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

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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

33 **1. Introduction**

34 Sunflower (*Helianthus annuus* L.) is a well-adapted, important oil crop in Europe and a typical oil
35 crop for the Mediterranean region and Italy. It is a valuable crop from different economic
36 perspectives, since i) it is suited for biodiesel productions (Pereyre-Iruju et al., 2009; Ragaglini et al.,
37 2010); ii) many of its cultivars are rich of oleic acid which has been proved to prevent cardiovascular
38 diseases, thus representing an essential dietary source for humans (FDA, 2018) and moreover iii) its
39 crop residues are promising substrates for biogas production (Monlau et al., 2012; Zhurka et al.,
40 2020).

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

45 Conversely, different studies have pointed out the high reliance of this crop on a good water
46 availability in all the growth phases and especially at flowering and seed filling stages (Flagella et al.,
47 2002; Iqbal et al., 2005; Ebrahimian et al., 2019). Indeed, in the Mediterranean region, under rainfed
48 conditions, sunflower sown in March-April showed consistent productivity variations, mainly related
49 to the rainfall occurring during the crop cycle (de La Vega and Hall, 2002). This risky trend could be
50 further amplified by climate change projections (IPCC, 2014) implying higher day and night
51 temperatures, variable rainfall distribution patterns, higher atmospheric CO₂, and hydrological
52 imbalances (Tariq et al., 2018).

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

56 Given that sowing time determines the amount of rainfall and temperature to which the crop is
57 exposed at the different growth stages (Zelege and Nendel, 2019), many studies identified in
58 anticipating sowing a win-win solution to skip the drought phase and pursuing the cultivation of a

59 profitable crop for high quality oil production (Quiles et al., 2002), thus preventing further
60 marginalization of drylands.

61 In most of the cases the hypotheses tested in the Mediterranean region were a conventional sowing
62 in Late March/April or even May *vs* an earlier sowing in early March/mid-March (Flagella et al.,
63 2002; Barros et al., 2004; Ferreira et al., 2001). In Sardinia, sunflower is generally sown in
64 March/April.

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

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

72 **2. Materials and Methods**

73 **2.1 Field experiment**

74 **2.1.1 Experimental site and experimental design**

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

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

84 In 2015, a later sowing date was also tested and coded on the basis of the number of weeks after
85 00SD. All treatments were tested under drip irrigation (I1) vs rainfed (I0) conditions.
86 Plot size was 45 m² (10 m × 4.5 m); row spacing was 0.75 m and plant spacing on the row was 0.15
87 m, corresponding to 8.8 seeds m⁻², aiming to an effective plant density of some 7 plants m⁻².
88 Prior to sowing, 30 kg ha⁻¹ N and 70 kg ha⁻¹ of P₂O₅ were applied as diammonium phosphate and
89 additional 35 kg ha⁻¹ N as ammonium nitrate were top dressed. Glyphosate was sprayed at a
90 concentration of 3 g L⁻¹ of water for pre-seeding weed control when necessary. Pre-emergence weed
91 control was performed using 900 g ha⁻¹ Pendimethalin. Creoline diffusers and transparent wires were
92 installed to prevent bird damages to seedlings at establishment. Seed predation from birds was also
93 prevented by protecting the sampled capitula of each plot with non woven fabric after pollination.

94 **2.1.2 Field measurements and laboratory analyses**

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

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

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

106 Achene yield (AY) and yield components (no. achenes per capitulum; 1,000 achenes weight) were
107 measured on the same 10 randomly selected capitula per plot used for the monitoring of plant
108 phenology. All achenes of each of the 10 capitula were counted and weighted. The aboveground

109 biomass (AGB) was measured on the same 10 plants per plot. The harvested achenes and AGB dry
110 matter were determined after drying in a ventilated oven at 60°C till constant weight.

