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The interplay of irrigation strategies and sowing dates on sunflower yield in semi-arid Mediterranean areas

Vittoria Giannini[1]*, Laura Mula[1]*, Marcella Carta[1], Giacomo Patteri[1], Pier Paolo Roggero[1]

[1] Department of Agricultural Sciences, University of Sassari, Viale Italia 39 A, 07100, Sassari (IT)

*these authors equally contributed to this study

Corresponding author: Vittoria Giannini, vgiannini@uniss.it

Other authors emails: lmula@uniss.it; mcarta1@uniss.it; gpatteri@uniss.it; pproggero@uniss.it

Abstract

Sunflower (*Helianthus annuus* L.) is one of the most cultivated oil crops in the world. Given its high dependence on water availability, this crop is severely threatened by climate change. Indeed, very hot and dry weather conditions occurring in the Mediterranean have a negative impact on sunflower yield, even reducing productivity. Many studies already identified in moving up sowing date a promising strategy to prevent summer drought stress causing sunflower yield losses, but scarce literature is available on winter sowing dates. The aim of the present research was understanding how much the interplay between the sowing date (even occurring in winter) and water regime could sustain sunflower cultivation in the Mediterranean.

A field experiment and a modelling study were carried out in order to study the effects of different sowing dates (00SD: ‘conventional sowing date’ occurring in March/April and ‘earlier sowing dates’ occurring in December- January-February, depending on years) under two different water regimes (irrigated and rainfed) on quantitative traits of high oleic cultivars of sunflower. Field experiment revealed that sowing in late February-Mid March was the most promising in terms of achene productivity.

Moreover, achene production of sunflower was simulated in EPIC under a baseline climatic scenario and for 4 hypothetical sowing dates (D1: 10th January, D2: 10th February, D3: 10th March, D4: 10th April) and different irrigation strategies. The most promising sowing date was D3 under rainfed condition, thus confirming field study; while the irrigation scenario supplying water from 20 days before anthesis up to flowering was the most fruitful in terms of achene production, thus representing an option for Mediterranean areas that can rely on little water availability.

Keywords:

EPIC, sunflower, yield gap, sowing date, water supply

1. Introduction

Sunflower (*Helianthus annuus* L.) is a well-adapted, important oil crop in Europe and a typical oil crop for the Mediterranean region and Italy. It is a valuable crop from different economic perspectives, since i) it is suited for biodiesel productions (Pereyre-Iruju et al., 2009; Ragaglini et al., 2010); ii) many of its cultivars are rich of oleic acid which has been proved to prevent cardiovascular diseases, thus representing an essential dietary source for humans (FDA, 2018) and moreover iii) its crop residues are promising substrates for biogas production (Monlau et al., 2012; Zhurka et al., 2020).

Sunflower is cropped as a spring-summer crop and it is commonly considered as a drought-tolerant species and consequently as a cropping opportunity for regions where water resources (used for irrigation) are decreasing such as in situations where soil water deficit is expected to increase dramatically (García-Vila et al., 2012).

Conversely, different studies have pointed out the high reliance of this crop on a good water availability in all the growth phases and especially at flowering and seed filling stages (Flagella et al., 2002; Iqbal et al., 2005; Ebrahimian et al., 2019). Indeed, in the Mediterranean region, under rainfed conditions, sunflower sown in March-April showed consistent productivity variations, mainly related to the rainfall occurring during the crop cycle (de La Vega and Hall, 2002). This risky trend could be further amplified by climate change projections (IPCC, 2014) implying higher day and night temperatures, variable rainfall distribution patterns, higher atmospheric CO_2, and hydrological imbalances (Tariq et al., 2018).

From an agronomic perspective, it is possible to prevent yield losses related to water deficiency and variability among years through different management strategies, such as drought escape, avoidance, or tolerance and/or irrigation provisioning (Debaeke and Abroudrare, 2004).

Given that sowing time determines the amount of rainfall and temperature to which the crop is exposed at the different growth stages (Zeleke and Nendel, 2019), many studies identified in anticipating sowing a win-win solution to skip the drought phase and pursuing the cultivation of a profitable crop for high quality oil production (Quiles et al., 2002), thus preventing further marginalization of drylands.

In most of the cases the hypotheses tested in the Mediterranean region were a conventional sowing in Late March/April or even May *vs* an earlier sowing in early March/mid-March (Flagella et al., 2002; Barros et al., 2004; Ferreira et al., 2001). In Sardinia, sunflower is generally sown in March/April.

The hypothesis of this study was that the anticipation of the sowing date, even in winter, could be effective in sewing up an appropriate climate adaptive management strategy for the development of this crop under the near future Mediterranean climatic conditions.

The aim of this study was to evaluate the responses of sunflower to sowing dates under rainfed or different irrigation scenarios, by combining a 4-years field experiment with crop modelling to identify suitable pathways to achieving a sustainable productivity for this crop under Mediterranean conditions.

2. Materials and Methods

2.1 Field experiment

2.1.1 Experimental site and experimental design

The field trial was conducted in Sardinia (Italy) in Ottava (40° 46’ N, 8° 29’ E, 81 m asl) for four consecutive years from 2015 to 2018. In Ottava, the soils are well drained and mostly classified as Lithic Xerorthents (Madrau et al., 2006), according to the USDA Soil Taxonomy. The high oleic early hybrids Montijo (SIS) and P63HH69 (Corteva agriscience) were used in 2015-16 and 2017-18, respectively.

Depending on the yearly rainfall and temperature pattern and the field trafficability, a range of sowing dates was compared over the four years. The benchmark date in all years was chosen according to the local practice on 20 March (15-25 March), henceforth defined as 00SD. Earlier sowing dates ranged from 17 Dec to 23 Feb and were coded on the basis of the number of weeks ahead of 00SD (Tab.1).

In 2015, a later sowing date was also tested and coded on the basis of the number of weeks after 00SD. All treatments were tested under drip irrigation (I1) *vs* rainfed (I0) conditions.

Plot size was 45 m^2 (10 m × 4.5 m); row spacing was 0.75 m and plant spacing on the row was 0.15 m, corresponding to 8.8 seeds m^{-2}, aiming to an effective plant density of some 7 plants m^{-2}.

Prior to sowing, 30 kg ha^{-1} N and 70 kg ha^{-1} of P_2O_5 were applied as diammonium phosphate and additional 35 kg ha^{-1} N as ammonium nitrate were top dressed. Glyphosate was sprayed at a concentration of 3 g L^{-1} of water for pre-seeding weed control when necessary. Pre-emergence weed control was performed using 900 g ha^{-1} Pendimethalin. Creoline diffusers and transparent wires were installed to prevent bird damages to seedlings at establishment. Seed predation from birds was also prevented by protecting the sampled capitula of each plot with non woven fabric after pollination.

2.1.2 Field measurements and laboratory analyses

The sunflower response to treatments was assessed based on a multidimensional measurement protocol.

The change of the phenological phase was recorded during the whole growing season according to Lancashire et al. (1991). Sixteen phenological observations over the sunflower crop cycle were recorded on 10 randomly selected plants in each plot. These records were used for the calculation of cumulative growing days degrees (CGDD; °C d) starting from the maximum daily air temperature (T max) and the minimum daily temperature (T min). Base temperature (T base) was set at 10 °C. The CGDD were determined for both the period between sowing and the end of anthesis at BBCH: 69 (CGDD-A) and the period between sowing and crop harvest (CGSS-H).

The number of plants m^{-2} was counted 30 days after sowing (DAS 30) and at harvest (number of capitula per m^{-2}) on a sampling area (5 m × 4 rows) in each plot.

Achene yield (AY) and yield components (no. achenes per capitulum; 1,000 achenes weight) were measured on the same 10 randomly selected capitula per plot used for the monitoring of plant phenology. All achenes of each of the 10 capitula were counted and weighted. The aboveground biomass (AGB) was measured on the same 10 plants per plot. The harvested achenes and AGB dry matter were determined after drying in a ventilated oven at 60°C till constant weight.

