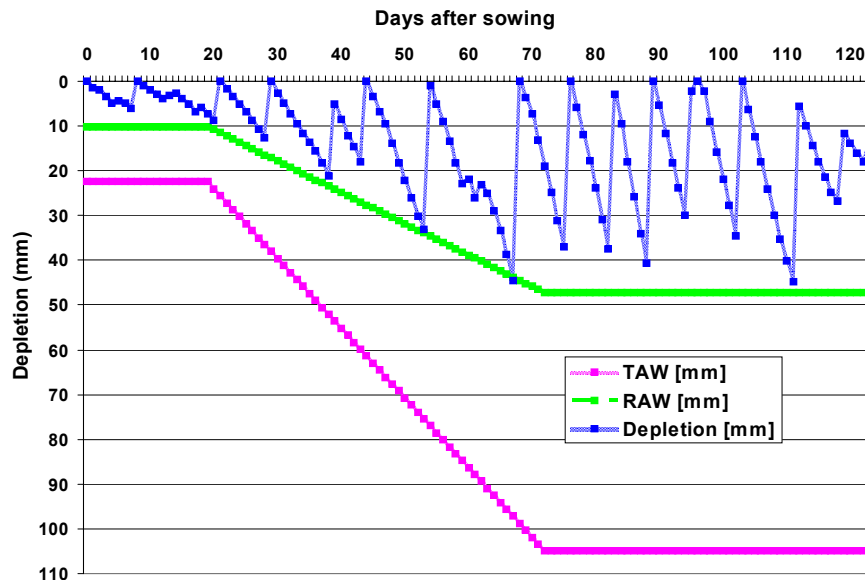

Fig. 2. The variation of the root zone soil water depletion for the treatment A – full irrigation, (TAW – total available water; RAW – readily available water).
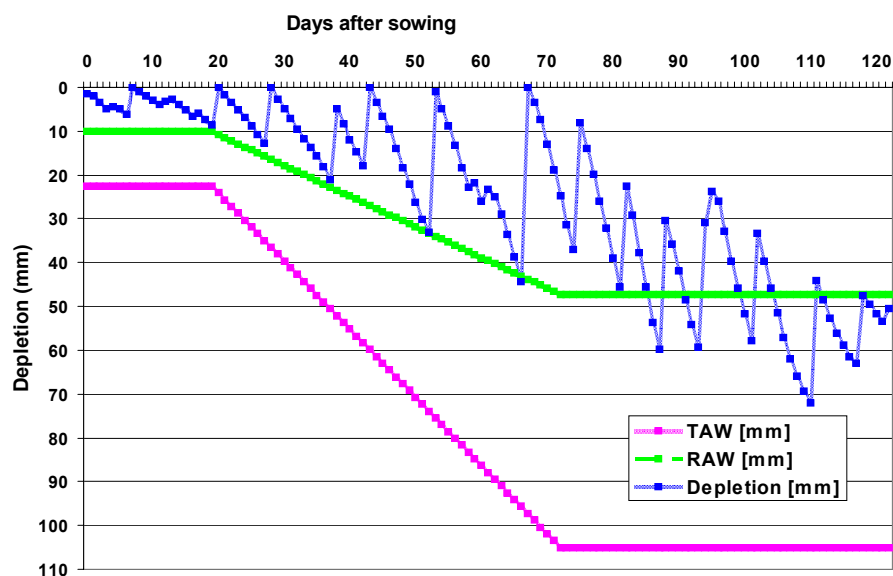

Fig. 3 The variation of the root zone soil water depletion for the treatment B - 100% of water supply until flowering and then reduction to 70% of crop water requirement. (TAW – total available water; RAW – readily available water)

During the treatment A (full irrigation during the whole season), the plants have been maintained under optimal water conditions, irrigating always before than root zone soil water content has gone below the allowable depletion threshold (Fig. 2). Twelve irrigations have been done amounting to a total net irrigation water supply of 418.9 mm (*Table 1*).

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In the case of treatment B (full irrigation until flowering – DAS 73, and then 70% of optimal water supply), total net irrigation supply was about 351.6 mm (84% of optimum water supply) distributed in twelve irrigation events. According to the soil water content estimation, the water stress started on DAS=85 and it was repeated several times, for a total of 19 days, reaching the maximum depletion of 70 mm on DAS 110, when Ks (ETc reduction coefficient) was estimated to 0.6 (Fig. 4).