111 **2.1.3 Rainfall, evapotranspiration, irrigation and water use efficiency**

112 According to the Köppen–Geiger climate classification map (Kottek et al., 2006), the climate of the
113 experimental site is predominantly hot dry summer Mediterranean (Csa). The long-term historical
114 daily weather data were collected from the weather station located in the experimental field, where
115 the trials on sunflower have been carried on (Ottava, Italy). The long-term average (1981-2018)
116 annual rainfall is 512 mm with average annual reference evapotranspiration (ET_o) of 1094 mm and
117 an aridity index of 0.47, corresponding to a semi-arid climate (Middleton and Thomas, 1997). Some
118 70% of the average annual rainfall falls between October and March and mean monthly air
119 temperature calculated over the same long-term period ranges from 9.9 °C in January and February
120 to 23.9 °C in August, with an annual mean of 16.3°C (Fig.1).

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

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

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

127 Water Use Efficiency (WUE_a) was determined as follows:

$$128 \text{ WUE}_a = \text{AY} / \text{ET}_a$$

129 where AY is the achene yield (kg ha⁻¹) and ET_a is the actual evapotranspiration (mm). This latter was
130 calculated using the Hargreaves equation. WUE is expressed in kg ha⁻¹ mm⁻¹.

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

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

136 **2.1.4 Statistical analyses**

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

143 **2.2 Crop modelling**

144 **2.2.1 Calibration and application of the EPIC model**

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

158 The simulation was performed using fixed sowing dates, while the harvest operations were scheduled
159 according to heat units accumulation. The crop was harvested at about 100% of total heat units

160 required for maturity. The simulations were carried out using the static soil option in order to avoid
161 variation of the soil properties that could have affected the crop production during the 50-year
162 simulation. The soil characteristics were set up after an initialization and reset each year to remove
163 trends related to soil dynamics and draw attention to the effect of climate.

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

166 **2.2.2 Drawing scenarios for sustainable sunflower management**

167 A baseline climatic scenario has been built from the data simulated with COSMO-CLM (Rockel et
168 al., 2008), using the specific 8 km horizontal resolution configuration developed for Italy by CMCC
169 (Bucchignani et al.; 2016 e Zollo et al., 2016), forced from global model ECHAM 5.4 developed by
170 CMCC (Scoccimarro et al., 2011). The baseline climate scenario was referred to the years 1972-2005,
171 using CO₂ concentration of 380 ppm.

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

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

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

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

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

187 The yield gaps are also expressed as $Y_{\text{wl}} = ([1 - Y_{\text{s}}/Y_{\text{wl}}] * 100\%)$.

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

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

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

198 **3. Results**

199 **3.1 Weather during the field experiments**

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

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

215 **3.2 Sunflower productivity, yield components and biometry**

216 The achieved sunflower plant density ranged between 8.9 ± 0.3 plants m^{-2} (\pm s.d.) (00SD) and $3.3 \pm$
217 1.1 plants m^{-2} (SD02) both observed in 2015. In the subsequent years no such differences were
218 observed in plant densities between sowing dates, that ranged between 7.1 and 7.9 plants m^{-2} (Tab.1).
219 With the only exception for 2018, all achene yield components were significantly affected by the
220 irrigation regime (Tab.2; Tab.S1), as well as AGB ($P=0.08$ in 2015).

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

224 Under 00SD, AY under rainfed conditions was on average 68% lower than that under irrigation in
225 2015-16-17 but only 18% lower in 2018, when rainfall during the crop cycle was only 9% lower than
226 the climatic average during the crop cycle (Tab. S1). Under anticipated sowing date scenarios, AY
227 under rainfed conditions was between 66% and 74% lower than under irrigation, except for the very
228 early sowing date in 2016, when AY under rainfed conditions was only 20% less than under irrigation
229 (Tab. S1).