2.1.3 Rainfall, evapotranspiration, irrigation and water use efficiency

According to the Köppen–Geiger climate classification map (Kottek et al., 2006), the climate of the experimental site is predominantly hot dry summer Mediterranean (Csa). The long-term historical daily weather data were collected from the weather station located in the experimental field, where the trials on sunflower have been carried on (Ottava, Italy). The long-term average (1981-2018) annual rainfall is 512 mm with average annual reference evapotranspiration (ETo) of 1094 mm and an aridity index of 0.47, corresponding to a semi-arid climate (Middleton and Thomas, 1997). Some 70% of the average annual rainfall falls between October and March and mean monthly air temperature calculated over the same long-term period ranges from 9.9 °C in January and February to 23.9 °C in August, with an annual mean of 16.3°C (Fig.1).

The mean annual rainfall during the conventional crop growing season (March-August) is 150 mm, i.e. some 20% of the corresponding ETo (770 mm).

For each growing season starting at different sowing dates, data of temperature and rainfalls were compared with the long-term ones.

For all the years, irrigation water was applied to I1 plots through hose irrigation starting from Mid-April, every week, to totally re-integrate the actual evapotranspiration.

Water Use Efficiency (WUE_a) was determined as follows:

$WUE_a = AY/ET_a$

where AY is the achene yield (kg ha^{-1}) and ET_a is the actual evapotranspiration (mm). This latter was calculated using the Hargreaves equation. WUE is expressed in kg ha^{-1} mm^{-1}.

The whole sunflower growing season was split in four intervals (initial, BBCH: 10-39; development, BBCH: 51-59; reproductive, BBCH: 61-69 and late season, BBCH: 71-83) and for each interval a K_c, estimated in similar pedo-climatic conditions by Mila et al. (2016), was assigned.

The actual evapotranspiration over the whole growing season was obtained by adding the partial actual evapotranspiration calculated for each growing season interval.

2.1.4 Statistical analyses

The statistical analyses were performed in RStudio application of R software (R Core Team, 2014) environment (packages nlme, emmeans, dplyr). The examined traits were processed statistically in an analysis of variance of the randomized complete block design (RCB) using a linear mixed effect model with sowing date and water regimes as fixed effects, while block/experimental plot as the random effects. The significance of differences between treatment means was evaluated by Tukey's test at $p < 0.05$.

2.2 Crop modelling

2.2.1 Calibration and application of the EPIC model

The EPIC (Environmental Policy Integrated Climate, version 1102) model (Williams 1995; Gassman et al. 2005; Izaurralde et al. 2012) was calibrated and applied using input parameters derived from the above-mentioned field experiments. EPIC was used to estimate the influence of temperature and rainfall on AY and AGB of both rainfed and irrigated sunflower in relation to the different sowing dates. The model was set using local soil and weather data, information about the actual field management as described in chapter 2.1.1 (including irrigation volumes and amount of fertilizers distributed), and crop-related data such as plant density and crop growing period. In this study, the model was calibrated for the achene yield and above-ground biomass of sunflower, while for the scenario analysis, the effect of watering regimes and sowing dates on the crop achene yield was used. The model performance was evaluated by calculating complementary indicators: relative root mean square error (RRMSE; Bellocchi et al., 2002), modeling efficiency (EF; Loague and Green, 1991), Willmott's Index of Agreement (d) (Willmott, 1982; Loague and Green, 1991), slope and intercept of the regression line and coefficient of determination (R^2).

The simulation was performed using fixed sowing dates, while the harvest operations were scheduled according to heat units accumulation. The crop was harvested at about 100% of total heat units required for maturity. The simulations were carried out using the static soil option in order to avoid variation of the soil properties that could have affected the crop production during the 50-year simulation. The soil characteristics were set up after an initialization and reset each year to remove trends related to soil dynamics and draw attention to the effect of climate.

The interannual seed production variability was simulated maintaining constant management conditions to assess the effects of temperature and precipitation.

2.2.2 Drawing scenarios for sustainable sunflower management

A baseline climatic scenario has been built from the data simulated with COSMO-CLM (Rockel et al., 2008), using the specific 8 km horizontal resolution configuration developed for Italy by CMCC (Bucchignani et al.; 2016 e Zollo et al., 2016), forced from global model ECHAM 5.4 developed by CMCC (Scoccimarro et al., 2011). The baseline climate scenario was referred to the years 1972-2005, using CO_2 concentration of 380 ppm.

Daily generated datasets were bias-corrected with monthly correction factors, calculated from precipitation, maximum and minimum temperature, and obtained by comparing the overlapping periods of the baseline climate scenario and the available local weather station.

The model was run with four different sowing dates (D1:10th January, D2: 10th February, D3: 10th March, D4: 10th April), under rainfed conditions, setting nitrogen fertilization input to 70 kg N ha^{-1} (conventional management) and plant density to 7.7 plants m^{-2} to simulate the achene yield (Ys) and the length of growing season (LGS). The crop harvest date was set at maturity in the crop model.

The interannual achene production variability was simulated by keeping the same management conditions already listed above for each of the hypothesized sowing dates, to distinguish the impacts of temperature and rainfall changes.

The water-limited achene yield potential (Y_{wl}) was calculated as the benchmark for rainfed sunflower, by removing nutritional stress. The potential achene yield (Y_p) was obtained removing both water and nitrogen stress.

The achene yield gap (Y_{gap}) was calculated between Y_{wl} and the simulated yield (Y_s) by removing water stress for each sowing date (van Ittersum et al., 2013).

The yield gaps are also expressed as Y_{wl} = ([1-Y_s/Y_{wl}]*100%).

In order to identify sustainable water application strategies able to fill the yield gap, two irrigation strategies were tested under baseline scenario.

The watering strategy a (wsa) consisted in irrigating with 50 mm applied 20 days before anthesis, that according to literature is considered the most water sensitive for the crop. EPIC simulated the irrigation, identifying the most critical moment according to the average GDD accumulated during the four years of experiment from the sowing to the 20-days-before-anthesis.

The watering strategy b (wsb) was more complex and was set on two conditions: the first was an irrigation per week and the second was starting with irrigation 20 days before anthesis and irrigating during flowering. Irrigation simulated within EPIC occurred to compensate water stress which is strictly a function actual evapotranspiration divided by potential evapotranspiration.

3. Results

3.1 Weather during the field experiments

In the 4-years experiment, the crop cycle length (sowing to harvest) under rainfed conditions was on average 144±18 (±standard deviation) days (20 March-11 August) and 1369±480 GDD (for 00SD, ranging from 196 to 238 days, corresponding to 719-2236 GDD, for the whole set of experimental treatments (Table 1). The average annual rainfall in 2015-18 during the 00SD crop cycle was on average 90±46 mm, 37% drier than the 1980-2018 average for the same period. Considering the crop cycle of the whole set of sowing dates under rainfed conditions in the four years, rainfall was always on average 35% lower than the long-term average (150 mm) in 2015-17 and 5% higher than the long-term average (200 mm) in the corresponding period of 2018. The average ETo in the same interval was 631±87 mm, only 10 mm higher than the corresponding the long-term average. Over the 00SD rainfed crop cycle, some 71% of the total rain (65-85% across all sowing dates) and 29% of the total ETo occurred between the sowing date and mid-May. In 2015-18, rainfall contributed between 7%

and 36% of the ETo during the crop cycle across the different sowing dates. On average, 286±159 mm was supplied with sprinkler irrigation to I1-00SD and between 125 and 415 mm to the irrigated plots sowed earlier than 00SD. Irrigation did not change the duration of the sowing-anthesis period but delayed harvesting date of some 170 GDD on average (Table 1).

3.2 Sunflower productivity, yield components and biometry

The achieved sunflower plant density ranged between 8.9 ± 0.3 plants m^{-2} (± s.d.) (00SD) and 3.3 ± 1.1 plants m^{-2} (SD02) both observed in 2015. In the subsequent years no such differences were observed in plant densities between sowing dates, that ranged between 7.1 and 7.9 plants m^{-2} (Tab.1). With the only exception for 2018, all achene yield components were significantly affected by the irrigation regime (Tab.2; Tab.S1), as well as AGB (P=0.08 in 2015).

A significant sowing date × water regime interaction was observed for NAC in 2015 and for AY, NAC, AWC, PH, STD and WUE_a in 2016 (Tab.2; Tab.S1). In 2018, the sowing date affected both AW and STD (Tab.2).