In the case of treatment C (deficit irrigation corresponding to 70% of full irrigation supply during the whole season), total net irrigation supply amounts to 298 mm and it was subdivided in twelve events (*Table 1*). The water stress started few days before the head visible stage (DAS 53), and it continued also in the pre-flowering period (one week before flowering Ks reaches 0.67). A moderate water stress was maintained later on until the harvesting and the total number of water stress days was estimated to 50 (Fig. 5).
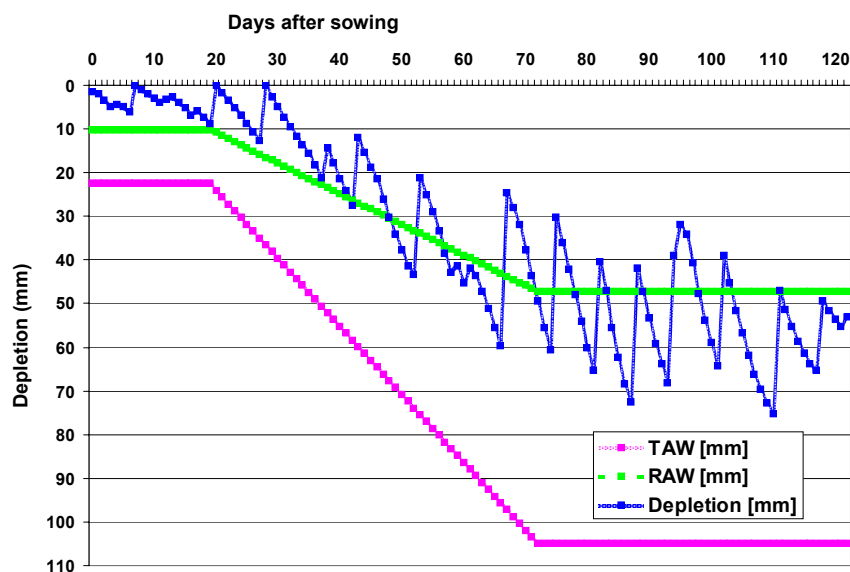

Fig. 4. The variation of the root zone soil water depletion for the treatment C – reduction of irrigation to 70% of crop water requirement during the whole season (TAW – total available water; RAW – readily available water)

Treatment D (70 % of optimal water supply prior to flowering and then without any irrigation supply) has received substantially less water than other treatments: net irrigation water supply was only 138.2 mm (33% of optimum water supply). This treatment had a first indication of water stress during mid of vegetative growth stage (DAS 42), but more intense stress started a week before heads appeared (DAS 53), with a Ks value lowering to 0.75 (DAS 52) (Fig. 6). Further on, until the flowering, plants were exposed to moderate water stress (minimum Ks =0.67 was on DAS 66). After flowering, this treatment did not receive any water supply by irrigation and the plants entered in a severe water stress. However, precipitation of about 52 mm occurred at the beginning of July and it contributed significantly to the attenuation of water stress conditions. Total number of days under water stress for the treatment D was 64, but with a period of 34 days of continuous, mainly severe, water stress in the period from flowering to harvesting.
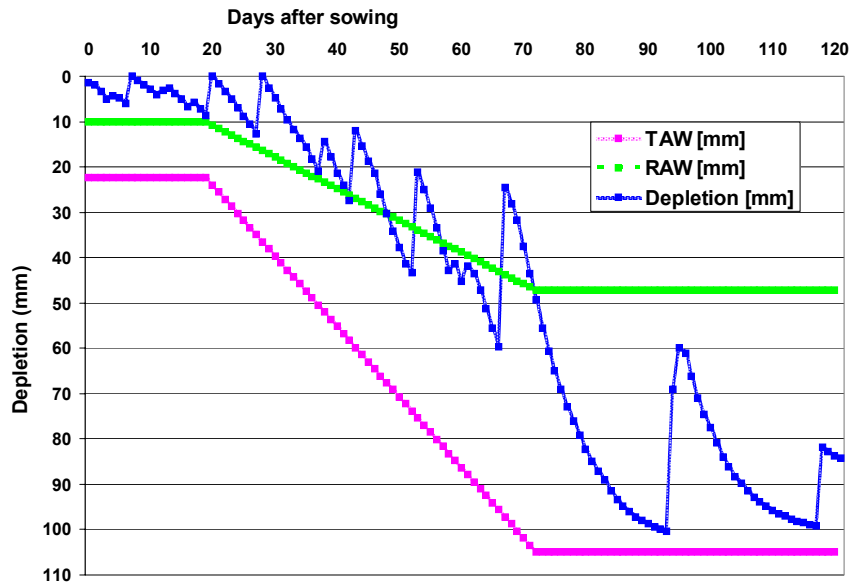
Fig. 5. The variation of the root zone soil water depletion for the treatment D – reduction to 70% of crop water requirement until flowering and after any irrigation was provided. (TAW – total available water; RAW – readily available water)

Treatment E (rainfed conditions) received only a total amount of precipitation of 111.0 mm. Such amount of rainfall was distributed unequally: 37.4 mm from sowing to flowering, 73.6 mm from flowering until harvesting. These values, along with the initial soil water content at field capacity, were the only water inputs for the treatment E. Consequently, the water stress started already during the emergence (Fig. 6) and lasted until the harvesting- only with the rain event of 11.8 mm occurred on DAS 28 and DAS=29 the plants partially recovered the root zone soil depletion. Total number of days under water stress was 108. Ks value for treatment E was in a gradual decrease during the whole season reaching two minimum values of 0.03 (DAS 93) and 0.10 (DAS 117). These conditions have been interrupted by rainfall several times resulting in a partial refill of root zone and an enhance of intensity of basic physiological processes. As in the case of treatment D, water stress intensity was diminished, although the plants have remained still under water stress conditions.