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

236 For all the years in which a significant effect of irrigation on sunflower productivity was observed,
237 AY was consistently higher under irrigation than under rainfed condition (2015: 2432 kg d.m. ha⁻¹ vs
238 754 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.
239 ha⁻¹) (Tab. S1). Conversely, the AY observed in 2018 was not affected by the irrigation regime, being
240 on average 1692 kg d.m. ha⁻¹.

241 **3.3 Sunflower Water Use Efficiency**

242 The water use efficiency of achene yield (WUE_a) was significantly affected by the irrigation regime
243 in all years but 2018 (Tab.2). Moreover, a significant sowing date × irrigation interaction was
244 observed in 2016. For each of these years (2015, 2016 and 2017), WUE_a under I1 regime was two or
245 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:
246 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.
247 S1).

248 The sowing date × irrigation interaction observed for WUE_a in 2016, revealed that WUE_a of 07SD
249 and 00SD under I0 were similar and lower than the respective WUE_a under I1 (07SD-I1: 0.94 kg ha⁻¹
250 mm⁻¹ and 00SD-I1: 0.90 kg ha⁻¹ mm⁻¹). Differently, in the same year, for the earliest sowing date
251 (13SD), WUE_a was higher under I0 than under I1 (0.42 vs 0.38 kg ha⁻¹ mm⁻¹), but still lower compared
252 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)
253 was lower compared to the previous years, but still higher, although not statistically greater, than the
254 one registered for I0 in the same year (0.40 kg ha⁻¹ mm⁻¹) (Tab. S1).

255 **3.4 Model simulation evaluation: Achene yield and Above-ground biomass**

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

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

263 **3.5 Scenarios for sustainable sunflower management**

264 **3.5.1 EPIC simulation of the effect of sowing date and water supply on sunflower yield**

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

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

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

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

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

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

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

287 **4. Discussion**

288 **4.1 Field experiment**

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

302 The observed achene yields, with the only exception for 2018, whose weather was completely
303 different from the other years when the experiment was run, showed that there was no substantial
304 advantage to anticipate sowing earlier than late February or Mid-March, in agreement with Perniola
305 et al. (2006). This pattern was related to a lower accumulation of CGDD-A (from sowing to the
306 anthesis) and of CGDD-H (from sowing to the harvest, thus including seed-filling phase) for earlier
307 sowing dates. Indeed, many studies highlighted the relevance of heat units accumulation on AW

308 during the seed-filling phase (between the end of anthesis and physiological maturity), in order to
309 prevent AY losses (Aguirrezábal et al., 2003; Qadir et al., 2007).

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

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

316 Keipp et al. (2020) showed that the AY under water stress was related to the seed filling phase and
317 that the observed AY reduction is not due to seed number but to single seed weight. In 2016, this
318 pattern was clearly evident for 07SD, which received irrigation when was at the phenological stage
319 of 31 (stem elongation), thus rainfed vs irrigated regime could affect significantly the flowering and
320 seed-filling phase. A similar pattern was observed for 00SD. Conversely, for 14SD, the irrigation
321 occurring at phenological stage of 51 (flowering) and prolonged only during milking phase was not
322 efficient (Göksoy et al., 2004) as also confirmed by Browne (1977) reporting that greatest damages
323 are generated when water stress occurs in the 20 days prior to flowering. Indeed, Rawson and Turner
324 (1983) identified in two-three weeks before flowering the optimal period for starting irrigation, while
325 negative effects for irrigation started to be apparent at anthesis, thus confirming our results. Moreover
326 Joshi et al. (2017) identified the best yielding watering strategy for confection sunflower in irrigating
327 up to when 50% of the disc flowers have completed flowering.

328 From the results obtained in 2016, which was the year in which more anticipated sowing dates were
329 tested thus covering a very large sowing window, it was possible to better understand the effects of
330 the sowing dates on NAC. The reduced NAC for early sowing dates could have been affected by
331 reduced visits by insect pollinators due to the earlier timing of anthesis, counteracted by the 1000
332 seeds weight that was larger compared to the later sowing dates. This inverse trend between seed

333 number and 1000 seeds weight was already reported by de la Vega and Hall (2002) and was related
334 to the genotype.