Under 00SD, AY under rainfed conditions was on average 68% lower than that under irrigation in 2015-16-17 but only 18% lower in 2018, when rainfall during the crop cycle was only 9% lower than the climatic average during the crop cycle (Tab. S1). Under anticipated sowing date scenarios, AY under rainfed conditions was between 66% and 74% lower than under irrigation, except for the very early sowing date in 2016, when AY under rainfed conditions was only 20% less than under irrigation (Tab. S1).

Under rainfed conditions, most of the AY variability across years and sowing dates was associated to AWC (R^2= 0.88; df=7) and NAC (R^2=52%; df=7); under irrigation, AY variability across years and sowing dates was mainly associated to AWC (R^2=0.78; df=7) and NAC (R^2=72%; df=7). The total AY variation including the irrigation effect was mainly associated to AWC (R^2= 92%; df=14) and NAC (R^2=72%; df=14). All R^2 were calculated excluding the data biased by the bird predation of seedlings in 2015 under SD02.

For all the years in which a significant effect of irrigation on sunflower productivity was observed, AY was consistently higher under irrigation than under rainfed condition (2015: 2432 kg d.m. ha^{-1} *vs* 754 kg d.m. ha^{-1}; 2016: 2437 kg d.m. ha^{-1} *vs* 902 kg d.m. ha^{-1}; 2017: 2661 kg d.m. ha^{-1} *vs* 894 kg d.m. ha^{-1}) (Tab. S1). Conversely, the AY observed in 2018 was not affected by the irrigation regime, being on average 1692 kg d.m. ha^{-1}.

3.3 Sunflower Water Use Efficiency

The water use efficiency of achene yield (WUE_a) was significantly affected by the irrigation regime in all years but 2018 (Tab.2). Moreover, a significant sowing date × irrigation interaction was observed in 2016. For each of these years (2015, 2016 and 2017), WUE_a under I1 regime was two or three times higher compared to I0 (2015- I1: 0.66 kg ha^{-1} mm^{-1} *vs* I0: 0.21 kg ha^{-1} mm^{-1}; 2016 – I1: 0.74 kg ha^{-1} mm^{-1} *vs* I0: 0.31 kg ha^{-1} mm^{-1}; 2017-I1: 0.90 kg ha^{-1} mm^{-1} *vs* I0: 0.32 kg ha^{-1} mm^{-1}) (Tab. S1).

The sowing date × irrigation interaction observed for WUE_a in 2016, revealed that WUE_a of 07SD and 00SD under I0 were similar and lower than the respective WUE_a under I1 (07SD-I1: 0.94 kg ha^{-1} mm^{-1} and 00SD-I1: 0.90 kg ha^{-1} mm^{-1}). Differently, in the same year, for the earliest sowing date (13SD), WUE_a was higher under I0 than under I1 (0.42 *vs* 0.38 kg ha^{-1} mm^{-1}), but still lower compared to the WUE_a registered for 07SD and 00SD under I1. In 2018, the WUE_a for I1 (0.6 kg ha^{-1} mm^{-1}) was lower compared to the previous years, but still higher, although not statistically greater, than the one registered for I0 in the same year (0.40 kg ha^{-1} mm^{-1}) (Tab. S1).

3.4 Model simulation evaluation: Achene yield and Above-ground biomass

The performance of the EPIC model was evaluated by comparing simulated and observed achene yield and above-ground biomass under different treatments (Suppl. mat. Tab. 2). The observed AY ranged from 577 to 1589 kg ha^{-1} (2015-2018) under rainfed condition, while the observed AY under irrigated management ranged from 1388 to 3137 kg ha^{-1} (2015 - 2018). The model showed a very good fit performance between simulated and observed AY data under both management strategies

(Fig. 2, Fig.3). About AGB, the fitting between observed and simulated data was better under rainfed than under irrigated condition (Fig.2, Fig.3).

3.5 Scenarios for sustainable sunflower management

3.5.1 EPIC simulation of the effect of sowing date and water supply on sunflower yield

Under baseline scenario, the comparison among the four different projected sowing dates (D1, D2, D3, D4) made evident that delaying sowing dates shortened the growth cycle (Tab. 3), while raising simulated achene yield (Y_s).

Water-limited yield (Y_{wl}), obtained removing nitrogen stress, followed the same path of Y_s, while the potential yield (Y_p) was gradually decreasing from D1 to D4. Although, the calculated water supply ranged between 250 and 275 mm among the 4 dates, the yield gap registered for the earlier sowing dates (D1 and D2) was much higher than for later sowing dates (D3 and D4) (Tab.4).

Figure 4 zooms in the trends of simulated above-ground biomass (AGB_s) accumulation over the growing season of sunflower sown at different dates, pointing D3 out as the most promising sowing date in terms of achene yield.

The monthly AGB_s accumulation curve showed, the highest AGB_s accumulation in June, regardless the sowing date (Fig. 4).

The simulated achene yield (Y_s) distribution for the four hypothesized sowing dates under rainfed conditions highlighted a greater stability of the Y_s (2000 kg ha^{-1}) for D3 (Fig.5).

From the drawn irrigation scenarios, it was evident that the hypothesis of a single irrigation of 50 mm applied 20 days before anthesis (water scenario a - wsa) although slightly increased Y_{wsa} for D1 and D2 compared to Y_{wl}, did not increase the Y_{wsa} for D3 and D4. Moreover, this single water intervention determined a flattering of Y_{wsa} on about 2050 kg ha^{-1} regardless of the sowing date (Tab. 5).

The irrigation strategy b – wsb consistently improved Y_{wsb} almost approaching Y_p for all the considered sowing dates. In particular, for D3 and D4, Y_p and Y_{wsb} were much closed than for D1 and D2. Moreover, the water supplied under wsb was about 100 mm lower than the water supplied to achieve Y_p (Fig.6, Table 5).

4. Discussion

4.1 Field experiment

The results obtained from the field experiment confirmed that under rainfed condition in a semi-arid Mediterranean climate, the achene production of sunflower is heavily constrained by soil water availability; indeed, under irrigation the achene yield was more than double than under rainfed conditions (Göksoy et al., 2004; Perniola et al., 2006). Many studies conducted on sunflower in the Mediterranean region under rainfed conditions have identified in the anticipation of the sowing date a good strategy to escape drought stress, thus preserving crop productivity (Ferreira and Abreu, 2001; Flagella et al., 2002; Barros et al., 2004). In most cases reported by the literature, the earlier sowing was performed as a shift from Mid-April or May to Mid-March (Ferreira and Abreu, 2001; Flagella et al., 2002; Demir et al., 2019). In our experiment, the earlier sowing dates ranged from December to Mid-March, while the benchmark sowing dates were centered on 20th March ± 1 week, thus already anticipated if compared to the mid-April conventional sowing dates mentioned by other authors for similar climatic regions (Ferreira and Abreu, 2001; Flagella et al., 2002; Killi and Altunbay, 2005; Perniola et al., 2006; Demir et al., 2019).

The observed achene yields, with the only exception for 2018, whose weather was completely different from the other years when the experiment was run, showed that there was no substantial advantage to anticipate sowing earlier than late February or Mid-March, in agreement with Perniola et al. (2006). This pattern was related to a lower accumulation of CGDD-A (from sowing to the anthesis) and of CGDD-H (from sowing to the harvest, thus including seed-filling phase) for earlier sowing dates. Indeed, many studies highlighted the relevance of heat units accumulation on AW during the seed-filling phase (between the end of anthesis and physiological maturity), in order to prevent AY losses (Aguirrezábal et al., 2003; Qadir et al., 2007).

The differences in AY observed in 2015 between 00SD and SD02 were mainly due to the differences in plant density caused by bird predation which halved plant density in the later sowing date (Linz et al., 2011). The resulting AY was only partially affected thanks to the plasticity of sunflower in terms of increasing AW and NAC in low density stands (Barros et al., 2004).

In 2016, the sowing date interacted with irrigation regime for AY and several other parameters (NAC, AWC, PH, STD). These results confirmed those obtained by Perniola et al. (2006).