The crop evapotranspiration (Fig. 7) was the highest for treatment A with full irrigation (473 mm) and it was slightly lower for treatment B, with a mild water stress after flowering, (456 mm), and for treatment C (10.4%) with a mild stress during whole season (424 mm). Treatments D and E, with a moderate to severe water stress, have significantly lower crop evapotranspiration of 293 mm and 180 mm, respectively. The cumulative ETc was almost the same for treatments A, B, C and D until the flowering. Then after, while ETc continued rapidly to increase in the treatments A, B and C, it increased very slowly in treatment D. Starting from flowering, treatments D and E had a very similar ETc trend. In fact, during the crop development phase the Kc of sunflower was lower than after the flowering which, together with relatively high Ks values, corresponding to mild water stress, contributes to a slight difference between ETc values for different treatments. After the flowering, when crop ET demand was higher and the water stress was more serious, the difference in ET_c had become more evident.
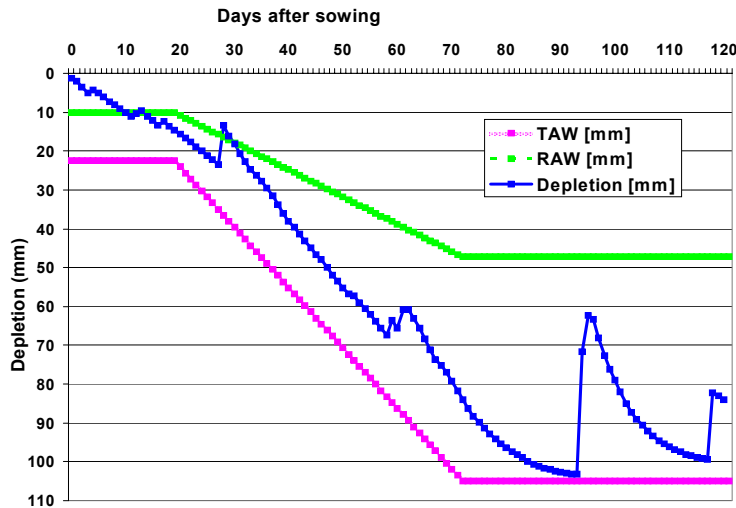
Fig. 6. The variation of the root zone soil water depletion for the rainfed treatment – E (TAW – total available water; RAW – readily available water).
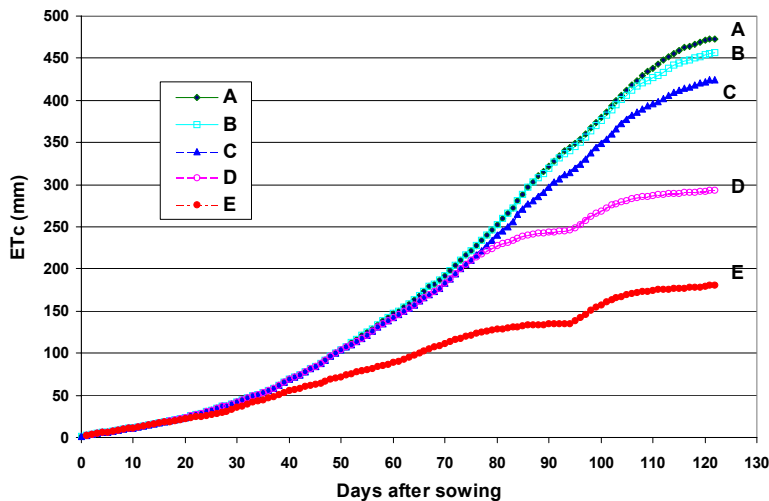

Fig. 7 Cumulative crop evapotranspiration for different treatments (A – full irrigation; B – 100% irrigation up to flowering and 70% thenafter; C – 70% irrigation; D – 70% irrigation up to flowering and then rainfed conditions; E – rainfed treatment)

Leaf Area Index (LAI)

The greatest number of leaves was observed one-to-two weeks before flowering and it was almost the same for all treatments (about 30) except the rainfed irrigation when it was slightly lower (about 28). After flowering, leaves started to yellow and then to dry.