335 Similarly, to the pattern observed for AY, also water use efficiency for the achene yield (WUEa) was
336 significantly higher for 00SD than for earlier sowing dates (although not significant effect for sowing
337 date was registered except for 2017). In our case, in which the conventional sowing date was already
338 anticipated than in other studies, there was a reduction of the irrigation volumes under irrigated
339 conditions and an increment of soil water availability in rainfed conditions since the crop could
340 benefit of early spring rainfall when temperatures were mild enough, which suggest to set the Mid-
341 march/earlyApril as a potential win-win solution in term of maximizing seed yield potential and water
342 use efficiency. Differently, the earlier sowing dates were not able to efficiently exploit the
343 precipitation occurring when the plants were in the initial development stage and when average
344 temperatures were still too cold for seed setting either for insufficient pollination and/or sub-optimal
345 weather condition during flowering, such as low radiation and too much wind (Scaven and Raffenty,
346 2013).

347 **4.2 EPIC Simulation**

348 **4.2.1 Model calibration**

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

355 **4.2.2. Sunflower productivity under baseline scenario depending on sowing date and water** 356 **supply**

357 The baseline climatic scenario confirmed that mid-March - early April (D3, D4) are the most
358 promising sowing date in terms of achene production compared to the earlier ones (D1, D2) under

359 semi-arid Mediterranean conditions. As already discussed in section 4.2.1, these results were
360 consistent to those reported by other studies showing advantage in terms of achene yield of early
361 sowing dates vs. end of April-May (d'Andria et al., 1995; Ferreira and Abreu, 2001).

362 Within baseline scenario, water availability for irrigation acquired an interesting perspective
363 especially under irrigation scenario b, suggesting a viable option for sunflower cultivation in
364 Mediterranean areas. Compared to 265mm supplied for potential yield, the water scenario b with 150
365 mm distributed in the period between 20 days before anthesis and flowering was able to guarantee
366 for the hypothesized sowing dates occurring in March-April (D3, D4) an overall achene yield
367 comparable to the potential one, while for the earlier dates (D1, D2) even higher achene yield
368 production than D3 and D4 but still far from the corresponding potential one. These findings found
369 support in results collected by previous research identifying in specifically drawn deficit irrigation
370 strategies, viable and sustainable production perspective for sunflower in semi-arid areas (Joshi et al.,
371 2017; Liu et al., 2018).

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

377 **5. Conclusion**

378 The results of this study revealed that a sowing date, occurring in Mid-March/early April, is the most
379 appropriate under Mediterranean rainfed condition, thus shifting earlier than the conventional sowing
380 dates investigated in many other studies. Conversely, further anticipating sowing dates caused seed
381 yield losses mainly due to lower heat unit accumulation during the seed-filling phase. Under semi-
382 arid Mediterranean conditions, sunflower showed significant reliance on irrigation, which is crucial
383 during the 20 days before flowering. Indeed, under a simulated scenario supply water from 20 days
384 before anthesis up to flowering, partially bridged the gap between water limited yield potential and

385 potential yield, almost approaching yield potential especially for earlier sowing dates (D1, D2). The
386 practical implication of simulation was that anticipating sowing dates could be a viable strategy in
387 the Mediterranean if at least little water is available, otherwise keeping sowing date around 10th March
388 is the most promising strategy for a high and stable achene production.