Keipp et al. (2020) showed that the AY under water stress was related to the seed filling phase and that the observed AY reduction is not due to seed number but to single seed weight. In 2016, this pattern was clearly evident for 07SD, which received irrigation when was at the phenological stage of 31 (stem elongation), thus rainfed *vs* irrigated regime could affect significantly the flowering and seed-filling phase. A similar pattern was observed for 00SD. Conversely, for 14SD, the irrigation occurring at phenological stage of 51 (flowering) and prolonged only during milking phase was not efficient (Göksoy et al., 2004) as also confirmed by Browne (1977) reporting that greatest damages are generated when water stress occurs in the 20 days prior to flowering. Indeed, Rawson and Turner (1983) identified in two-three weeks before flowering the optimal period for starting irrigation, while negative effects for irrigation started to be apparent at anthesis, thus confirming our results. Moreover Joshi et al. (2017) identified the best yielding watering strategy for confection sunflower in irrigating up to when 50% of the disc flowers have completed flowering.

From the results obtained in 2016, which was the year in which more anticipated sowing dates were tested thus covering a very large sowing window, it was possible to better understand the effects of the sowing dates on NAC. The reduced NAC for early sowing dates could have been affected by reduced visits by insect pollinators due to the earlier timing of anthesis, counteracted by the 1000 seeds weight that was larger compared to the later sowing dates. This inverse trend between seed number and 1000 seeds weight was already reported by de la Vega and Hall (2002) and was related to the genotype.

Similarly, to the pattern observed for AY, also water use efficiency for the achene yield (WUEa) was significantly higher for 00SD than for earlier sowing dates (although not significant effect for sowing date was registered except for 2017). In our case, in which the conventional sowing date was already anticipated than in other studies, there was a reduction of the irrigation volumes under irrigated conditions and an increment of soil water availability in rainfed conditions since the crop could benefit of early spring rainfall when temperatures were mild enough, which suggest to set the Mid-march/earlyApril as a potential win-win solution in term of maximizing seed yield potential and water use efficiency. Differently, the earlier sowing dates were not able to efficiently exploit the precipitation occurring when the plants were in the initial development stage and when average temperatures were still too cold for seed setting either for insufficient pollination and/or sub-optimal weather condition during flowering, such as low radiation and too much wind (Scaven and Raffenty, 2013).

4.2 EPIC Simulation

4.2.1 Model calibration

The EPIC model successfully simulated the sunflower achene and biomass production. The accuracy of EPIC in simulating sunflower growth dynamics was in line with studies performed under similar agro-climatic conditions on oilseed rape (Deligios et al., 2013) and on sunflower (Kiniry et al., 1992, Farina et al, 2011). Nevertheless, the model underestimated the high AGB values under irrigation while providing a reasonable average AGB of the four years, as already observed with the same model for other crops' performances (Le et al., 2018)

4.2.2. Sunflower productivity under baseline scenario depending on sowing date and water supply

The baseline climatic scenario confirmed that mid-March - early April (D3, D4) are the most promising sowing date in terms of achene production compared to the earlier ones (D1, D2) under semi-arid Mediterranean conditions. As already discussed in section 4.2.1, these results were consistent to those reported by other studies showing advantage in terms of achene yield of early sowing dates vs. end of April-May (d'Andria et al., 1995; Ferreira and Abreu, 2001).

Within baseline scenario, water availability for irrigation acquired an interesting perspective especially under irrigation scenario b, suggesting a viable option for sunflower cultivation in Mediterranean areas. Compared to 265mm supplied for potential yield, the water scenario b with 150 mm distributed in the period between 20 days before anthesis and flowering was able to guarantee for the hypothesized sowing dates occurring in March-April (D3, D4) an overall achene yield comparable to the potential one, while for the earlier dates (D1, D2) even higher achene yield production than D3 and D4 but still far from the corresponding potential one. These findings found support in results collected by previous research identifying in specifically drawn deficit irrigation strategies, viable and sustainable production perspective for sunflower in semi-arid areas (Joshi et al., 2017; Liu et al., 2018).

The practical implication of the simulation made evident that sowing in March- April (D3, D4) could be a promising solution to escape drought and keep high achene production, under rainfed conditions. Differently, anticipated sowing season occurring into winter season and already documented to generate thermal responses because of low radiation levels (Ferreira et al., 2001) if combined with water stress due to absence of water can determine detrimental effects on yield production.

5. Conclusion

The results of this study revealed that a sowing date, occurring in Mid-March/early April, is the most appropriate under Mediterranean rainfed condition, thus shifting earlier than the conventional sowing dates investigated in many other studies. Conversely, further anticipating sowing dates caused seed yield losses mainly due to lower heat unit accumulation during the seed-filling phase. Under semi-arid Mediterranean conditions, sunflower showed significant reliance on irrigation, which is crucial during the 20 days before flowering. Indeed, under a simulated scenario supply water from 20 days before anthesis up to flowering, partially bridged the gap between water limited yield potential and potential yield, almost approaching yield potential especially for earlier sowing dates (D1, D2). The practical implication of simulation was that anticipating sowing dates could be a viable strategy in the Mediterranean if at least little water is available, otherwise keeping sowing date around 10th March is the most promising strategy for a high and stable achene production.

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7. CRediT Roles

V.G.: formal analysis, data curation, writing- original draft, writing- review & editing, visualization; **L.M**.: formal analysis, data curation, writing- review & editing, visualization; **M.C.**: conceptualization, investigation and data curation; **G.P.**: investigation; **P.P.R.**: conceptualization, methodology, resources, supervision, writing- review & editing, project administration

8. Tables captions

Table 1. Sowing date, Harvest date, Length of the crop growing season, cumulative growing degree days from sowing to harvest (CGDD-H), cumulative growing degree days from sowing to anthesis (CGDD-A), final plant density ±standard deviation (in italics).

Table 2. ANOVA significance table for the effects of sowing date and water regime and their interactions on crop growth and harvest agronomic parameters (AGB: Above-ground biomass; AY: Achene Yield; AN: Achene number per unit of surface; AW: weight of 1000 achenes; NAC: number of achenes per capitulum; AWC: achene weight per capitulum; PH: Plant height; STD: stem diameter; WUE_a: water use efficiency referred to achene production). Significant P values are reported in bold.

Table 3. Effects of baseline climatic scenarios on LGS= length of growing season and Y_s= simulated achene yield ± standard deviation (*in italics*), depending on four different sowing dates

Table 4. Water-limited achene yield (Ywl) and potential yield (Yp) for each hypothesized sowing date under baseline scenario. Y gap is calculated according to van Ittersum et al. (2013). W supply is the amonut of water required to reach Yp

Table 5. Achene yield simulated under two different irrigation scenarios (Ywsa with a single irrigation with 50 mm and Ywsb with irrigation from 20days before anthesis up to flowering) and four hypothesized sowing dates. W supply indicates the amount of water required for Ywsb according to different sowing date

9. Figures captions

Figure 1. 38-year-trend (1981-2019) of average rainfall and temperature in comparison with the years of the experiment. The arrows indicate the sowing dates and the harvest time for irrigated (↓) and rainfed treatment

(⇩). Acronyms explenation: 00SD- conventional sowing date; SD02- 2 weeks after 00SD; 13SD- 13 weeks before 00SD; 07SD- 7 weeks before SD; 04SD- 4 weeks before SD; 10SD- 10 weeks before SD; H is the harvested date happening in different days depending on the sowing date and water regime.

Figure 2. Comparison between simulated and observed achene yield (left) and above-ground biomass (right) sowed at different dates (ESD1, ESD2, CSD) under rainfed conditions in 2015, 2016, 2017 and 2018 growing season.

Figure 3. Comparison between simulated and observed achene yield (left) and above-ground biomass (right) sowed at different dates (ESD1, ESD2, CSD) under irrigated conditions in 2015, 2016, 2017 and 2018 growing season.

Figure 4. Simulated achene yield (Y_s) and Above-Ground biomass (AGB_s) accumulation curve for different sowing dates under baseline climatic scenario under rainfed conditions

Figure 5. Simulated achene yield (Y_s) frequency distribution under baseline scenario at different times after sowing for sunflower sown in first ten days of January (D1), February (D2), March (D3) and April (D4) under rainfed condition

Figure 6. Simulated achene yield (Y_s) for different sowing dates (D1- 10th January; D2 – 10th February; D3 – 10th March; D4- 10th April) under different scenarios (baseline Ywl- water limited scenario; baseline Yp- potential yield scenario; baseline Ywsa- single irrigation of 50 mm scenario; baseline Ywsb – irrigation from 20 days before anthesis and prolonged during flowering).