The variation of the leaf area index as a function of days after sowing is presented in Fig. 8. The LAI increased almost linearly until the flowering (around DAS 75 and GDD 890) for all treatments except for rainfed irrigation (treatment E). The maximum values of LAI=3.7 were observed for treatments A and B (full irrigation until flowering), while for treatments C and D (70% irrigation until flowering) the LAI was 2.72, or 26.3% lower. This means that LAI decrease was almost linearly proportional to the water reduction in treatments C and D. The peak LAI of treatment E (rainfed agriculture) was 1.82 and it has been reached slightly earlier, at GDD 750 corresponding to DAS 67.

It can be noted that both the treatments D and E, affected by severe water stress, toward the end of the crop cycle (DAS 103) recovered leaf area as a consequence of a rainfall of 51.8 mm occurred on DAS=94-96. The leaf recovery behaviour of sunflower was observed also in Muro et al. (2001) and in Moriondo et al. (2003).
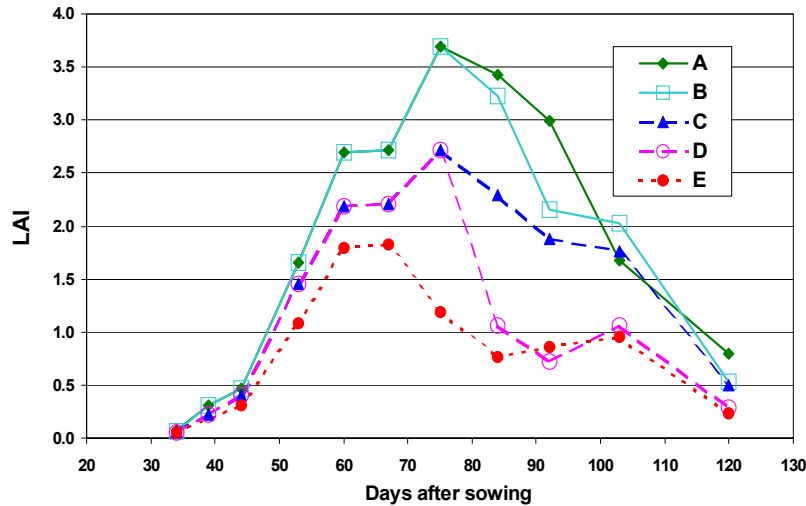
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Fig. 8. Seasonal variation of leaf area index of sunflower during a whole crop cycle

Radiation interception

Fraction of intercepted radiation (FINT) for five treatments was measured (Fig. 9) and used for the intercepted photosynthetic active radiation (IPAR) calculation. Maximum FINT values for all treatments were observed one week before flowering, which correlates to the highest number of leaves on plants. Maximum FINT values for treatments A and B were 86% while for treatments C and D it was slightly lower, 74%. Treatment E had the lowest maximum FINT value of 48%, measured both on 54th and 69th day after sowing. After the flowering FINT decreased substantially for all treatments reaching at the harvesting the value of about 25% for treatments A, B and C, 22.6% for treatment D and 12.7% for treatment E. The most significant decrease was in the case of treatment D where FINT has fallen from 74% at time of flowering to 42% a week prior to maturity and to 22.6% at harvesting.

As expected, the greatest values of cumulative IPAR were obtained for treatments A and B, 688.3 and 680.3 MJm^{-2}, respectively. Cumulative IPAR was 608.4 and 530.8 MJm^{-2} for treatments C and D respectively, whereas for the rainfed treatment it was almost half (357.1 MJm^{-2}) of the full irrigated treatment.

The relationship between the fraction of intercepted radiation and leaf area index is given in Fig. 10, together with the curve of best-fitting quadratic regression function. An increase of LAI is followed by an increase of the fraction of intercepted radiation (FINT) by means of the quadratic regression function

$$F_{int} = -0.0561 \cdot LAI^2 + 0.4381 \cdot L + 0.0037 \qquad (6)$$

fitted very well the measured data (R^2=0.926).