389 **6. Acknowledgments**

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391 (University of Sassari) and NOVAMONT S.p.a. on: ‘Identification of agronomic protocols for the
392 cultivation of oil crops in Sardinia’

393 **7. CRediT Roles**

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

398 **8. Tables captions**

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

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

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

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

412 **Table 5.** Achene yield simulated under two different irrigation scenarios (Y_{wsa} with a single irrigation with
413 50 mm and Y_{wsb} with irrigation from 20days before anthesis up to flowering) and four hypothesized sowing
414 dates. W supply indicates the amount of water required for Y_{wsb} according to different sowing date
415

416 **9. Figures captions**

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

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

422 **Figure 2.** Comparison between simulated and observed achene yield (left) and above-ground biomass (right)
423 sowed at different dates (ESD1, ESD2, CSD) under rainfed conditions in 2015, 2016, 2017 and
424 2018 growing season.

425 **Figure 3.** Comparison between simulated and observed achene yield (left) and above-ground biomass (right)
426 sowed at different dates (ESD1, ESD2, CSD) under irrigated conditions in 2015, 2016, 2017 and
427 2018 growing season.

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

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

433 **Figure 6.** Simulated achene yield (Y_s) for different sowing dates (D1- 10th January; D2 – 10th February; D3 –
434 10th March; D4- 10th April) under different scenarios (baseline Y_{wl} - water limited scenario; baseline Y_p -
435 potential yield scenario; baseline Y_{wsa} - single irrigation of 50 mm scenario; baseline Y_{wsb} – irrigation from
436 20 days before anthesis and prolonged during flowering).

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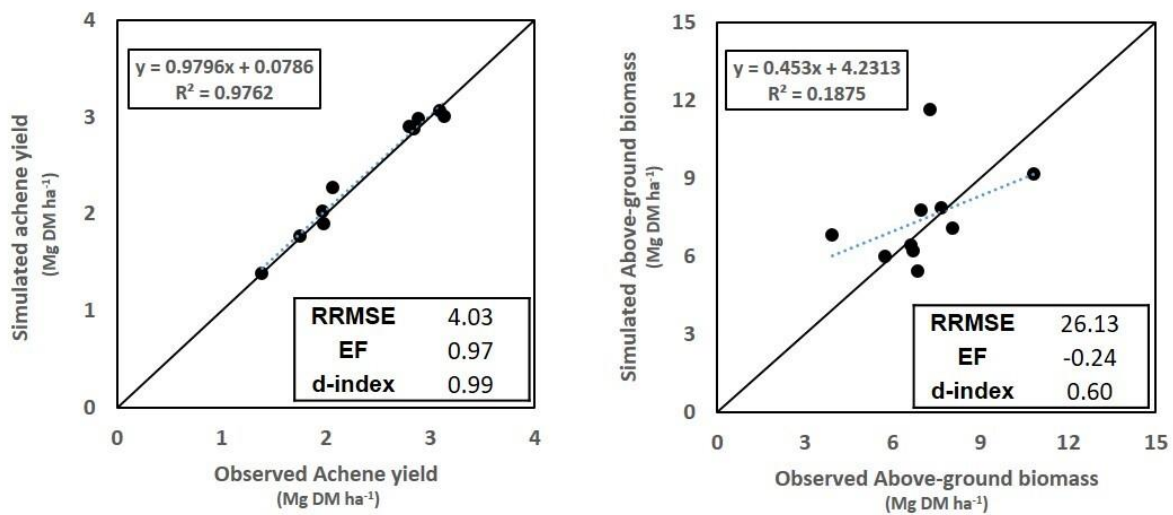


Fig. 3- Comparison between simulated and observed (a) seed yield (b) above-ground biomass sowed at different dates (ESD1, ESD2, CSD) under irrigated conditions in 2015, 2016, 2017 and 2018 growing season.