10. References

- Aguirrezábal, L. A., Lavaud, Y., Dosio, G. A., Izquierdo, N. G., Andrade, F. H., & González, L. M. 2003. Intercepted solar radiation during seed filling determines sunflower weight per seed and oil concentration. Crop Science, 43(1), 152-161. https://doi.org/10.2135/cropsci2003.1520

- Barros, J. F., de Carvalho, M., Basch, G. 2004. Response of sunflower (Helianthus annuus L.) to sowing date and plant density under Mediterranean conditions. European Journal of Agronomy, 21(3), 347-356. https://doi.org/10.1016/j.eja.2003.10.005

-Bellocchi, G., Acutis, M., Fila, G., 2002. An indicator of solar radiation model performance based on a fuzzy expert system. Agron. J. 94 (6), 1222–1233. https://doi.org/10.2134/agronj2002.1222

- Browne, C. L. 1977. Effect of date and final irrigation on yield and yield components of sunflowers in a semi-arid environment. Australian Journal of Experimental Agriculture, 17(86), 482-488. https://doi.org/10.1071/EA9770482

-Bucchignani E., Montesarchio M., Zollo A.L., Mercogliano P. 2016. High-resolution climate simulations with COSMO-CLM over Italy: performance evaluation and climate projections for the XXI century. International Journal of Climatology 36(2), 735-756. https://doi.org/10.1002/joc.4379

- d'Andria, R., Chiarandà, F. Q., Magliulo, V., Mori, M. 1995. Yield and soil water uptake of sunflower sown in spring and summer. Agronomy journal, 87(6), 1122-1128. https://doi.org/10.2134/agronj1995.00021962008700060014x

- Debaeke, P., Aboudrare, A. 2004. Adaptation of crop management to water-limited environments. European Journal of Agronomy, 21(4), 433-446. https://doi.org/10.1016/j.eja.2004.07.006

- De la Vega, A.J., Hall, A.J., 2002. Effects of planting date, genotype, and their interactions on sunflower yield. I. Determinants of oil-corrected grain yield. Crop Sci. 42, 1191–1201. https://doi.org/10.2135/cropsci2002.1191

-Deligios, P. A., Farci, R., Sulas, L., Hoogenboom, G., Ledda, L. 2013. Predicting growth and yield of winter rapeseed in a Mediterranean environment: Model adaptation at a field scale. Field Crops Research, 144, 100-112. https://doi.org/10.1016/j.fcr.2013.01.017

-Demir, I. 2019. The effects of sowing date on growth, seed yield and oil content of sunflower (helianthus annuus l.) cultivars under rainfed conditions. FEB-FRESENIUS ENVIRONMENTAL BULLETIN, 6849.

- Ebrahimian, E., Seyyedi, S. M., Bybordi, A., & Damalas, C. A. 2019. Seed yield and oil quality of sunflower, safflower, and sesame under different levels of irrigation water availability. Agricultural water management, 218, 149-157. https://doi.org/10.1016/j.agwat.2019.03.031

-FDA (2018) https://www.foodnavigator-usa.com/Article/2018/11/19/FDAapprovesqualifiedhealthclaimforhigholeicoilsandreducedriskofcoronaryheartdisease (2018)

- Farina, R., Seddaiu, G., Orsini, R., Steglich, E., Roggero, P. P., Francaviglia, R. 2011. Soil carbon dynamics and crop productivity as influenced by climate change in a rainfed cereal system under contrasting tillage using EPIC. Soil and Tillage Research, 112(1), 36-46. https://doi.org/10.1016/j.still.2010.11.002

- Ferreira, A. M., Abreu, F. G. 2001. Description of development, light interception and growth of sunflower at two sowing dates and two densities. Mathematics and Computers in simulation, 56(4-5), 369-384. https://doi.org/10.1016/S0378-4754(01)00308-1

- Flagella, Z., Rotunno, T., Tarantino, E., Di Caterina, R., De Caro, A. 2002. Changes in seed yield and oil fatty acid composition of high oleic sunflower (Helianthus annuus L.) hybrids in relation to the sowing date and the water regime. European journal of agronomy, 17(3), 221-230. https://doi.org/10.1016/S1161-0301(02)00012-6

-García-Vila. M., Fereres, E., Prieto, M.H., Ruz, C., Soriano, M.A. 2012. Sunflower. In: Crop yield response to water FAO Irrigation and Drainage, Paper 66

-Gassman, P.W., Williams, J.R., Benson, V.W., Izaurralde, R.C., Hauck, L.M., Jones, C.A., Atwood, J.D., Kiniry, J.R., and Flowers, J.D. 2005. Historical development and applications of the EPIC and APEX models. In ASAE/CSAE Annual International Meeting. American Society of Agricultural and Biological Engineers, Ottawa, ON, Canada.

-Göksoy, A.T., Demir, A.O., Turan, Z.M., Dagüstü, N. 2004. Responses of sunflower (Helianthus annuus L) to full and limited irrigation at different growth stages. Field Crops Res 87: 167–178. Doi : 10.1016/j.fcr.2003.11.004

- IPCC. 2014. Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, R.K. Pachauri and L.A. Meyer (eds.)]. IPCC, Geneva, Switzerland, 151 pp.

- Iqbal, N., Ashraf, M. Y., Ashraf, M. 2005. Influence of water stress and exogenous glycinebetaine on sunflower achene weight and oil percentage. International Journal of Environmental Science & Technology, 2(2), 155-160. https://doi.org/10.1007/BF03325870

-Izaurralde, R. C., McGill, W. B., Williams, J. R. In *Managing agricultural greenhouse gases: Coordinated agricultural research through* GRACEnet *to address our changing climate* (Liebig, M. A., Franzluebbers, A. J. & Follett, R. F. eds) 409–429 (Elsevier, 2012)

-Joshi, V. R., Heitholt, J. J., Garcia y Garcia, A. 2017. Response of confection sunflower (Helianthus annuus L.) grown in a semi- arid environment to planting date and early termination of irrigation. Journal of Agronomy and Crop Science, 203(4), 301-308. https://doi.org/10.1111/jac.12212

-Keipp, K., Hütsch, B. W., Ehlers, K., Schubert, S. 2020. Drought stress in sunflower causes inhibition of seed filling due to reduced cell- extension growth. Journal of Agronomy and Crop Science. 206(5), 517-528. https://doi.org/10.1111/jac.12400

-Killi, F. A. T. I. H., Altunbay, S. G. 2005. Seed yield, oil content and yield components of confection and oilseed sunflower (Helianthus annuus L.) cultivars planted in different dates. Int. J. Agri. Biol, 7(1), 21-24.

- Kiniry, J. R., Blanchet, R., Williams, J. R., Texier, V., Jones, C. A., Cabelguenne, M. 1992. Sunflower simulation using the EPIC and ALMANAC models. Field Crops Research, 30(3-4), 403-423. https://doi.org/10.1016/0378-4290(92)90008-W

- Kottek, M., Grieser, J., Beck, C., Rudolf, B., Rubel, F. 2006. World map of the Köppen-Geiger climate classification updated. Meteorologische Zeitschrift Vol. 15 No. 3, p. 259 – 263. DOI: 10.1127/0941-2948/2006/0130

- Lancashire, P. D., Bleiholder, H., Boom, T. V. D., Langelüddeke, P., Stauss, R., Weber, E., Witzenberger, A. 1991. A uniform decimal code for growth stages of crops and weeds. Annals of applied Biology, 119(3), 561-601. https://doi.org/10.1111/j.1744-7348.1991.tb04895.x

- Le, K. N., Jeong, J., Reyes, M. R., Jha, M. K., Gassman, P. W., Doro, L., ... & Boulakia, S. 2018. Evaluation of the performance of the EPIC model for yield and biomass simulation under conservation systems in Cambodia. Agricultural systems, 166, 90-100. https://doi.org/10.1016/j.agsy.2018.08.003

-Linz, G. M., Homan, H. J., Werner, S. J., Hagy, H. M., Bleier, W. J. 2011. Assessment of bird-management strategies to protect sunflowers. BioScience, 61(12), 960-970. https://doi.org/10.1525/bio.2011.61.12.6