As reported in the literature (Watson, 1958; Stern and McDonald, 1962; Davison and Donald, 1985; Bange et al., 1997a; Ferreira and Abreu, 2001) crop seems to produce more leaf area in comparison to that strictly for maximum interception. In fact, Fig. 10 indicates that with LAI higher than 3, crop faces overlapping between leaves and FINT decreases. Bange et al., (1997a) reported that there was no increase in the fraction of light interception above a LAI of 4, showing that maximum LAI was not directly related to maximum light interception.
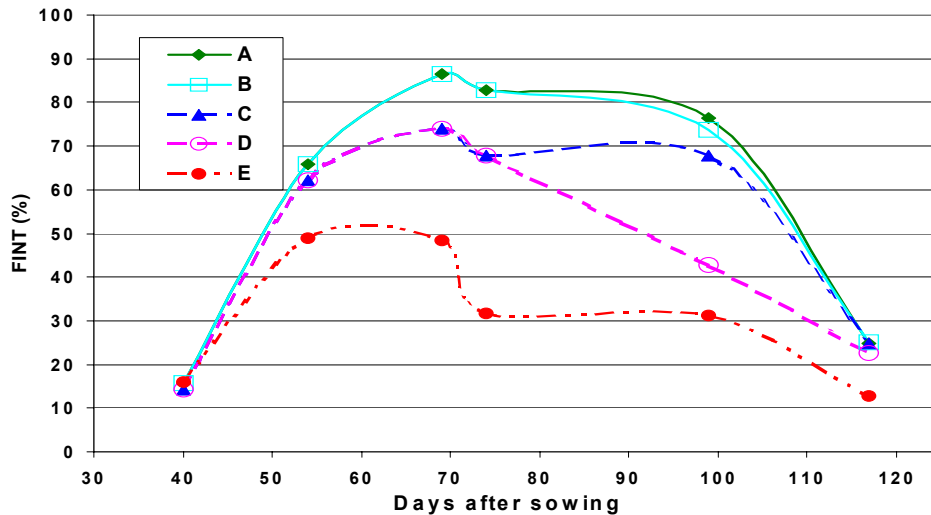
Fig. 9. Fraction of intercepted radiation (FINT) for different irrigation treatments during sunflower growing season.
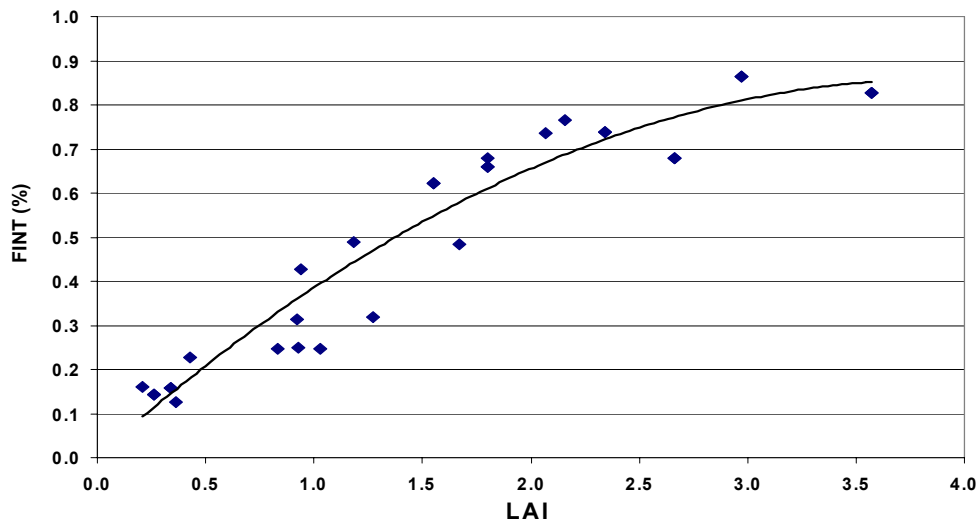

Fig. 10. Fractional interception of solar radiation as a function of leaf area index (all the treatments are plotted together)

Measurements of the fraction of intercepted radiation have shown a high correlation with LAI values indicating LAI=3 as an upper limit for the absorption of photosynthetically active radiation. Maximum FINT values were observed one week before flowering corresponding to maximum leaf number. Total intercepted radiation has decreased with the intensity of water stress. This decrease was just 1% for treatment B, 11% for treatment C, but 23 and 49% for treatments D and E, due to defoliation.

Dry matter production

The variation of the above ground biomass during the whole crop cycle is shown in Fig.11. This figure clearly indicates that the amount of water applied had an essential impact on the amount of dry matter produced. The full irrigation treatment (A) had the highest final above ground dry biomass of 14.9 tha^{-1}. Afterward, treatment B had 13.0 tha^{-1} of biomass (87.5% of treatment A) while for treatment C (70% irrigation supply) the biomass was only 9.9 tha^{-1}, or about 66.5% of the full irrigation treatment. The treatments D and E had at harvesting approximately the same dry biomass (around 6.5 tha^{-1}, or 43.6% of full irrigation treatment) although the amount of water applied to these two

treatments was very different. In the case of treatment D, the intensity of water stress was very high immediately after the flowering when vegetative part was already well-established and water was missing to cover evapotranspirative demands. This resulted in an earlier senescence of leaves and their falling causing a slowly decrease of biomass approaching the values of rainfed treatment. Rainfed treatment had much lower biomass at flowering than treatment D and it was better adopted to water stress conditions.

In generally, the above ground biomass at harvesting has increased until the maturity and then it was slightly declined. Such decrease can be related to the increase in respiratory activities, leaf loss and the elevated synthesis of lipids which is not compensated by a commensurate accumulation of dry matter in the seeds (Evans, 1972).