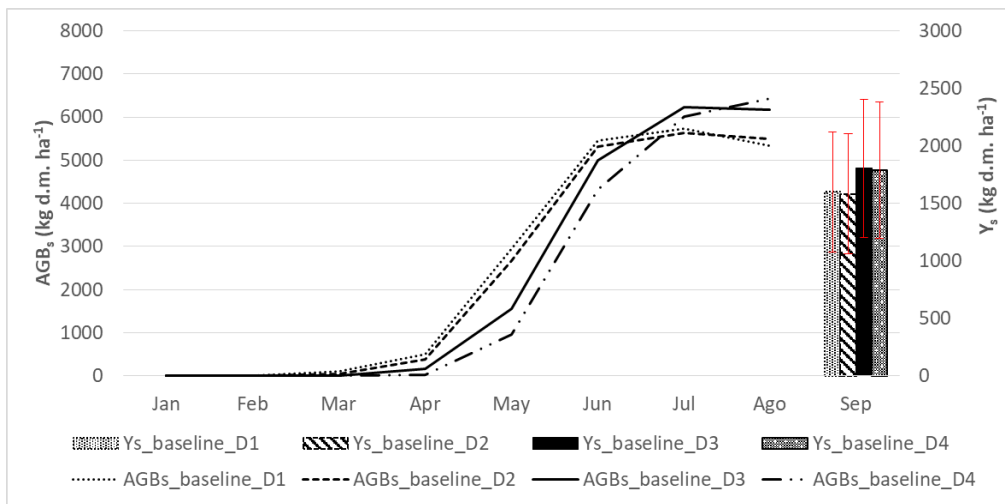


Fig. 4- Simulated achene yield (Y_s) and Above-Ground biomass (AGB_s) accumulation curve for different sowing dates under baseline climatic scenario under rainfed conditions

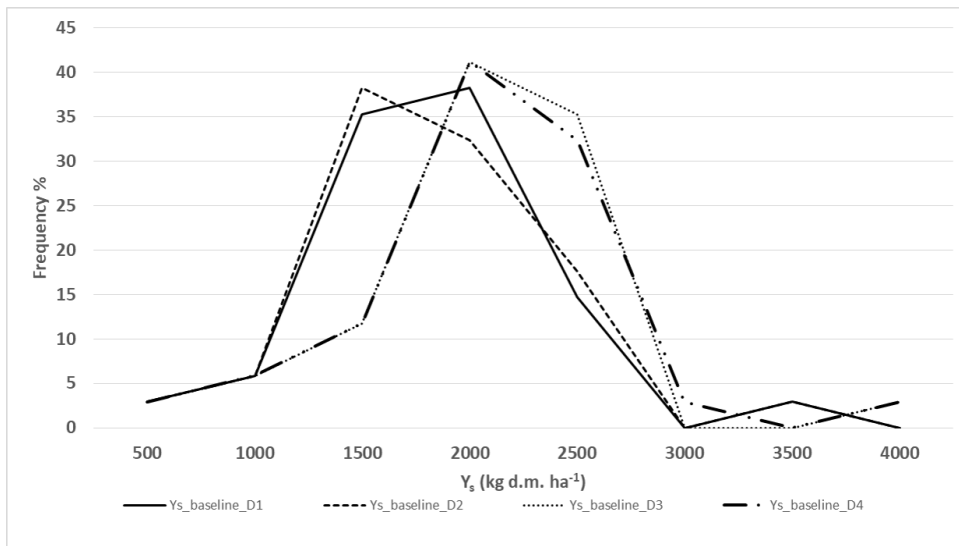


Fig.5- Simulated achene yield (Y_s) frequency distribution under baseline scenario at different times after sowing for sunflower sown in first ten days of January (D1), February (D2), March (D3) and April (D4) under rainfed condition