-Liu, R., Abdelraouf, E. A. A., Bicego, B., Joshi, V. R., y Garcia, A. G. 2018. Deficit irrigation: a viable option for sustainable confection sunflower (Helianthus annuus L.) production in the semi-arid US. Irrigation Science, 36(6), 319-328. https://doi.org/10.1007/s00271-018-0588-6

-Loague, K., Green, R.E. 1991. Statistical and graphical methods for evaluating solute transport models: overview and application. J. Contam. Hydrol. 7, 51–73. https://doi.org/10.1016/0169-7722(91)90038-3

- Madrau, S., Deroma, M.A., Loi, G., Baldaccini, P., 2006. Il database pedologico georeferenziato e la Carta dei Suoli della Sardegna, Gallizzi ed., Sassari

-Mila, A. J., Akanda, A. R., Biswas, S. K., Ali, M. H. 2016. Crop Co-efficient Values of Sunflower for Different Growth Stages by LysimeterStudy. British Journal of Environment and Climate Change, 6(1), 53-63. DOI: 10.9734/BJECC/2016/24246

- Middleton, N., Thomas, D. 1997. World atlas of desertification. ed. 2. Arnold, Hodder Headline, PLC.

- Monlau, F., Barakat, A., Steyer, J. P., Carrere, H. 2012. Comparison of seven types of thermo-chemical pretreatments on the structural features and anaerobic digestion of sunflower stalks. Bioresource technology, 120, 241-247. https://doi.org/10.1016/j.biortech.2012.06.040

-Pereyra-Irujo, G. A., Izquierdo, N. G., Covi, M., Nolasco, S. M., Quiroz, F., Aguirrezábal, L. A. 2009. Variability in sunflower oil quality for biodiesel production: a simulation study. Biomass and bioenergy, 33(3), 459-468. https://doi.org/10.1016/j.biombioe.2008.07.007

-Perniola, M., Nardiello, I., Lovelli, S. 2006. Effect of sowing date on water use efficiency of sunflower crop. Italian Journal of Agronomy, 387-392. https://doi.org/10.4081/ija.2006.387

- Qadir, G., Cheema, M. A., Hassan, F., Ashraf, M., Wahid, M. A. 2007. Relationship of heat units accumulation and fatty acid composition in sunflower. Pakistan Journal of Agricultural Sciences, 44(1), 24-29.

- Quiles, J.L., Ramírez-Tortosa, M.C., Gómez, J.A., Huertas, J.R., Matiax, J., 2002. Role of vitamin E and phenolic compounds in the antioxidant capacity, measured by ESR, of virgin olive, olive and sunflower oils after frying. Food Chem. 76 (4), 461–468. https://doi.org/10.1016/S0308-8146(01)00307-7

- Ragaglini, G., Triana, F., Villani, R., Bonari, E. 2011. Can sunflower provide biofuel for inland demand? An integrated assessment of sustainability at regional scale. Energy, 36(4), 2111-2118. https://doi.org/10.1016/j.energy.2010.03.009

- Rawson, H. M., Turner, N. C. 1983. Irrigation timing and relationships between leaf area and yield in sunflower. Irrigation Science, 4(3), 167-175.

- Rockel, B., Will, A., Hense, A. 2008. The regional climate model COSMO-CLM (CCLM). Meteorologische Zeitschrift, 17(4), 347-348. DOI 10.1127/0941-2948/2008/0309

-Scaven, V. L., Rafferty, N. E. 2013. Physiological effects of climate warming on flowering plants and insect pollinators and potential consequences for their interactions. Current zoology, 59(3), 418-426. https://doi.org/10.1093/czoolo/59.3.418

- Scoccimarro, E., Gualdi, S., Bellucci, A., Sanna, A., Giuseppe Fogli, P., Manzini, E., ... & Navarra, A. 2011. Effects of tropical cyclones on ocean heat transport in a high-resolution coupled general circulation model. Journal of Climate, 24(16), 4368-4384. https://doi.org/10.1175/2011JCLI4104.1

-Tariq, M., Ahmad, S., Fahad, S., Abbas, G., Hussain, S., Fatima, Z., ... & Adnan, M. 2018. The impact of climate warming and crop management on phenology of sunflower-based cropping systems in Punjab, Pakistan. Agricultural and Forest Meteorology, 256, 270-282. https://doi.org/10.1016/j.agrformet.2018.03.015

- Van Ittersum, M. K., Cassman, K. G., Grassini, P., Wolf, J., Tittonell, P., Hochman, Z. 2013. Yield gap analysis with local to global relevance—a review. Field Crops Research, 143, 4-17. https://doi.org/10.1016/j.fcr.2012.09.009

-Williams J.R. 1995. The EPIC model, 1995. In: Singh V.P. (ed) Computer models of watershed hydrology. Water Resources Publications, Highlands Ranch, pp 909–1000.

-Willmott, C.J., 1982. Some comments on the evaluation of model performance. Bull. Meteorol. Soc. 63, 1309–1313

- Zeleke, K., Nendel, C. 2019. Growth and yield response of faba bean to soil moisture regimes and sowing dates: Field experiment and modelling study. Agricultural water management, 213, 1063-1077. https://doi.org/10.1016/j.agwat.2018.12.023

- Zhurka, M., Spyridonidis, A., Vasiliadou, I. A., & Stamatelatou, K. 2020. Biogas Production from Sunflower Head and Stalk Residues: Effect of Alkaline Pretreatment. Molecules, 25(1), 164. https://doi.org/10.3390/molecules25010164

-Zollo A.L., Rillo V., Bucchignani E., Montesarchio M., Mercogliano P. 2016. Extreme temperature and precipitation events over Italy: assessment of highresolution simulations with COSMO-CLM and future scenarios. International Journal of Climatology 36(2), 987-1004. https://doi.org/10.1002/joc.4401

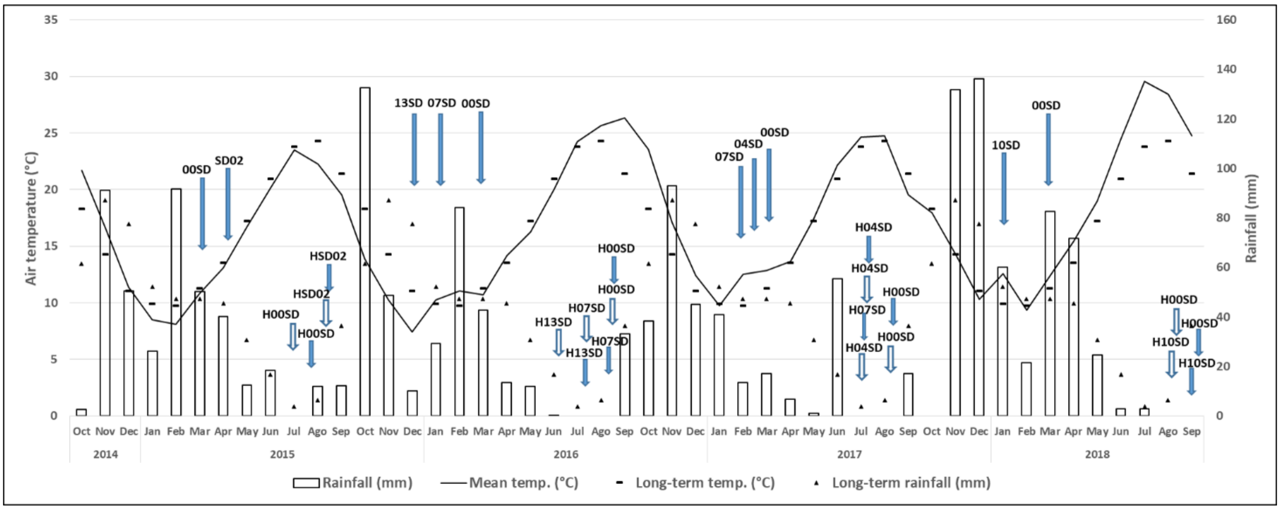


Figure 1 – 38-year-trend (1981-2019) of average rainfall and temperature in comparison with the years of the experiment. The arrows indicate the sowing dates and the harvest time for irrigated (⬇) and rainfed treatment(⇩). Acronyms explenation: 00SD- conventional sowing date; SD02- 2 weeks after 00SD; 13SD- 13 weeks before 00SD; 07SD- 7 weeks before SD; 04SD- 4 weeks before SD; 10SD- 10 weeks before SD; H is the harvested date happening in different days depending on the sowing date and water regime.