Such results indicated that the crop growth rate was the highest in the period of few weeks before flowering confirming Sanbro_MR cultivar as a "early vigour" hybrid. A comparison between different treatments has shown that both biomass and yield gradually decrease with decrease of the amount of water applied. Different authors (Andrade, 1995; d´Andria et al., 1995; Cantagallo et al., 1997; Tollenear and Dwyer, 1999; Goksoy, 2004) reported that the greatest sensitivity to water stress in sunflower corresponds to the period of 20 days before and after flowering which is confirmed in this work. In fact, severe water stress happened to treatments D and E after flowering which seriously reduced both biomass growths, yield and harvest index.
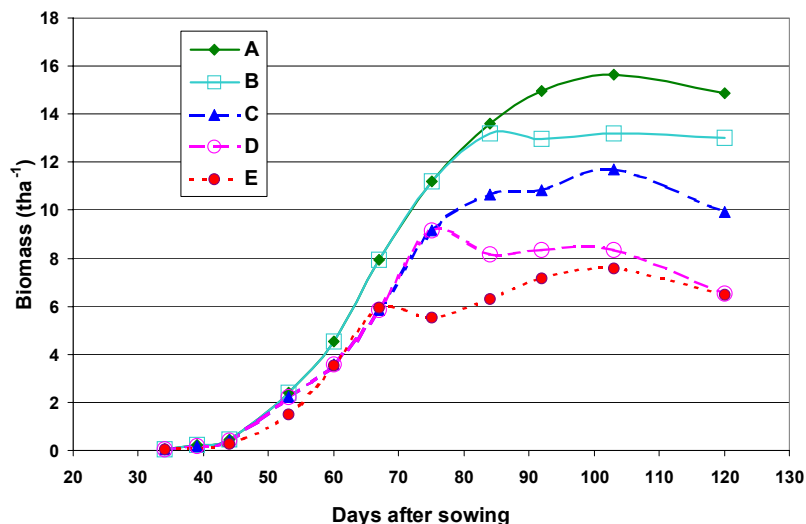

Fig. 11. Above ground dry biomass for five different irrigation treatments

Yield and harvest index

The average yield was related to the amount of water supply in all treatments except of treatment D. The highest average yield was obtained for treatment A with optimal water supply (6.14 tha^{-1}) and it was for about 18% lower than the maximum obtainable yield at that field (7.51 tha^{-1}). The yield of treatment B was not significantly lower than treatment A yield, 12% (5.41 tha^{-1}), while for the other treatments yield was significantly lower: for treatment C - 31.2% (4.22 tha^{-1}), for treatment D - 65% (2.10 tha^{-1}), and for rainfed treatment was lower around 66% (2.07 tha^{-1}). Both treatments, D and E reached similar value of yield although treatment D received about 140 mm of irrigation, while treatment E was maintained under rainfed conditions during the whole season. The yield obtained in this work is greater than that reported in the most of other publications, although some experiments carried out in Australia (Bange et al., 1997b) and in Spain (Fereres, E., pers, comm.) confirms the trustworthiness of the results.

The harvest indices (HI) indicate a huge difference among five water regimes. Treatments with severe water stress (D and E) had harvest index around 0.32, while treatments A, B and C had harvest index of 0.41, 0.42 and 0.43, respectively. In fact, the highest harvest index was obtained for

treatment C maintained over the whole season under limited water supply (70% of optimum). A slightly higher HI for treatments B and C comparing to A can be explained with a mild water stress that affected plants and they repartitioned less assimilates to vegetative part and more to storage organs in order to adapt to water stress conditions. The harvest index values greater than 0.4 are unusually high as compared to the common data from the literature (Andrade, 1995; Beckie and Brandt, 1996; Flenet et al., 1996a; Cabelguenne et al., 1999; Razi and Assad, 1999; Soriano et al., 2004). Nevertheless, some similar values of harvest index were obtained and published elsewhere (Vagvolgyi, 1991; Botella Miralles et al., 1997; Lopez Pereira et al., 2000; Sadras and Calvino, 2001).

The obtained results confirmed that harvest index behavior depends on the intensity of water stress; it may increase slightly under mild to moderate water stress, while it will likely to decrease substantially under severe water stress conditions.

Radiation Use Efficiency

The radiation use efficiency (RUE) is expressed as the ratio between the biomass and the cumulative intercepted PAR. There is a high variation of radiation use efficiency among treatments especially at harvesting. The RUE at maturity was greater for about 20 to 45% in respect to the RUE at harvesting. The lowest decrease of RUE at harvesting (about 20%) was observed for well-watered treatments A and B, while the decrease at harvesting was the greatest for treatment D (46%), and then for treatments C (37%) and E (30%). In fact, the drop of biomass at harvesting was more noteworthy for the water stressed plants than for those maintained under well-watered conditions.