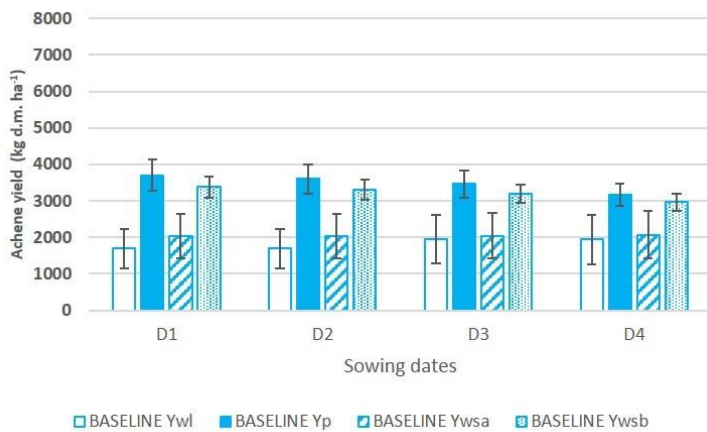


Fig.6- Simulated achene yield (Y_s) for different sowing dates (D1- 10th January; D2 – 10th February; D3 – 10th March; D4- 10th April) under different scenarios (baseline Ywl- water limited scenario; baseline Yp- potential yield scenario; baseline Ywsa- single irrigation of 50 mm scenario; baseline Ywsb – 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 \pm standard deviation (*in italics*).

Treatment	Sowing Date	Harvest Date	Length of crop growing season (days)	CGDD-H	CGDD-A	Plant density (plants m ² \pm sd)
2015_I0_00SD	20-Mar-15	27-Jul-15	130	1006	823	8.9 (<i>\pm0.3</i>)
2015_I1_00SD	20-Mar-15	3-Aug-15	137	1098	823	8.9 (<i>\pm0.3</i>)
2015_I0_SD02	3-Apr-15	6-Aug-15	126	1108	988	4.3 (<i>\pm1.8</i>)
2015_I1_SD02	3-Apr-15	13-Aug-15	133	1199	988	3.3 (<i>\pm1.1</i>)
2016_I0_13SD	17-Dec-15	29-Jun-16	196	719	342	8.0 (<i>\pm0.5</i>)
2016_I1_13SD	17-Dec-15	15-Jul-16	212	935	364	7.4 (<i>\pm0.4</i>)
2016_I0_07SD	29-Jan-16	29-Jul-16	183	1111	581	6.7 (<i>\pm1.3</i>)
2016_I1_07SD	29-Jan-16	23-Aug-16	208	1498	581	6.6 (<i>\pm1.4</i>)
2016_I0_00SD	15-Mar-16	5-Aug-16	144	1171	603	6.8 (<i>\pm0.8</i>)
2016_I1_00SD	15-Mar-16	31-Aug-16	170	1578	603	6.9 (<i>\pm1.9</i>)
2017_I0_07SD	3-Feb-17	3-Jul-17	151	893	516	6.8 (<i>\pm1.5</i>)
2017_I1_07SD	3-Feb-17	11-Jul-17	159	1014	516	6.5 (<i>\pm2.0</i>)
2017_I0_04SD	23-Feb-17	12-Jul-17	140	978	529	8.5 (<i>\pm0.1</i>)
2017_I1_04SD	23-Feb-17	26-Jul-17	154	1182	529	8.3 (<i>\pm0.2</i>)
2017_I0_00SD	23-Mar-17	2-Aug-17	133	1222	571	6.5 (<i>\pm0.9</i>)
2017_I1_00SD	23-Mar-17	2-Aug-17	133	1222	571	6.9 (<i>\pm0.6</i>)
2018_I0_10SD	10-Jan-18	28-Aug-18	231	2147	762	7.7 (<i>\pm0.7</i>)
2018_I1_10SD	10-Jan-18	4-Sep-18	238	2236	762	7.6 (<i>\pm0.4</i>)
2018_I0_00SD	15-Mar-18	30-Aug-18	169	2076	823	7.8 (<i>\pm0.9</i>)
2018_I1_00SD	15-Mar-18	6-Sep-18	176	2169	823	8.4 (<i>\pm0.2</i>)

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 \pm 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 (<i>±524</i>)
D2	231	1580 (<i>±523</i>)
D3	207	1800 (<i>±602</i>)
D4	183	1790 (<i>±593</i>)

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 amount of water required to reach Y_p .

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

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

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

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:



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Supplementary Material

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