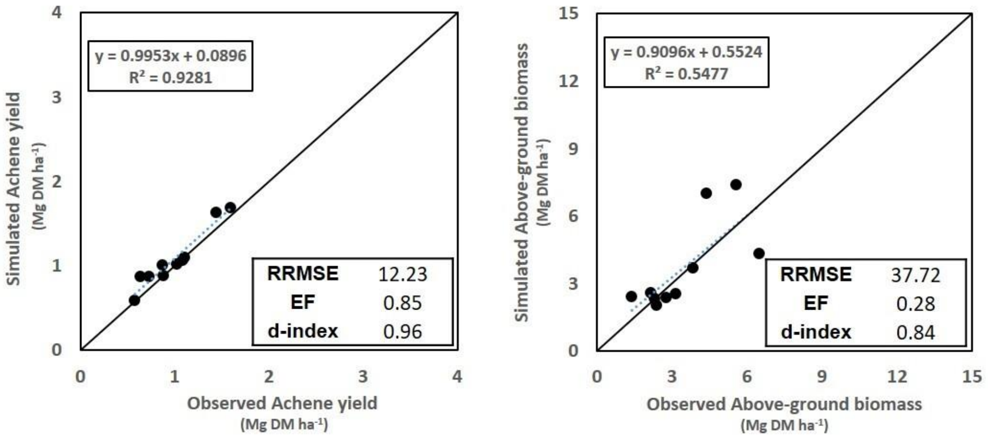
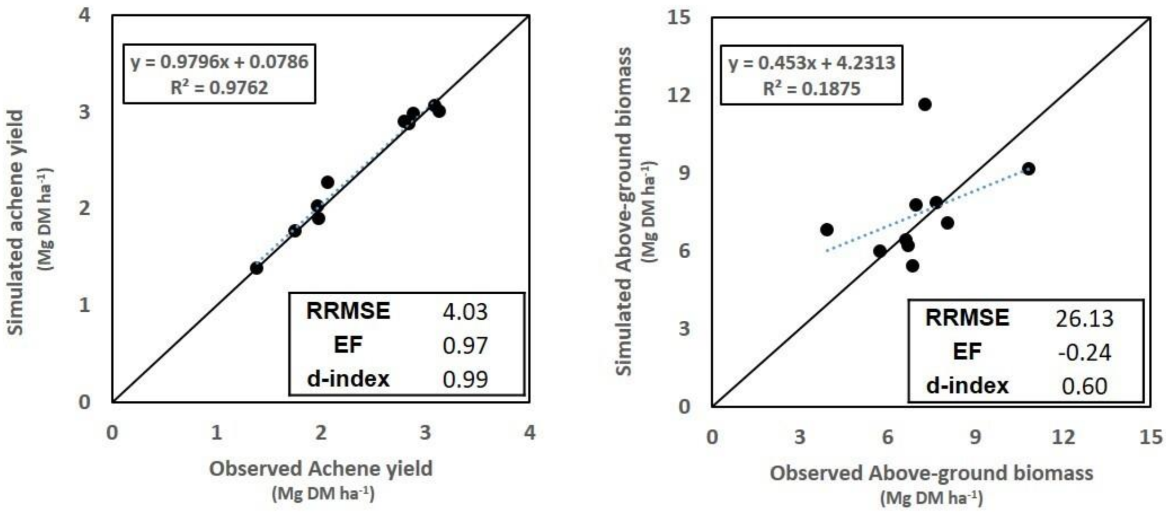


Fig. 2- Comparison between simulated and observed (a) seed yield (b) above-ground biomass sowed at different dates (ESD1, ESD2, CSD) under rainfed conditions in 2015, 2016, 2017 and 2018 growing season.



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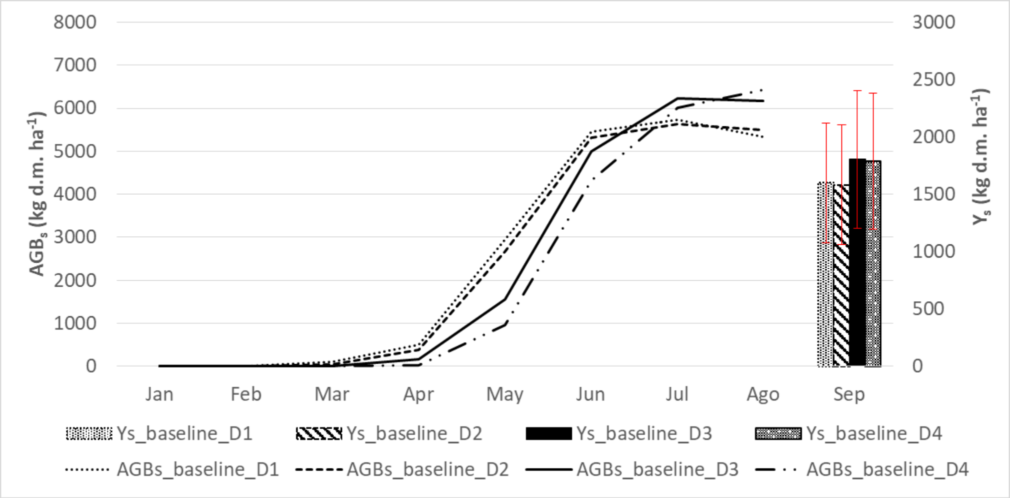

Fig. 4- Simulated achene yield (Y_s) and Above-Ground biomass (AGB_s) accumulation curve for different sowing dates under baseline climatic scenario under rainfed conditions

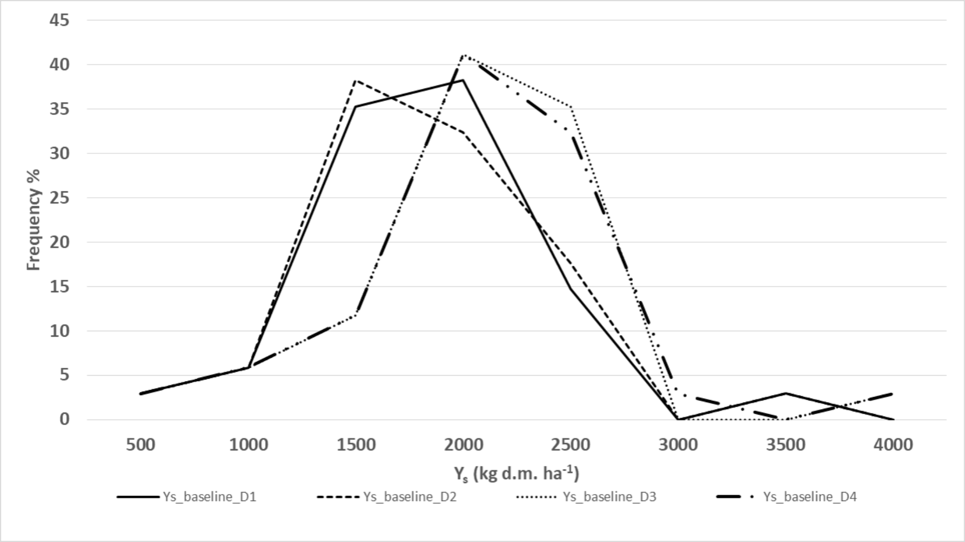

Fig.5- Simulated achene yield (Y_s) frequency distribution under baseline scenario at different times after sowing for sunflower sown in first ten days of January (D1), February (D2), March (D3) and April (D4) under rainfed condition

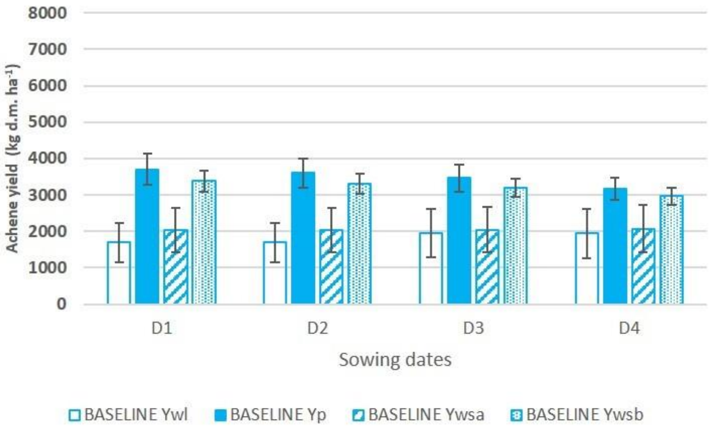

Fig.6- Simulated achene yield (Y_s) for different sowing dates (D1- 10th January; D2 – 10th February; D3 – 10th March; D4- 10th April) under different scenarios (baseline Ywl- water limited scenario; baseline Yp- potential yield scenario; baseline Ywsa- single irrigation of 50 mm scenario; baseline Ywsb – irrigation from 20 days before anthesis and prolonged during flowering).