In the case of radiation use efficiency, a breakdown of linearity (Fig. 13) was observed at the anthesis and the regression analysis has been done distinguishing two stages: pre- and post-anthesis periods. In Table 2 the RUE values of pre-anthesis and post-anthesis periods are compared. The correlation coefficients for the pre-anthesis period were very high and the slopes were similar for all treatments. The RUE up to flowering was 13% lower for 70% irrigation treatments and rainfed treatment in respect to full irrigation treatment. In the post-anthesis season, in the case of treatment D, there was a substantial decrease of biomass after the flowering causing the negative slope for that treatment.
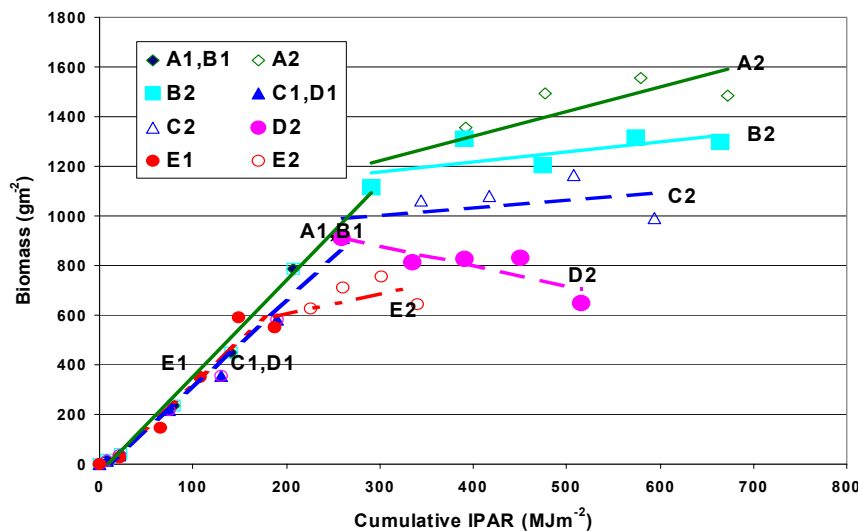

Fig. 13. Pre- and post-anthesis radiation use efficiency for five sunflower treatments

Table 2. The best fitting slope of linear relationship between the biomass and *IPAR* for different irrigation treatments (1 is for pre-anthesis period; 2 is for post-anthesis period and R^2 is the regression coefficient)

Treatment	Slope (gMJ^{-1})	R^2
A1	3.88	0.99
B1	3.88	0.99
C1	3.41	0.99
D1	3.41	0.99
E1	3.43	0.94
A2	0.99	0.71
B2	0.40	0.45
C2	0.31	0.17
D2	-0.81	0.72
E2	0.82	0.39

These results have shown a regularity of RUE decrease with the increase of intensity of water stress. The RUE slopes were linear and constant until the anthesis confirming what found in many experiments and for several species (e.g. Monteith, 1990; Gosse et al., 1986; Sinclair and Muchow, 1999). Furthermore, this work has confirmed also the breakdown of RUE linearity at anthesis, as reported in many studies (e.g. Gimenez et al. 1994; Albrizio and Steduto 2005). The change in slope can be explained on the base of the change in composition of reproductive biomass during seed filling, when oil is the main compound being synthesized (Penning de Vries, 1974).

Biomass and Yield Water Use Efficiency

Water-Use Efficiency (WUE) term is used to describe the relationship between the crop growth development and the amount of water consumed. This work deals with both biomass and yield WUE defining them as the ratio between the biomass and crop evapotranspiration and the product of biomass WUE times the HI, respectively.

The variation of relationship between biomass and cumulative ETc during the growing season is presented for different irrigation treatments in Fig. 14. An evident breakdown of data was observed distinguishing between initial growth stage, intensive crop growth up to anthesis and post-anthesis periods. Consequently, the biomass WUE was analysed for each of three above mentioned stages separately. The results of biomass WUE values for three different crop growth periods are presented in Fig. 14 and Table 3.
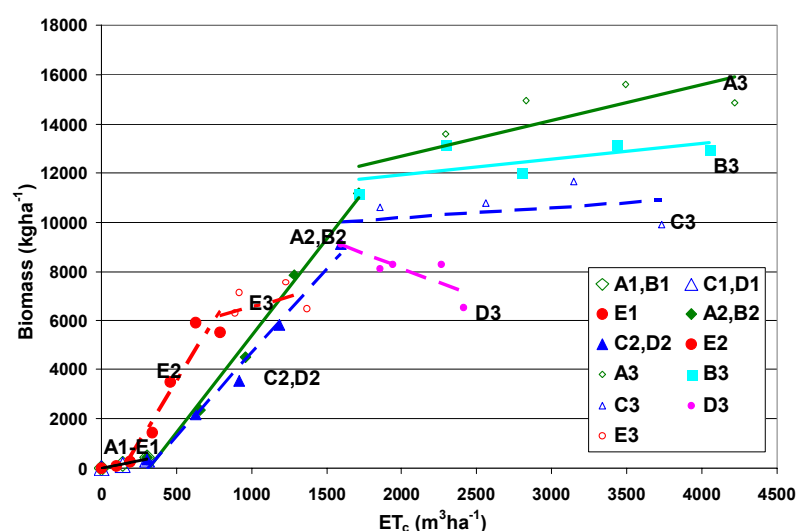

Fig. 14. Biomass water use efficiency for five sunflower treatments with regression lines distinguishing between three stages (1 - initial, 2 - intensive growth and 3 - post-anthesis)

Table 3. Slopes of the best fitting regression lines between the biomass and ET_c for different irrigation treatments (1 is for initial period; 2 is for intensive growth up to anthesis 3 is for post-anthesis period and R^2 is the correlation coefficient – goodness of fit)

Treatment	Slope (kgm^{-3})	R^2
A1, B1	1.37	0.99
C1, D1	1.15	0.99
E1	1.32	0.97
A2, B2	7.88	0.99
C2, D2	6.79	0.99
E2	9.99	0.90
A3	1.45	0.66
B3	0.44	0.44
C3	0.39	0.13
D3	-2.38	0.67
E3	1.62	0.26

The correlation coefficient of regression lines was very high for the first and second stage (from 0.9 to 0.99), while for the third period (post-anthesis) it was much lower. During the initial growth stage, the slopes of regression lines were very similar among treatments (between 1.15 and 1.37) while in the phase of intensive crop growth they increased to 7.9, 6.8 and 10.0 for full irrigation, 70% irrigation and rainfed treatment, respectively. The slopes of the post-anthesis period were less consistent.

Seasonal biomass WUE for full irrigation treatment was slightly greater than the values commonly found in the literature. This can be explained by high early vigour of the Sanbro_MR cultivar and regular irrigations in vegetative growth stage, which both had an impact on T/ET ratio and improved water use efficiency. Biomass WUE decreases regularly with the intensity of water stress, similarly to the RUE.

Water use efficiency was established also referred to the yield (YWUE). In this case, the greatest YWUE is for the full irrigation treatment (1.3 kgm^{-3}), followed by: treatment B (1.19 kgm^{-3}), rainfed treatment (1.15 kgm^{-3}), treatment C (1.0 kgm^{-3}) and treatment D (0.72 kgm^{-3}). The maximum values of YWUE reported in the literature were 1.05 kgm^{-3} in Connor et al., (1985), referring to a field experiment and 1.23 kgm^{-3} in Flénet et al., (1996a), referring to an experiment in the plastic pots.

CONCLUSIONS

The overall results of this work pointed out deficit irrigation as an acceptable strategy for sunflower highlighting the importance of irrigation between head appearance - flowering – maturity period. A comparison of results for different water regimes has shown that both biomass and yield gradually decrease with the reduction of water supply. This work indicated mild water stress strategies (treatment of full irrigation until flowering and 70% of water supply then after and treatment of 70% of full irrigation supply during the whole season) as acceptable deficit irrigation practices. Treatment with 70% of irrigation before flowering and then after without any water supply was completely discarded. Instead rainfed irrigation is suggested provided that soil water content is at field capacity around the sowing. In fact, mild water stress induces a different partitioning of assimilates favouring the storage organs rather than the vegetative part of plants. Nevertheless, a strong decline of production can be expected under sever water stress conditions when vegetative part is already well-established and water is missing to cover evapotranspirative demand.

Both RUE and WUE showed a not conservative behaviour during the crop cycle of sunflower for all different water regimes. In the case of RUE an evident change in slope occurred after anthesis, while in the case of WUE three different slopes were observed distinguishing 3 stages during the crop cycle: (i) initial growth; (ii) intensive crop growth up to anthesis; (iii) post-anthesis up to maturity.

This change in slope during the crop cycle of sunflower deserves a special consideration when modelling crop growth and yield production, especially in those crops having a high energy cost for lipids synthesis during seed filling and for those hybrids having a high early vigour.

Sunflower hybrid tested in this experiment has demonstrated capability to produce some yield even though it has been maintained under rainfed conditions during the whole growing season. This was possible due to several rainfall events occurring couple of weeks before and after flowering, i.e. during the most critical crop growth stages. Nevertheless, additional efforts should be done to improve water use efficiency in rainfed agriculture choosing early sowing of sunflower instead of late sowing (lifted T/ET ratio) or choosing sunflower cultivars with high early vigour (like Sanbro_MR). In fact, high early vigour plants, with a strong biomass increase in the early development stages, can provide a notable contribution to higher transpiration efficiency (T/ET ratio) and reduce soil evaporation.

Acknowledgements

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