Table 1. Sowing date, Harvest date, Length of the crop growing season, cumulative growing degree days from sowing to harvest (CGDD-H), cumulative growing degree days from sowing to anthesis (CGDD-A), final plant density ±standard deviation (*in italics*).

Treatment	Sowing Date	Harvest Date	Length of crop growing season (days)	CGDD-H	CGDD-A	Plant density (plants m^{-2} ± sd)
2015_I0_00SD	20-Mar-15	27-Jul-15	130	1006	823	8.9 *(±0.3)*
2015_I1_00SD	20-Mar-15	3-Aug-15	137	1098	823	8.9 *(±0.3)*
2015_I0_SD02	3-Apr-15	6-Aug-15	126	1108	988	4.3 *(±1.8)*
2015_I1_SD02	3-Apr-15	13-Aug-15	133	1199	988	3.3 *(±1.1)*
2016_I0_13SD	17-Dec-15	29-Jun-16	196	719	342	8.0 *(±0.5)*
2016_I1_13SD	17-Dec-15	15-Jul-16	212	935	364	7.4 *(±0.4)*
2016_I0_07SD	29-Jan-16	29-Jul-16	183	1111	581	6.7 *(±1.3)*
2016_I1_07SD	29-Jan-16	23-Aug-16	208	1498	581	6.6 *(±1.4)*
2016_I0_00SD	15-Mar-16	5-Aug-16	144	1171	603	6.8 *(±0.8)*
2016_I1_00SD	15-Mar-16	31-Aug-16	170	1578	603	6.9 *(±1.9)*
2017_I0_07SD	3-Feb-17	3-Jul-17	151	893	516	6.8 *(±1.5)*
2017_I1_07SD	3-Feb-17	11-Jul-17	159	1014	516	6.5 *(±2.0)*
2017_I0_04SD	23-Feb-17	12-Jul-17	140	978	529	8.5 *(±0.1)*
2017_I1_04SD	23-Feb-17	26-Jul-17	154	1182	529	8.3 *(±0.2)*
2017_I0_00SD	23-Mar-17	2-Aug-17	133	1222	571	6.5 *(±0.9)*
2017_I1_00SD	23-Mar-17	2-Aug-17	133	1222	571	6.9 *(±0.6)*
2018_I0_10SD	10-Jan-18	28-Aug-18	231	2147	762	7.7 *(±0.7)*
2018_I1_10SD	10-Jan-18	4-Sep-18	238	2236	762	7.6 *(±0.4)*
2018_I0_00SD	15-Mar-18	30-Aug-18	169	2076	823	7.8 *(±0.9)*
2018_I1_00SD	15-Mar-18	6-Sep-18	176	2169	823	8.4 *(±0.2)*

Table 2. ANOVA significance table for the effects of sowing date and water regime and their interactions on crop growth and harvest agronomic parameters (AGB: Above-ground biomass; AY: Achene Yield; AN: Achene number per unit of surface; AW: weight of 1000 achenes; NAC: number of achenes per capitulum; AWC: achene weight per capitulum; PH: Plant height; STD: stem diameter; WUE_a: water use efficiency referred to achene production). Significant P values are reported in bold.

Sources of variation	AGB	AY	AN	AW	NAC	AWC	PH	STD	WUE_a
Year: 2015									
Sowing date	0.7681	0.2637	**0.0204**	0.3766	**0.0087**	0.0841	0.3436	0.2731	0.2211
Irrigation	0.0767	**0.0027**	**0.0146**	**0.0004**	**0.0001**	**0.0017**	**<.0001**	**0.0027**	**0.0027**
Sowing date x Irrigation	0.4112	0.5642	0.4553	0.6523	**0.0394**	0.1523	0.4680	0.1511	0.5316
Coefficient of variation	115%	75%	48%	39%	48%	89%	15%	32%	75%
Year: 2016									
Sowing date	0.2380	0.1359	**0.0078**	**<.0001**	**1e-04**	**0.0107**	0.1032	**0.0003**	0.1699
Irrigation	**0.0010**	**0.0001**	**0.0012**	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**0.0002**
Sowing date x Irrigation	0.0575	0.0269	0.0615	0.1277	**1e-02**	**0.0052**	**0.0013**	**0.0046**	**0.0066**
Coefficient of variation	63%	69%	62%	30%	63%	71%	22%	28%	67%
Year: 2017									
Sowing date	0.8007	**0.0286**	**0.0328**	0.5963	0.0639	0.699	0.3479	0.2679	**0.0214**
Irrigation	**0.0004**	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**0.0004**	**<.0001**
Sowing date x Irrigation	0.7742	0.5247	0.9301	0.4165	0.7271	0.8264	0.1316	0.7760	0.4124
Coefficient of variation	55%	64%	46%	25%	43%	61%	22%	21%	62%
Year: 2018									
Sowing date	0.1326	0.6606	0.1708	**0.0005**	0.2639	0.4356	0.8450	**0.0195**	0.5772
Irrigation	0.7110	0.4123	0.3545	0.5594	0.4033	0.4473	0.3743	0.3870	0.1829
Sowing date x Irrigation	0.4864	0.9236	0.7088	0.3733	0.8086	0.8155	0.5446	0.6400	0.8796
Coefficient of variation	50%	47%	46%	27%	44%	46%	16%	27%	47%

Table 3. Effects of baseline climatic scenarios on LGS= length of growing season and Y_S= simulated achene yield ± standard deviation (*in italics*), depending on four different sowing dates.

Scenario	**BASELINE**	
Sowing dates	**LGS** (n day)	**Y_s** (kg ha^{-1})
D1	259	1600 *(±524)*
D2	231	1580 *(±523)*
D3	207	1800 *(±602)*
D4	183	1790 *(±593)*

Table 4. Water-limited achene yield (Y_{wl}) and potential yield (Y_p) for each hypothesized sowing date under baseline scenario. Y gap is calculated according to van Ittersum et al. (2013). W supply is the amonut of water required to reach Yp.

Scenario	**BASELINE**			
Sowing dates	**Y_{wl}** (kg ha^{-1})	**Y_p** (kg ha^{-1})	**W_{supply}** (mm)	**Y_{gap}** (kg ha^{-1})
D1	1701 *(±540)*	3704 *(±436)*	275 *(±65)*	2004
D2	1690 *(±539)*	3608 *(±402)*	271 *(±66)*	1917
D3	1956 *(±669)*	3461 *(±364)*	265 *(±63)*	1505
D4	1938 *(±673)*	3168 *(±312)*	250 *(±62)*	1230

Table 5. Achene yield simulated under two different irrigation scenarios (Ywsa with a single irrigation with 50 mm and Ywsb with irrigation from 20days before anthesis up to flowering) and four hypothesized sowing dates. W supply indicates the amount of water required for Ywsb according to different sowing date.

Scenario	**BASELINE**		
Sowing dates	**Y_{wsa}** (kg ha^{-1})	**Y_{wsb}** (kg ha^{-1})	**W_{supply}** (mm)
D1	2037 *(±606)*	3375 *(±298)*	166 *(±69)*
D2	2039 *(±615)*	3305 *(±285)*	160 *(±66)*
D3	2039 *(±622)*	3201 *(±250)*	153 *(±67)*
D4	2072 *(±652)*	2964 *(±232)*	136 *(±68)*

Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: