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Delayed sowing improved barley yield in a no-till rainfed Mediterranean agroecosystem

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Keywords

Dryland cropping systems; Mediterranean; no-till; sowing date; winter cereals.

ABSTRACT

The effect of delaying sowing date and maturity class on no-till barley and soft wheat performance was studied over two periods of three years each. A 3 (sowing date) x 2 (maturity class) randomized complete block (RCB) design was run for 3 years with barley (B-) (2006-7 to 2008-9) and soft wheat (W-) (2009-10 to 2011-12) in NE Spain. Sowing dates corresponded to October (D1 - the standard farming practice), November (D2), and December (D3). Maturity classes corresponded to early (-EC) and medium (-MC). Crop above-ground biomass, grain yield and yield components were analyzed. The water-use efficiency of the above-ground biomass and yield (WUE_b and WUE_y), and nitrogen-use efficiency (NUE), were calculated. Averaging barley maturity classes and cropping seasons, D2 and D3 increased their grain yields 59% and 46%, respectively, when compared to D1. A greater number of grains per spike, as well as higher WUE_b and NUE were observed in D2 and D3 compared to D1 in two of the three barley cropping seasons. Similarly, a greater thousand kernel weight and higher WUE_y was observed when sowing was delayed. Averaged across years, WEC presented a greater yield and above-ground biomass for D2 and D3 compared to D1, while for WMC there were no grain yield differences seen between the sowing dates, above-ground biomass or yield components. Our results demonstrate that, in Western Mediterranean areas, sowing delay under no-till (NT) conditions can increase grain yield, WUE and NUE of winter barley, and also of wheat but only during wet years.

Abbreviations

NT, no-till; NUE, nitrogen use efficiency; TKW, thousand kernel weight, WUE_b, water-use efficiency for above-ground biomass; WUE_y, water-use efficiency for yield.

Core ideas

- Sowing delay and cultivar effects on cereal production and water and N use efficiencies were studied.
- Sowing delay increased grain yield due to greater number of grains per m2.
- Sowing delay maximized the efficiency in the use of resources

Semi-arid Mediterranean agroecosystems are severely limited by soil water availability. Rainfall is characterized by strong interannual and seasonal irregularity, being mainly concentrated in the fall and spring. Winter cereals, represented by barley (*Hordeum vulgare* L.) and wheat (*Triticum* sp.), are well adapted to Mediterranean conditions given the partial synchronization of their cycle with the period of greatest water availability (Cooper et al., 1987).

The Ebro valley (NE Spain) is a semi-arid area representative of these Mediterranean conditions where rainfed systems have a precipitation gradient from 300 to 700 mm yr^{-1}. In this area, cropping systems are mainly based on winter cereals since the economic benefit of other winter broadleaf crops such as vetch (*Vicia sativa* L.) or rapeseed (*Brassica napus* L.) in severe dryland conditions (with less than 450 mm of annual rainfall) is doubtful (Álvaro-Fuentes et al., 2009). The choice between barley and wheat depends on the severity of the local climate, barley being better adapted to drier conditions than wheat. This means barley monocrops exist in certain areas, with varying proportions of barley and wheat being found as the climate becomes wetter. Conventionally, farmers in the area sow winter cereals early, just after the first fall rains, around mid-October (both for barley and wheat). One of the reasons for this is to reduce the risk of terminal drought during the grain filling period, common in the Mediterranean areas due to high temperatures and a low soil water content at the end of spring (Loss and Siddique, 1994; González et al., 2007), which in some cases is exacerbated by dry winds (McAneney and Arrúe, 1993). In Australian Mediterranean agriculture, greater grain yield and water-use efficiency have been reported when earlier grain filling occurs (Kirkegaard et al., 2014). Moreover, early sowing leads to vigorous crop establishment under warm conditions (Piggin et al., 2015). However, early sowing of cereals can increase susceptibility to biotic attacks (Thackray et al., 2009) related to the warm, wet conditions at the beginning of fall in the western Mediterranean region. The main problems for winter cereals in the area include various grasses (e.g. ripgut brome, *Bromus diandrus* Roth.; annual ryegrass, *Lolium rigidum* Gaudin), diseases such as Helminthosporium leaf blights (HLB), and insects such as cereal ground beetle (*Zabrus tenebrioides* Goeze), although only the first have a significant economic impact. Earlier sowing impedes complete mechanical or chemical control of weed seedling emergence and also favors the possibility of earlier pest and disease attacks. Moreover, until a few years ago, for some particular weeds, such as ripgut brome, there were no selective herbicides available for barley. As a consequence, their control in NT systems was based on non-selective pre-sowing herbicides such as glyphosate (N-(phosphonomethyl)-glycine), with no control during crop growth. Therefore, in some Mediterranean areas, and in the Ebro valley in particular, winter cereals sown early, especially as monocrops, led to important infestations of this particular brome (García et al., 2014).

In the Ebro valley, NT has been progressively introduced over the past 30 years with the aim of both reducing costs and either maintaining or increasing yields (Cantero-Martínez et al., 2003). The use of long-term NT in semi-arid rainfed conditions leads to greater soil water storage during the previous harvest-to-tillering period and increased precipitation storage efficiency compared with traditional inversion tillage systems based on moldboard ploughing (Lampurlanés et al., 2016). Greater early crop growth has been observed under NT (Santiveri et al., 2004). Similarly, water- and nitrogen-use efficiency are also increased (Angás et al., 2006; Cantero-Martínez et al., 2007). However, early sowing could also increase susceptibility to insects, diseases and weeds under NT. As a consequence, management strategies must be improved in order to overcome the limitations posed by those biotic factors while reducing the impact of climatic stresses during the grain-filling period as much as possible. To this end, selecting an adequate sowing date and maturity class appear to be key management practices. Moreover, NT bears traffic load better and leads to lower work intensity (Bueno et al., 2006; Soane et al., 2012; Wolf and Edmisten, 1989), widening the window of feasible sowing dates to wetter soil conditions.

However, interannual rainfall variability, characteristic of the Mediterranean climate, complicates the selection of an optimum sowing date (Mahdi et al., 1998). For instance, in a Mediterranean area in southern Spain, Ramos et al. (1993) observed greater production of dual-purpose (forage and grain production) triticale when sowing in the last week of November or first week of December compared to earlier sowings. In a study carried out in Syria, Mahdi et al. (1998) studied the effect of different sowing dates on durum wheat grain yield. While in one growing season they observed a 15% reduction in yield when postponing the November 1st sowing by 15 and 30 days, they observed a 16% yield increase in the next growing season. However, these last two studies were undertaken under conventional tillage and were only performed over two growing seasons. In the Mediterranean region, choosing a maturity class is another important decision that must be made by farmers. They used to believe that late maturity classes were the best option for higher yields. The interaction between sowing date and maturity class may affect water-use patterns during crop growth: late maturity classes sown earlier tend to use more water due to greater production of biomass during vegetative stages, reducing the availability of this resource during the grain-filling period; in contrast, early maturity classes seeded later may have less pre-anthesis evapotranspiration. This second case could result in a better balance of water-use between the vegetative and reproductive periods in cereals (Connor and Loomis, 1991).

The objective of this work was to evaluate the effect of sowing date and maturity class on grain yield and water- and nitrogen-use efficiency of barley and soft wheat managed under NT conditions. We hypothesized that late sowings and early maturity classes would perform better due to an improved use of soil water and nitrogen.

MATERIALS AND METHODS

Site conditions and experimental design

A field experiment was established in Agramunt (41º 48' N, 1º 7' E; 330 m asl), NE Spain. The area is representative of dryland semi-arid Mediterranean conditions with a mean annual rainfall of 430 mm, potential evapotranspiration (PET) of 855 mm, and an air temperature of 13.8 ºC. The soil was a Typic Xerofluvent (Soil Survey Staff, 2014). The soil water-holding capacity was 185 mm in the first 90 cm of depth. Other properties of the Ap horizon (0-28 cm) included: bulk density: 1.4 g cm^{-3}; soil organic carbon: 10.5 g kg^{-1}; pH (H_2O:soil, 1:2.5): 8.5; electrical conductivity (1:5): 0.15 dS m^{-1}; $CaCO_3$ eq. (%): 40; and loam texture being sand (2000-50 µm), silt (50-2 µm), and clay (< 2 µm) content: 475, 417 and 118 g kg^{-1}, respectively.

Prior to establishing the experiment, the area was devoted to barley production with summer fallow managed under reduced tillage based on two chisel passes. A 3 (sowing date) x 2 (maturity class) randomized complete block (RCB) design was run for 3 years with barley (B-) (2006-7 to 2008-9) and soft wheat (W-) (2009-10 to 2011-12). Sowing dates corresponded to October (D1 - the standard farming practice), November (D2), and December (D3). Maturity classes corresponded to early (-EC) and medium (-MC). Sowings of the D1 treatment were carried out between October 15th and 20th, this treatment being considered a reference as it is typical of the farming regime in the area. D2 was sown between November 5th and 10th, and the D3 treatment was sown between November 25th and December 5th. In the first period (the 2006-2007, 2007-2008 and 2008-2009 seasons), barley was grown, comparing two maturity classes: Hispanic (barley early maturity class, BEC) and Sunrise (barley medium maturity class, BMC). In the second period (the 2009-2010, 2010-2011 and 2011-2012 growing seasons), two soft wheat maturity classes were compared: Bokaro (wheat medium maturity class, WMC) and Artur Nick (wheat early maturity class, WEC). These medium and early maturity classes correspond to facultative and spring cultivars, respectively. The experiment was completely randomized in three blocks; individual plot was 6 m wide x 48 m long. Air temperature and rainfall were recorded hourly using an automated weather station located in the experimental area.

Crop management practices

The experiment was managed under NT, with the use of a 3 m-wide no-till drill with disk openers. Three to five days before sowing, the weeds were controlled by applying 1.5 L ha^{-1} of glyphosate (N-(phosphonomethyl)glycine). The sowing rate was 450 seeds m^{-2} in rows spaced 17 cm apart for the two crops studied. In the first two seasons (2006-07 and 2007-08) a post-emergence herbicide treatment with tribenuron-methyl [methyl 2-[4-methoxy-6-methyl-1,3,5-triazin-2-yl(methyl)carbamoylsulfamoyl]benzoate] (10 g a.i. ha^{-1}) was applied on 15 February in 2007 and on 23 January in 2008 to control broadleaf weeds. In 2008-09, a post-emergence herbicide treatment with a mix of isoproturon [3-(4-isopropylphenyl)-1,1-dimethylurea] plus diflufenican [2’,4’-difluoro-2-(α,α,α-trifluoro-m-tolyloxy)nicotinanilide] (1243 + 69 g a.i. ha^{-1}) was applied on 19 February. In 2009-10, post-emergence weed control (specifically for ripgut brome, *Bromus diandrus* Roth.) was carried out with mesosulfuron-methyl [methyl 2-[(4,6-dimethoxypyrimidin-2-ylcarbamoyl)sulfamoyl]-a-(methanesulfonamido)-p-toluate] plus iodosulfuron-methyl-sodium [sodium ({[5-iodo-2-(methoxycarbonyl)phenyl]sulfonyl}carbamoyl)(4-methoxy-6-methyl-1,3,5-triazin-2-yl)azanide] (15 + 3 g a.i. ha^{-1}) on 5 March. In 2010-11, a post-emergence control of broadleaf and grass weeds was accomplished with tribenuron-methyl plus metsulfuron-methyl (10 + 5 g a.i. ha^{-1}) on 30 March. Mesosulfuron-methyl plus iodosulfuron-methyl-sodium (15 + 3 g a.i. ha^{-1}) was applied on 9 February and on 13 April in D1 and D2 and

D3, respectively. In 2011-2012 herbicide applications aimed at reducing ripgut brome levels and control broadleaf weeds. Tribenuron-methyl plus metsulfuron-methyl [methyl 2-(4-methoxy-6-methyl-1,3,5-triazin-2-ylcarbamoylsulfamoyl)benzoate] (10 + 5 g a.i. ha^{-1}) was applied 20 February while mesosulforon-methyl plus iodosulfuron-methyl-sodium (15 + 3 g a.i. ha^{-1}) was applied on 31 January in D1 and on 13 march in D2 and D3.

Nitrogen fertilizer was top dressed at the end of February (i.e., the tillering stage), at a rate of 50 kg N ha^{-1}, in the form of urea-ammonium nitrate solution (32% N; consisting of 16% urea-N, 8% ammonium-N and 8% nitrate-N) sprayed using stream bars. This rate was decided upon according to the potential grain yield of the site (i.e, 2.8 Mg ha^{-1}), and the annual N mineralization was estimated to be 30 kg N ha^{-1} for NT (Angás et al., 2006). Time of application was chosen to minimize N volatilization losses. Traditionally, farmers of the region applied greater N rates than the one used in our experiment and carried out pre-sowing applications. However, more than two decades of research carried out in a contiguous experimental area has demonstrated the feasibility to reduce traditional N rates to a half and the inadequacy of pre-sowing applications given the usually high levels of soil mineral N before sowing (Cantero-Martínez et al., 1995, 2016; Plaza-Bonilla et al., 2017). Crop growth is limited by the low temperatures during the period between sowing and tillering in this Mediterranean region, fact that reduces early N uptake to a minimum.

The grain was harvested using a commercial combine at the end of June or the beginning of July. Crop residues were chopped and uniformly spread over the soil surface.

Soil and crop sampling and measurements

Soil samples were taken prior to sowing and after harvest in each cropping season studied. In each plot, two representative areas of 2x2 m were identified and three soil samples per area were taken using a mechanized soil corer, in 30-cm increments, up to a soil depth of 90 cm. Once bulked for each depth, part of the sample was dried at 105ºC for 48 h to quantify gravimetric moisture. Soil nitrate was determined by mixing 50 g of soil with 100 ml of 1M KCl. The extracts were analyzed using a continuous flow autoanalyzer (Seal Autoanalyzer 3, Seal Analytical, Norderstedt, Germany). The soil water and mineral N content of the entire soil profile (0-90 cm) were calculated using soil bulk density, measured employing the cylinder method (Grossman and Reinsch, 2002).

The dates of anthesis and physiological maturity were recorded for each treatment and year. Crop above-ground biomass was measured at physiological maturity by cutting the plants at soil level along a 0.5 m transect of the seeding line in three locations per plot. Once in the laboratory, the heads were separated from the rest of the plant (i.e., leaves and stems); both fractions were then dried at 65ºC for 48 h and weighed. After this, in order to calculate the yield components, the ears were counted and threshed and the number of grains and their weight were recorded. These measurements allowed the number of spikes m^{-2} to be calculated, as well as the number of grains per spike, the thousand kernel weight (TKW), and the harvest index (HI). The grain yield of each treatment was measured by harvesting the plots with a commercial combine, subsequently weighing the grain and taking a sub-sample to standardize the values at 10% grain moisture.

Calculation of water- and nitrogen-use efficiency

Water use (WU) during the period between sowing and harvest was calculated as the difference between soil water content (0-90 cm soil depth) at the beginning of October and at the harvest of each treatment plus the amount of rainfall received during that period. As in previous works in the same area, water loss as runoff and deep drainage was considered negligible due to the negligible slope (< 2%) and the severely water-limited conditions (Cantero-Martínez et al., 2007; McAneney and Arrúe, 1993). The above-ground biomass and grain yield at 10% moisture were divided by WU to quantify the agronomic water-use efficiency for above-ground biomass (WUE_b) and water-use efficiency for grain yield (WUE_y), respectively. WUE calculations were based on soil water content in mid-October (right before sowing D1 treatment). This fact could affect WUE values of D2 and D3 treatments if water losses as evaporation between soil sampling and sowing dates were high. However, under Mediterranean conditions, soil water evaporation is minimum during the period between mid-October until February, when soil water recharge takes place (Lampurlanés et al., 2016). Mean PET from 15 October to 5 December (i.e. from D1 sowing date to the latest sowing date of D3 treatment) amounts 62 mm, according to the records of the nearest meteorological station, which only represents a 7% of mean annual values. Thus, in D2 and D3 the amount of water lost as evaporation would be lower than 62 mm after discounting the fraction accounting for crop transpiration, and taking into account that soil management was based on no-till, which minimizes soil water evaporation (Unger et al., 1991).

Nitrogen use efficiency was calculated as the ratio of grain yield to N supply. N supply was the sum of soil mineral N at sowing (0-90 cm depth), N applied as fertilizer (i.e., 50 kg N ha^{-1}), and mineralized N. This latter was estimated to be 30 kg N ha^{-1} according to the results obtained by Angás et al. (2006) under similar NT conditions.

Data analysis

The data are reported in dry wt. per unit area except for yield, which was recorded at 10% moisture. The data were checked for normality and analyzed using the JMP Pro 11 statistical package (SAS Institute Inc., 2014). Non-normal data was log-transformed for the analysis and back-transformed for its presentation. To compare the effects of cropping season, sowing date, maturity class, and the interaction of these parameters, an analysis of variance (ANOVA) for a randomized block design was performed for each crop using a general linear model. Differences between treatments were taken to be significant at the 0.05 probability level using a LSD test. Linear relationships between yield components and grain yield were tested using the same software. The slopes of the regressions were tested for differences between sowing dates.

RESULTS

Weather conditions during the experimental period

Air temperatures during the experiment were typical of the Mediterranean region, with cold winters, hot summers, and intermediate values in fall and spring. The fall and winter months showed the lowest temperature range (Fig. 1). Rainfall in the 2006-2007, 2007-2008 and 2008-2009 seasons when barley was cropped was 409, 333 and 528 mm (Fig. 1b, 1c and 1d). The first two cropping seasons were characterized by dry fall and winter periods, although the 2008-2009 season received 78 mm more winter rainfall than the historical average (Fig. 1d). However, the three cropping seasons presented greater spring rainfall (233, 219 and 218 mm for 2006-2007, 2007-2008 and 2008-2009) than the historical value (138 mm), coinciding with the anthesis stage of the crop.

Cumulative rainfall during the three wheat cropping seasons was highly heterogeneous. The 2009-2010 season was considerably wetter (703 mm) than the 30-yr average (430 mm) with significant rainfall values in winter (303 mm) and spring (195 mm) (Fig. 1e). In contrast, the two last cropping seasons analyzed were extremely dry (211 and 228 mm in the 2010-2011 and 2011-2012 seasons, respectively) (Fig. 1f and 1g). The 2010-2011 season was characterized by a dry summer (42 mm), fall (1 mm) and winter (45 mm). Similarly, the 2011-2012 season was characterized by dry summer and winter periods, with only 35 mm and 15 mm, respectively. In 2010-2011 and 2011-2012, the spring rainfall was 123 and 132 mm, respectively, lower than the 30-yr average (144 mm).

Sowing date and maturity class effects on barley yield and water- and N-use efficiency

Barley yield and above-ground biomass were significantly affected by the interaction between maturity class and sowing date, and the sowing date x year and maturity class x year interactions (Table 1). As an average of the two maturity classes studied, D2 and D3 showed greater barley grain yields than D1 in the three cropping seasons studied (Fig. 2). The greatest grain yield of BEC was observed for D2, while for BMC both D2 and D3 presented greater yields than D1 (Table 1).

The number of spikes m^{-2} was significantly affected by sowing date, maturity class and year main effects but not interactions (Table 1). D1 and D2 showed a greater number of spikes m^{-2} than D3 as an average of maturity classes and cropping seasons. The number of grains per spike was significantly affected by the sowing date x year and maturity class x year interactions. An increased number of grains per spike was observed when the sowing date was delayed in 2006-2007 and 2008-2009, while in 2007-2008 the D2 treatment showed the greatest values (Fig. 2). Moreover, BMC had a greater number of grains per spike than BEC in the three cropping seasons. The TKW was significantly affected by all main effects and their interactions. Increased TKW was observed when the date of sowing was delayed in the three cropping seasons, with the exception of 2008-2009 for BEC (Fig. 2). The harvest index was affected by all the effects and their interactions, except the interaction between sowing date and maturity class (Table 1). Delaying sowing (D2 and D3 compared to D1) led to higher HI in 2006-2007 for both maturity classes (BMC and BEC) and in 2007-2008 for BMC (Fig. 2). However, that trend was not observed in 2008-2009.

Barley WU was only significantly affected by the interaction between year and sowing date ($P = 0.005$) (data not shown). Significant differences in WU between sowing dates were only observed in 2006-2007 with lower values for D1 compared to D2 and D3 (data not shown). Barley WUE_b and WUE_y were significantly affected by sowing date x year and maturity class x year interactions. WUE_y was also affected by the interaction between sowing date and maturity class, and by the triple interaction (Table 1). Greater WUE_b was observed in D2 and D3 compared to D1 in 2006-2007 and 2008-2009 as an average of maturity classes, while D2 showed the highest values in 2007-2008 (Fig. 2). The WUE_y of BMC and BEC increased significantly when the sowing date was delayed from D1 to D2 and D3 (Fig. 2).

Barley NUE was significantly affected by the sowing date x maturity class, sowing date x year as well as maturity class x year interactions (Table 1). NUE increased significantly when the sowing date was delayed from D1 to D2 and D3 in 2006-2007 and 2008-2009, as an average of maturity class (Fig. 2). When distinguishing between maturity classes, the delay of sowing date (D2 and D3 compared to D1) also significantly increased barley NUE (Table 1).

Sowing date and maturity class effects on wheat yield and water- and N-use efficiency

Wheat grain yield was significantly affected by maturity class x sowing date, sowing date x year, as well as maturity class x year interactions (Table 2). Wheat above-ground biomass was significantly affected by the interaction between sowing date and year, and by the interaction between maturity class and year (Table 2). In 2009-2010 the delay of sowing led to an increase in grain yield and above-ground biomass, while the contrary result was observed in 2010-2011 and 2011-2012 (Fig. 3). The delay of sowing only positively affected the grain yield of WEC as an average of the three cropping seasons studied (Table 2).

The three wheat yield components studied were significantly affected by the interaction between sowing date and year (Table 2). In 2009-2010 the delay of sowing led to greater number of spikes per m^2 and grains per spike, but had no effect on TKW (Fig. 3). In contrast, in the 2010-2011 and 2011-2012 seasons lower TKW was observed when sowing was delayed, while in 2010-2011 the delay of sowing led to a lower number of grains per spike (Fig. 3). The wheat HI was significantly affected by the interaction between sowing date and maturity class, and the interaction between sowing date and year (Table 2). However, a delay in sowing produced no consistent trend in this variable.

Wheat WU was only affected by year ($P < 0.001$) with 2009-2010 > 2011-2012 > 2010-2011 (data not shown). Wheat WUE_b was affected by the interaction between maturity class and year, and the interaction between sowing date and year (Table 2). In turn, WUE_y was affected by year x sowing date interaction. The delay in sowing had contrary effects on WUE_b and WUE_y depending on the cropping season. Thus, while D2 and D3 showed higher WUE_b and WUE_y values than D1 in 2009-2010, the opposite trend was observed in 2010-2011 and 2011-2012 (Fig. 3). Wheat NUE was affected by maturity class and the interaction between sowing date and year (Table 2). Compared to D1, later sowing dates (i.e., D2 and D3) led to increased NUE in the 2009-2010 cropping season (Fig. 3). Moreover, greater NUE was observed in WMC than in WEC as an average of cropping seasons (Table 2).

The later barley sowings (D2 and D3) showed a significant linear relationship between grain yield and the number of spikes m^2, no significantly different between them at $P < 0.05$. Contrarily, no relationship was found in D1 (Fig. 4a) ($P = 0.76$). As a difference, the three barley sowing dates (D1, D2 and D3) showed the same ($P < 0.05$) linear relationship between the number of grains per spike and grain yield (Fig. 4b). No relationship was found between TKW and barley grain yield ($P = 0.17$). In the case of wheat, grain yield was linearly related to the number of spikes m^2 and to the number of grains per spike, with no differences between sowing dates according to the analysis of covariance performed (Fig. 4d, 4e). In contrast, wheat TKW showed a non-significantly different linear relationship with grain yield between D2 and D3, while no relationship was found for D1 at $P < 0.05$ (Fig. 4f).

DISCUSSION

Sowing date delay and maturity class effects on barley and wheat yields and yield components

The delay of sowing date had a positive influence on grain yield in the three seasons cropped with barley, and in the first season cropped with wheat (a wet year). The improved performance of barley in 2/3 years and wheat in 1/3 years from delayed sowing dates in the rainfed semi-arid conditions of the experiment could be explained by a better synchronization between water use and crop requirements. Rainfall distribution during the growing season and water storage during summer fallow play a major role on winter cereal production in dryland Mediterranean areas (Basso et al., 2012; Sadras et al., 2012; Lampurlanés et al., 2016). The lower number of grains per spike and TKW in D1 indicates increased water deficit when these yield components were determined compared to the later sowings. García del Moral et al. (2003) pointed out that under poor conditions a reduced tillering rate can become a useful trait for conserving resources that are more efficiently used during the critical phases of yield determination. Terminal drought represents one of the key factors in yield reduction in water-limited areas (González et al., 2007).

The increased number of grains per spike and TKW in the three seasons of barley and the first season of wheat, observed for D2 and D3, could also have been favored by the rainfall received during the late spring, in similar or greater quantities than the historical average, which is better used by crops. Late spring rains often occur in western Mediterranean regions. The increased number of grains per spike and greater TKW would explain the greater barley harvest index in the 2006-2007 and 2007-2008 seasons for the D2 and D3 sowing dates. In contrast, in the 2008-2009 season there was more rainfall during the fall, which significantly enhanced the production of above-ground barley biomass in D2 and D3 and slightly reduced the HI.

In Mediterranean areas with colder fall conditions than those in our experiment greater yields have been reported at earlier sowing dates due to a longer season (Richards et al., 2014; Stephens and Lyons, 1998). However, according to our results, in regions with a mild fall this general assumption does not apply. In this regard, as our data suggest, the use of longer maturity classes of barley (i.e. BMC vs. BEC) at an early sowing date could lead to a water deficit during the grain filling period, resulting in lower TKW and reducing crop yields. Interestingly, the opposite was found to be true for wheat, where a lower yield was observed in WEC compared to WMC as an average of cropping seasons. This result could be explained by the erratic nature of spring rainfall which defines a narrow and highly variable window of late water available to crops, favoring different maturity classes depending on the cropping season.

Uunder the western Mediterranean conditions of the experiment the first half of fall presents warm temperatures that do not limit the development of certain pathogens and weeds. At the experimental site, the 30-yr air temperature averages for October and November are 14.5 and 7.9 ºC, respectively. The use of NT combined with the early sowing of cereal monocrops favor the development of small-seeded grasses such as ripgut brome. During the experimental period no active ingredients were commercially available for the post-emergence control of this weed under barley production, relying solely on non-selective pre-sowing herbicides (glyphosate). However, this herbicide is more effective for delayed sowing dates since (i) the window of weed emergence during fall rains is longer, and (ii) wetter soil conditions favor glyphosate uptake by weeds. In our experiment, García et al. (2014) measured ripgut brome density in the 2008-2009, 2009-2010 and 2010-2011 seasons at herbicide applications. For the D1, D2 and D3 sowing dates ripgut brome density was recorded as 540, 105 and 32 plants m^{-2} in 2008-2009; 1284, 27 and 9 plants m^{-2} in 2009-2010; and 102, 3 and 1 plants m^{-2} in 2010-2011 (García et al., 2014). Thus, the greater yields reached in D2 and D3 compared to D1 in the three seasons of barley and in the first year of wheat could be also partly explained by less competition with weeds for water. In the case of wheat, the competition between the crop and weeds would have been lower in subsequent seasons (2010-11 and 2011-12) given the application of a selective herbicide to control ripgut brome which reduced significantly the seedbank of this weed as García et al. (2014) showed.

Sowing date delay and maturity class effects on water- and nitrogen-use efficiency

In the case of barley, WU only differed between sowing dates for the 2006-2007 harvest, with lower values for D1. Lower biomass was caused by reduced water uptake. Therefore, increased WUE in D2 and D3 was the result of increased biomass. However, in the case of wheat, which has a longer development period than barley, cultivars sown at delayed dates may reduce WUE_y and NUE as a result of a water deficit during the grain filling period. This latter aspect appears to be corroborated by the decreased wheat WUE_y observed in D3 in the 2010-2011 season, as well as in D2 and D3 in the 2011-2012 season, when there was an important water deficit for much of the growing cycle. Compared to 2009-10, there was a 57% and 53% reduction in WU in 2010-2011 and 2011-2012, which led to a strong diminution in the yield components. In severely water-limited western Mediterranean areas, farmers tend to favor barley over wheat, given the shorter cycle of the former, aiming at reducing terminal drought effects as much as possible (Ryan et al., 2008). Our data corroborates that late wheat sowings perform poorly in very dry years.

Soil mineral N at sowing and N use did not differ significantly between treatments during the barley cropping seasons. However, a lower mineral N content at sowing would be expected for the most productive sowing dates, resulting from increased N uptake. The observed result could be the consequence of greater N uptake by grass weeds in D1. The role played by other processes in the N cycle, mainly losses, would be secondary. In average years, well-managed Mediterranean dryland agroecosystems lose little N through leaching and denitrification. Regarding to this, in a contiguous experiment managed under NT and similar rates of N, Plaza-Bonilla et al. (2014) reported a loss of N of less than 0.5 kg N_2O-N ha^{-1} yr^{-1}. According to Angás et al. (2006) the area presents highly unusual rainfall conditions for leaching, which occurs once every 7-10 years. However, N losses by volatilization can be very high in specific cases (Sanz-Cobena et al., 2008). Despite ammonia volatilization could have been a major loss pathway given the pH of the soil of the experiment and the type of fertilizer used, the use of urea-ammonium nitrate solutions in the area has become a common farmers' practice in the area given it is cheaper, easy to use and it gives the possibility to mix the tank with pesticides. Therefore, as Angás et al. (2006) suggested, the development of injection techniques would be a valuable way to improve the efficiency of fertilizer.

The two-fold increase in barley NUE values in 2008-2009, characterized by a wet spring, demonstrates the principal role played by water availability at the end of the season in the more efficient use of nitrogen. However, this result could also be partially explained by the lower amount of mineral N available at sowing, which was 266, 179 and 94 kg N ha^{-1} for the 2006-2007, 2007-2008 and 2008-2009 seasons, as an average of the treatments. The decreased soil N availability resulted from the lower quantities of mineral N rate applied during the experiment (i.e. 50 kg N ha^{-1}) compared with the rate applied by the farmer (double or more in some cases). In our experiment that rate was established in order to achieve a soil status that was less susceptible to N losses to the environment.

Wheat maturity class choice played a major role in WUE_y and NUE. The shorter cycle of WEC than WMC could have reduced the susceptibility to terminal drought, increasing WUE_y and NUE.

CONCLUSIONS

No-till farming is an increasingly adopted soil management practice in semi-arid dryland areas. Among other benefits, it facilitates the delay of cereal sowing date due to improved trafficability, widening the window for sowing and partly avoiding mild temperatures in the western Mediterranean that increase susceptibility to pests, weeds and diseases. In our work, the delay of sowing (from October to mid-November and beginning of December) increased yield in years with normal (or greater than normal) rainfall, 2/3 years in barley and 1/3 years in wheat. The increased water availability in later stages when delaying sowing led to better conditions for defining the number of grains per spike and the TKW. Delayed sowing in average years maximized resource use efficiency for water and nitrogen, increasing the sustainability of the system. However, in years with extreme drought conditions (such as 2010-2011 and 2011-2012 in our experiment), the delay in sowing increased susceptibility to terminal drought, negatively affecting the TKW and reducing grain yield. Although we only compared two cultivars of each species, the data suggests that the best combination of sowing date and maturity class is highly dependent on the erratic rainfall during late spring.

Acknowledgements

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REFERENCES

Álvaro-Fuentes, J., J. Lampurlanés, and C. Cantero-Martínez. 2009. Alternative crop rotations under Mediterranean no-tillage conditions: biomass, grain yield, and water-use efficiency. Agron. J. 101:1227-1233.

Angás, P., J. Lampurlanés, and C. Cantero-Martínez. 2006. Tillage and N fertilization effects on N dynamics and barley yield under semiarid Mediterranean conditions. Soil & Till. Res. 87:59-71.

Basso, B., C. Fiorentino, D. Cammarano, G. Cafiero, and J. Dardanelli. 2012. Analysis of rainfall distribution on spatial and temporal patterns of wheat yield in Mediterranean environment. Eur. J. Agron. 41:52-65.

Bueno, J., C. Amiama, J.L. Hernanz, and J.M. Pereira. 2006. Penetration resistance, soil water content, and workability of grassland soils under two tillage systems. T. ASAE 49:875-882.

Cantero-Martínez, C., P. Angás, and J. Lampurlanés. 2003. Growth, yield and water productivity of barley (*Hordeum vulgare* L.) affected by tillage and N fertilization in Mediterranean semiarid, rainfed conditions of Spain. Field Crop Res. 84:341-357.

Cantero-Martínez, C., P. Angás, and J. Lampurlanés. 2007. Long-term yield and water use efficiency under various tillage systems in Mediterranean rainfed conditions. Ann. Appl. Biol. 150:293-305.

Cantero-Martínez, C., D. Plaza-Bonilla, P. Angás, and J. Álvaro-Fuentes. 2016. Best management practices of tillage and nitrogen fertilization in Mediterranean rainfed conditions: Combining field and modelling approaches. Eur. J. Agron. 79:119-130.

Cantero-Martínez, C., J.M. Villar, I. Romagosa, and E. Fereres. 1995. Nitrogen fertilization of barley under semi-arid rainfed conditions. Eur. J. Agron. 4:309-316.

Connor, D.J., and R.S. Loomis. 1991. Strategies and tactics for water-limited agriculture in low rainfall Mediterranean climates. In: Acevedo, E., C. Giménez, E. Fereres, and J.P. Srivastrava. (Eds). Improvement and management of winter cereals under temperature, drought and salinity stresses. Proceedings of the ICARDA-INIA Symposium, Madrid, Spain. 26-29 Oct. 1991. Inst. Nacional de Investigaciones Agrarias (INIA), Madrid, Spain. p. 441–465.

Cooper, P.J.M., P.J. Gregory, D. Tully, and H.C. Harris. 1987. Improving water-use efficiency of annual crops in the rain-fed farming systems of West Asia and North-Africa. Exp. Agr. 23:113-158.

García, A.L., J. Torra, A. Royo-Esnal, C. Cantero-Martinez, and J. Recasens. 2014. Integrated management of Bromus diandrus in dryland cereal fields under no-till. Weed Res. 54:408-417.

García del Moral, L.F., M.B. García del Moral, J.L. Molina-Cano, and G.A. Slafer. 2003. Yield stability and development in two- and six-rowed winter barleys under Mediterranean conditions. Field Crop Res. 81:109-119.

González, A., I. Martín, and L. Ayerbe. 2007. Response of barley genotypes to terminal soil moisture stress: phenology, growth and yield. Aust. J. Agr. Res. 58:29-37.

Grossman, R.B., and T.G. Reinsch. 2002. Bulk density and linear extensibility. In: Dane, J.H., and G.C. Topp. (Eds) Methods of soil analysis. Part 4. Physical methods. SSSA Book Ser. 5. SSSA, Madison, pp 201–228

Kirkegaard, J.A., J.R. Hunt, T.M. McBeath, J.M. Lilley, A. Moore, K. Verburg, M. Robertson, Y. Oliver, P.R. Ward, S. Milroy, and A.M. Whitebread. 2014. Improving water productivity in the Australian grains industry – a nationally coordinated approach. Crop Pasture Sci. 65:583–601

Lampurlanés, J., D. Plaza-Bonilla, J. Álvaro-Fuentes, and C. Cantero-Martínez. 2016. Long-term analysis of soil water conservation and crop yield under different tillage systems in Mediterranean rainfed conditions. Field Crop Res. 189:59-67. DOI: 10.1016/j.fcr.2016.02.010.

Loss, S.P., and K.H.M. Siddique. 1994. Morphological and physiological traits associated with wheat yield increases in Mediterranean environments. Adv. Agron. 52:229-276.

Mahdi, L., C.J. Bell, and J. Ryan. 1998. Establishment and yield of wheat (*Triticum turgidum* L.) after early sowing at various depths in a semi-arid Mediterranean environment. Field Crop Res. 58:187-196.

McAneney, K.J., and J.L. Arrúe, J.L. 1993. A wheat-fallow rotation in northeastern Spain: water balance-yield considerations. Agronomie 13:481-490.

Piggin, C., A. Haddad, Y. Khalil, S. Loss, and M. Pala. 2015. Effects of tillage and time of sowing on bread wheat, chickpea, barley and lentil grown in rotation in rainfed systems in Syria. Field Crop Res. 173:57-97.

Plaza-Bonilla, D., J. Álvaro-Fuentes, J.L. Arrúe, and C. Cantero-Martínez. 2014. Tillage and nitrogen fertilization effects on nitrous oxide yield-scaled emissions in a rainfed Mediterranean area. Agric. Ecosys. Environ. 189:43-52.

Plaza-Bonilla, D., C. Cantero-Martínez, J. Bareche, J.L. Arrúe, J. Lampurlanés, and J. Álvaro-Fuentes. 2017. Do no-till and pig slurry application improve barley yield and water and nitrogen use efficiencies in rainfed Mediterranean conditions? Field Crop Res. 203:74-85.

Ramos, J.M., M.B. García del Moral, J. Marinetto, and L.F. García del Moral. 1993. Sowing date and cutting frequency effects on triticale forage and grain production. Crop Sci. 33:1312-1315.

Richards, R.A., J.R. Hunt, J.A. Kirkegaard, and J.B. Passioura. 2014. Yield improvements and adaptation of wheat to water-limited environments in Australia-a case study. Crop Pasture Sci. 65:676-689.

Ryan, J., M. Singh, and M. Pala. 2008. Long-term cereal-based rotation trials in the Mediterranean region: implications for cropping sustainability. Adv. Agron. 97:273-319.

Sadras, V.O., C. Lawson, P. Hooper, and G.K. Mc Donald. 2012. Contribution of summer rainfall and nitrogen to the yield and water use efficiency of wheat in Mediterranean-type environments of South Australia. Eur. J. Agron. 36:41-54.

Santiveri, F., J. Lloveras, S. Martí and C. Cantero-Martínez. 2004. Crop emergence and early crop growth of barley affected by crop residue under different tillage systems and N fertilization rates in semiarid conditions of Northeast Spain. In: Cantero, C. and D. Gabiña, editors, Mediterranean rainfed agriculture: strategies for sustainability. Options Mediterranées: Série A. Séminaries Mediterranéens; no. 60 Final Seminar of the Regional Action Programme on Rainfed Agriculture (RAP-RAG), Zaragoza, Spain. 2-3 June 2003. Centre Int. de Hautes Études Agronomiques Méditerranéennes (CIHEAM), Zaragoza, Spain. p. 63-71.

Sanz-Cobena, A., T.H. Misselbrook, A. Arce, J.I. Mingot, J.A. Diez, and A. Vallejo. 2008. An inhibitor of urease activity effectively reduces ammonia emissions from soil treated with urea under Mediterranean conditions. Agric. Ecosys. Environ. 126:243-249.

SAS Institute Inc,. 2014. Using JMP1 11, Second edition SAS Institute Inc., Cary, NC.

Soane, B.D., B.C. Ball, J. Arvidsson, G. Basch, F. Moreno, and J. Roger-Estrade. 2012. No-till in northern, western and south-western Europe: A review of problems and opportunities for crop production and the environment. Soil Till. Res. 118:66-87.

Soil Survey Staff. 2014. Keys to Soil Taxonomy, 12th ed. USDA-Natural Resources Conservation Service, Washington, DC.

Stephens, D.J., and T.J. Lyons. 1998. Variability and trends in sowing dates across the Australian wheatbelt. Aust. J. Agric. Res. 49:1111-1118.

Thackray, D.J., A.J. Diggle, and R.A.C. Jones. 2009. BYDV PREDICTOR: a simulation model to predict aphid arrival, epidemics of *Barley yellow dwarf virus* and yield losses in wheat crops in Mediterranean-type environment. Plant Pathol. 58:186-202.

Unger, P.W., Stewart, B.A., Parr, J.F., and R.P. Singh. 1991. Crop residue management and tillage methods for conserving soil and water in semi-arid regions. Soil Till. Res. 20:219-240.

Wolf, D.D., and K.L. Edmisten. 1989. Late season alfalfa plantings: conventional vs. no-till methods. Crop Sci. 29:170-175.

Figure captions

Fig. 1 Weekly precipitation (columns), and average maximum (black circles) and minimum (white circles) temperatures at the Agramunt experimental site: 30-yr average and cropping seasons studied (from 2006-2007 to 2008-2009 for barley and from 2009-2010 to 2011-2012 for wheat). At the top of each sub-figure the grey-edged symbols indicate the dates of sowing, anthesis and physiological maturity for the D1 (circles), D2 (triangles) and D3 (squares) sowing dates and for the early- (black-filled symbols) and medium (empty symbols) maturity classes. Note the different Y-axes.

Fig. 2 Barley grain yield, above-ground biomass, spikes m^{-2}, grains $spike^{-1}$, thousand kernel weight (TKW), harvest index, water-use efficiency for biomass and yield (WUE_b and WUE_y) and nitrogen-use efficiency (NUE) during the 2006-2007, 2007-2008 and 2008-2009 cropping seasons as affected by sowing date (D1-October, D2-November, and D3-December) and maturity class (medium, BMC; early, BEC). Vertical bars indicate standard deviation. For a given year, different lower-case letters indicate significant differences between sowing dates and maturity classes. For a given year, different lower-case italic letters and different upper-case letters indicate significant differences between sowing dates and maturity classes, respectively ($P<0.05$, LSD test).

Fig. 3 Wheat grain yield, above-ground biomass, spikes m^{-2}, grains $spike^{-1}$, thousand kernel weight (TKW), harvest index, water-use efficiency for biomass and yield (WUE_b and WUE_y) and nitrogen-use efficiency (NUE) during the 2009-10, 2010-11 and 2011-12 cropping seasons as affected by sowing date (D1-October, D2-November, and D3-December) and maturity class (medium, WMC; early, WEC). Vertical bars indicate standard deviation. For a given year, different lower-case letters indicate significant differences between sowing dates and maturity classes. For a given year, different lower-case italic letters and different upper-case letters indicate significant differences between sowing dates and maturity classes, respectively ($P<0.05$, LSD test).

Fig. 4 Linear relationship between grain yield and spikes m^{-2}, grains $spike^{-1}$ and thousand kernel weight (TKW) of barley (a, b and c, respectively) and wheat (d, e and f, respectively) as affected by sowing date (D1-October, D2-November, and D3-December). Each legend shows the sowing dates with the same significant linear relationship at $P < 0.05$. Non-significant linear relationships are not shown. Note the different axes.

Table 1 Analysis of variance of barley grain yield, above-ground biomass, spikes m^{-2}, grains spike^{-1}, thousand kernel weight (TKW), harvest index (HI), water-use efficiency for above-ground biomass (WUE$_b$) and grain yield (WUE$_y$), and nitrogen use efficiency (NUE) as affected by sowing date (D1, October; D2, November, and D3, December), maturity class (BEC and BMC, barley early and medium maturity class, respectively) and year, and their interactions.

Treatments and ANOVA effects	**Grain yield**	**Abg. biomass**	**Spikes m^{-2}**	**Grains spike^{-1}**	**TKW**	**HI**	**WUE$_b$**	**WUE$_y$**	**NUE**
	-- kg ha^{-1}--	-- g m^{-2}--			-- g--		-- kg ha^{-1} mm^{-1}--	-- kg ha^{-1} mm^{-1}--	-- kg ha^{-1} kg N^{-1}--
D1 (October)	2481 c†	792 b	843 a	12 b	35.0 c	0.46 b	20.4 b	6.4	10.8 b
D2 (November)	3946 a	1029 a	895 a	15 a	38.5 b	0.50 a	26.2 a	10.0	17.1 a
D3 (December)	3623 b	949 a	729 b	16 a	40.5 a	0.51 a	23.7 a	8.9	14.4 a
BEC	3336	897	888 a	13 b	41.1 a	0.50 a	22.8	8.4	14.4 a
BMC	3364	957	757 b	17 a	35.0 b	0.47 b	24.1	8.7	13.8 b
2006-07	3418 b	1011 a	1034 a	14 b	31.0 b	0.43 c	29.5 a	9.9	9.9 b
2007-08	2519 a	660 b	625 c	14 b	41.3 a	0.53 a	18.6 b	7.3	9.8 b
2008-09	4113 c	1092 a	808 b	16 a	41.8 a	0.50 b	22.3 b	8.4	24.2 a
D1-BEC	2635 c	779 d	942	10	38.7 c	0.47	20.4	6.7 d	12.6 b
D2-BEC	3892 a	929 bc	940	13	40.5 b	0.51	23.7	9.7 ab	17.4 a
D3-BEC	3481 b	982 b	783	14	44.1 a	0.53	24.3	8.7 c	12.8 a
D1-BMC	2326 d	806 cd	745	15	31.4 e	0.45	20.5	6.1 d	9.0 c
D2-BMC	4001 a	1130 a	851	17	36.5 d	0.48	28.8	10.3 a	16.8 a
D3-BMC	3765 a	917 bcd	675	18	36.9 d	0.49	23.1	9.1 bc	15.9 a
		ANOVA					***P*-values**		
Sowing date (SD)	<0.001	<0.001	0.006	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Maturity class (C)	0.728	0.133	0.003	<0.001	<0.001	<0.001	0.370	0.313	0.012
Year (Y)	<0.001	<0.001	<0.001	0.003	<0.001	<0.001	<0.001	<0.001	<0.001
SD x C	0.013	0.037	0.513	0.505	<0.001	0.447	0.055	0.014	0.007
SD x Y	<0.001	<0.001	0.095	<0.001	<0.001	<0.001	0.009	<0.001	<0.001
C x Y	<0.001	0.003	0.133	0.003	<0.001	<0.001	0.049	<0.001	<0.001
SD x C x Y	0.078	0.014	0.373	0.881	0.010	<0.001	0.182	0.002	0.120

† For a given variable, different letters indicate significant differences between treatments at $P < 0.05$ (LSD test).

Table 2 Analysis of variance of wheat grain yield, above-ground biomass, spikes m^{-2}, grains spike^{-1}, thousand kernel weight (TKW), harvest index (HI), water-use efficiency for above-ground biomass (WUE$_b$) and grain yield (WUE$_y$), and nitrogen use efficiency (NUE) as affected by sowing date (D1, October; D2, November, and D3, December), maturity class (WEC and WMC, wheat early and medium maturity class, respectively) and year, and their interactions.

Treatments and ANOVA effects	**Grain yield**	**Abg. biomass**	**Spikes m^{-2}**	**Grains spike^{-1}**	**TKW**	**HI**	**WUE$_b$**	**WUE$_y$**	**NUE**
	-- kg ha^{-1}--	-- g m^{-2}--			-- g--		-- kg ha^{-1} mm^{-1}--	-- kg ha^{-1} mm^{-1}--	-- kg ha^{-1} kg N^{-1}--
D1 (October)	1183 b†	570 b	322	26 b	30 a	0.43	19	4.0	7.2 b
D2 (November)	1572 a	732 a	349	33 a	27 b	0.45	20	4.4	10.1 a
D3 (December)	1625 a	656 ab	335	30 a	25 c	0.43	17	4.0	10.2 a
WMC	1541 a	659	346	30	26 b	0.44	17 b	4.3	9.9 a
WEC	1379 b	647	324	30	29 a	0.44	20 a	4.0	8.4 b
2009-10	2198 a	907 a	373 a	35 a	32 a	0.47 a	16 b	3.9 b	13.6 a
2010-11	1185 b	521 b	275 b	31 b	26 b	0.46 a	22 a	4.8 a	6.0 c
2011-12	997 c	532 b	358 a	24 c	24 c	0.39 b	18 b	3.7 b	7.8 b
D1-WMC	1393 a	617	337	30 b	29	0.45 a	19	4.5	8.7
D2- WMC	1576 a	737	366	31 ab	26	0.45 ab	18	4.3	10.4
D3- WMC	1654 a	622	335	29 b	24	0.42 bc	16	4.1	10.7
D1-WEC	973 b	524	307	23 c	31	0.42 c	19	3.5	5.8
D2- WEC	1568 a	728	332	35 a	29	0.45 ab	22	4.5	9.7
D3- WEC	1596 a	691	334	32 ab	26	0.44 abc	19	4.0	9.6
ANOVA					***P-values***				
Sowing date (SD)	0.004	0.013	0.277	0.001	<0.001	0.228	0.254	0.323	0.003
Maturity class (C)	0.008	0.791	0.122	0.913	<0.001	0.377	0.028	0.153	0.040
Year (Y)	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	0.001	<0.001	<0.001
SD x C	0.009	0.307	0.566	0.010	0.689	0.012	0.753	0.089	0.426
SD x Y	<0.001	<0.001	<0.001	<0.001	0.001	0.006	<0.001	<0.001	<0.001
C x Y	0.025	0.022	0.002	0.536	0.042	0.615	0.035	0.136	0.505
SD x C x Y	0.055	0.922	0.366	0.179	0.001	0.128	0.884	0.223	0.631

† For a given variable, different letters indicate significant differences between treatments at $P < 0.05$ (LSD test).

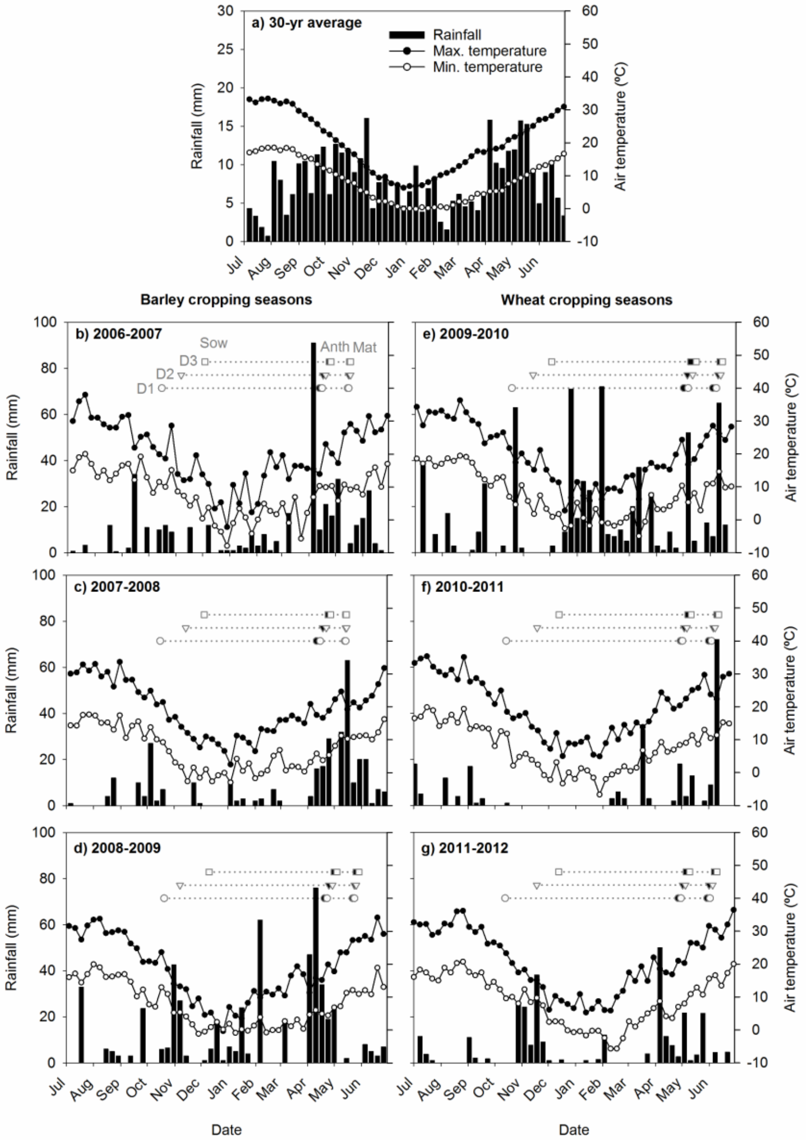
a) 30-yr average
Rainfall
Max. temperature
Min. temperature
Rainfall (mm)
Air temperature (ºC)
Jul
Aug
Sep
Oct
Nov
Dec
Jan
Feb
Mar
Apr
May
Jun
Barley cropping seasons
Wheat cropping seasons
b) 2006-2007
Sow
Anth
Mat
D3
D2
D1
c) 2007-2008
d) 2008-2009
e) 2009-2010
f) 2010-2011
g) 2011-2012
Date

Fig.1

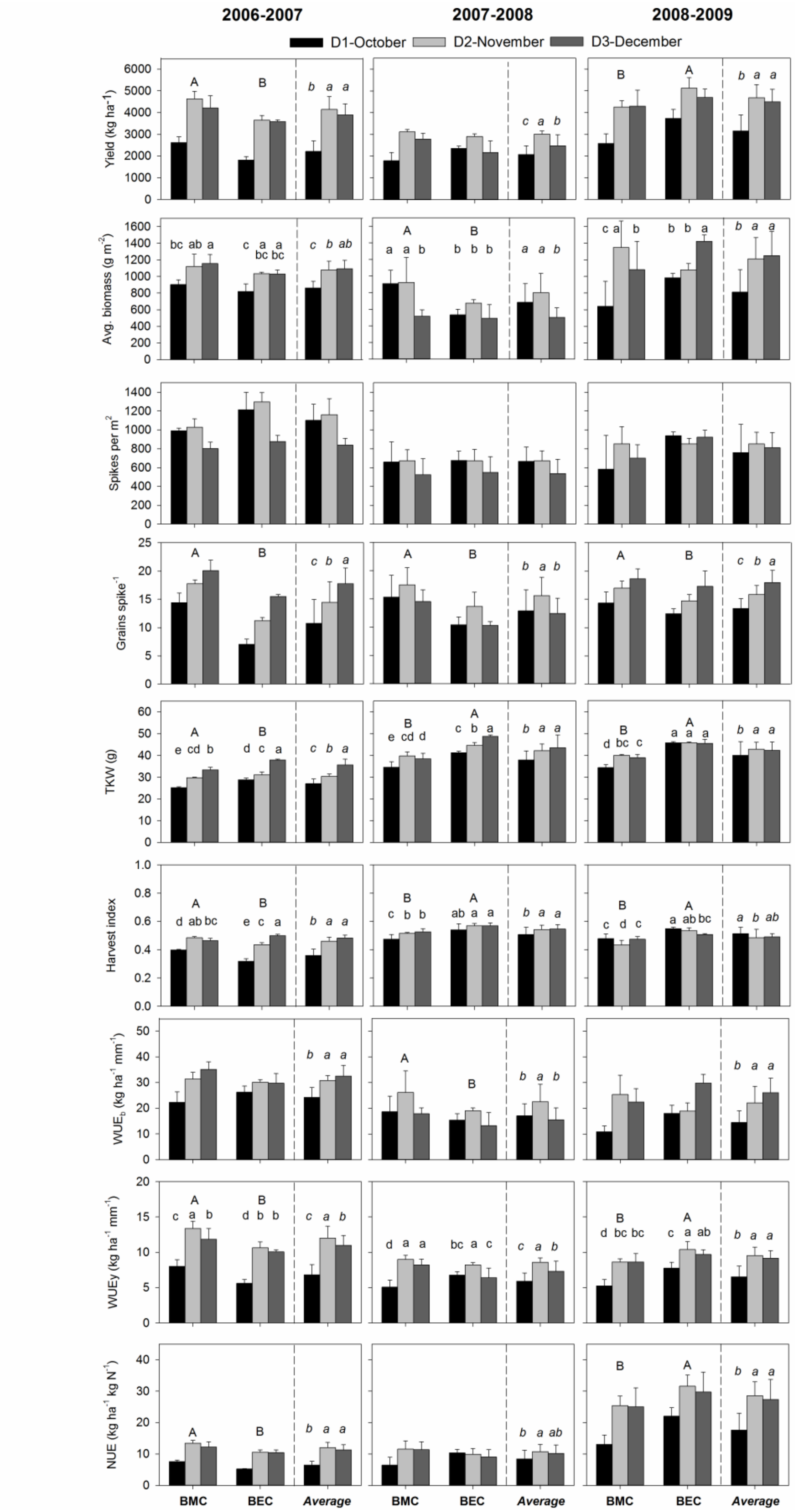
2006-2007
2007-2008
2008-2009
D1-October
D2-November
D3-December
Yield (kg ha-1)
Avg. biomass (g m-2)
Spikes per m2
Grains spike-1
TKW (g)
Harvest index
WUEb (kg ha-1 mm-1)
WUEy (kg ha-1 mm-1)
NUE (kg ha-1 kg N-1)
BMC
BEC
Average

Fig. 2

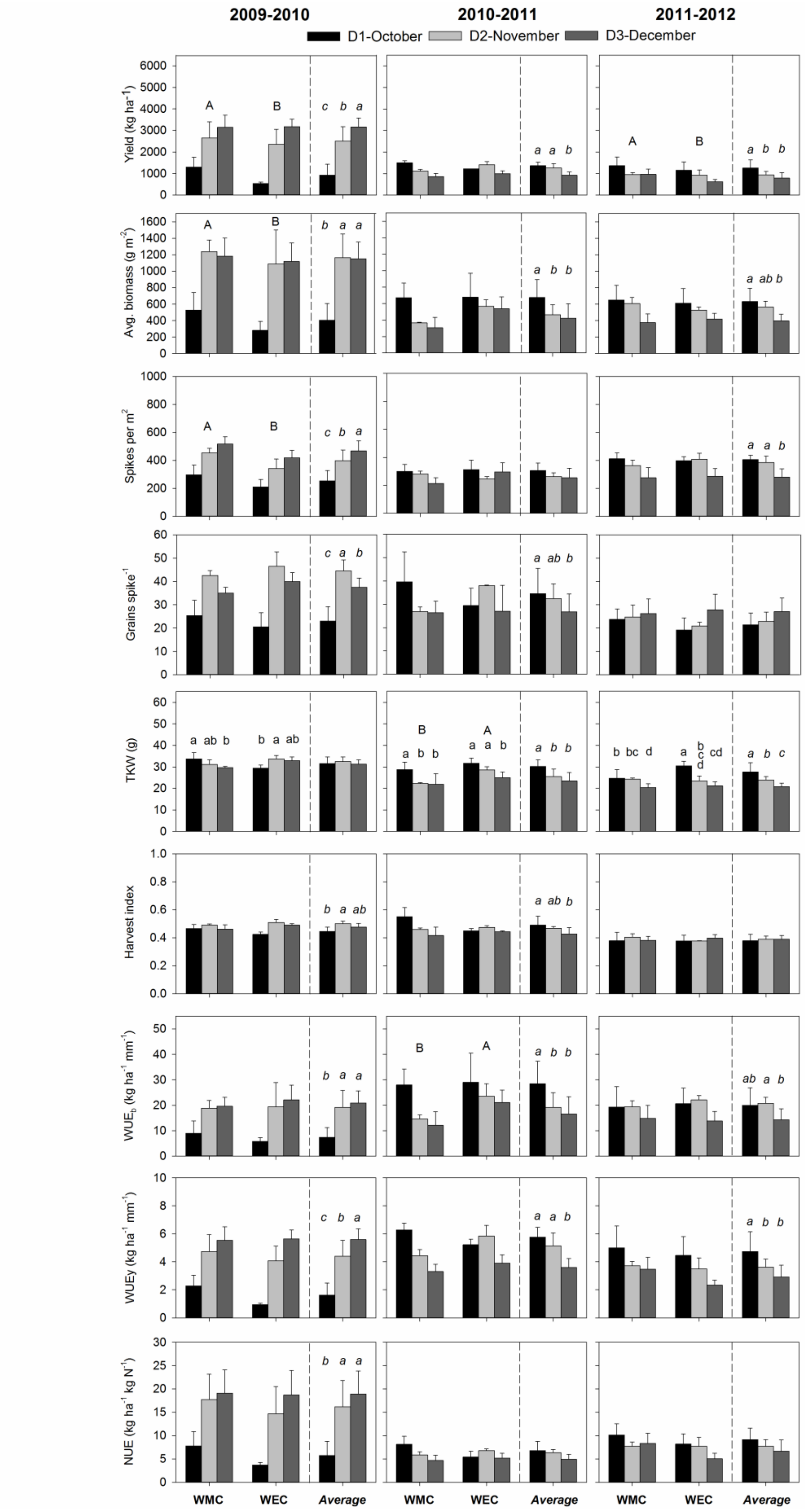
2009-2010
2010-2011
2011-2012
D1-October
D2-November
D3-December
Yield (kg ha^{-1})
Avg. biomass (g m^{-2})
Spikes per m^{2}
Grains spike^{-1}
TKW (g)
Harvest index
WUE$_b$ (kg ha^{-1} mm^{-1})
WUEy (kg ha^{-1} mm^{-1})
NUE (kg ha^{-1} kg N^{-1})
WMC
WEC
Average
WMC
WEC
Average
WMC
WEC
Average

Fig. 3

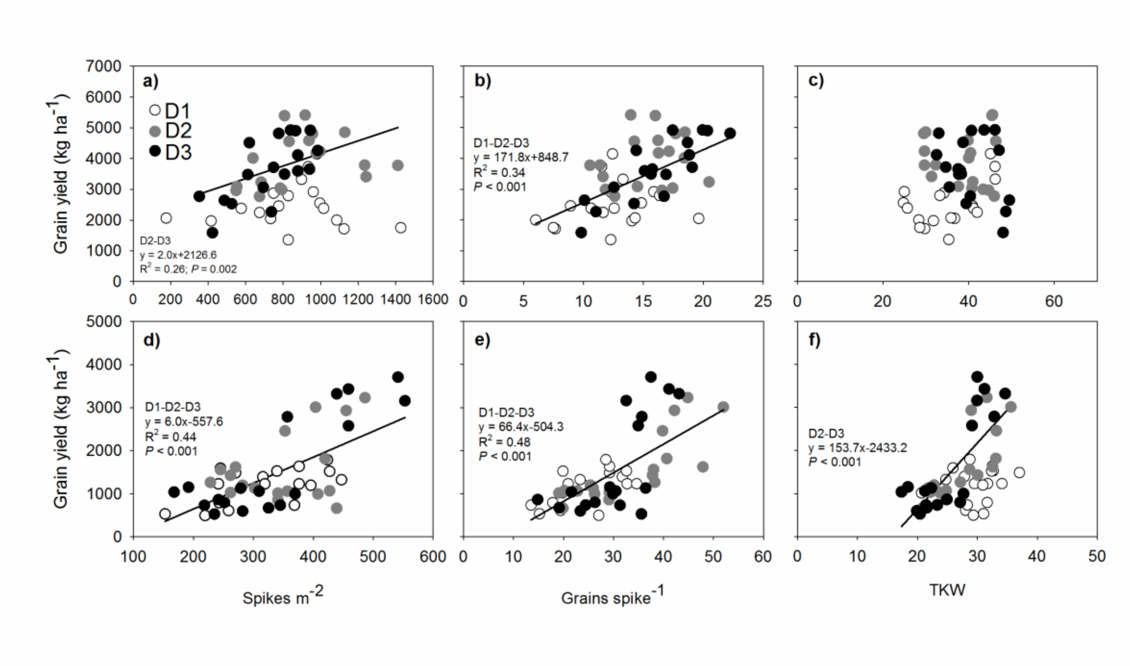
Grain yield (kg ha^{-1})
a)
○ D1
● D2
● D3
D2-D3
y = 2.0x+2126.6
R^2 = 0.26; P = 0.002
7000
6000
5000
4000
3000
2000
1000
0
0
200
400
600
800
1000
1200
1400
1600
b)
D1-D2-D3
y = 171.8x+848.7
R^2 = 0.34
P < 0.001
0
5
10
15
20
25
c)
0
20
40
60
Grain yield (kg ha^{-1})
d)
D1-D2-D3
y = 6.0x-557.6
R^2 = 0.44
P < 0.001
5000
4000
3000
2000
1000
0
100
200
300
400
500
600
Spikes m^{-2}
e)
D1-D2-D3
y = 66.4x-504.3
R^2 = 0.48
P < 0.001
0
10
20
30
40
50
60
Grains spike^{-1}
f)
D2-D3
y = 153.7x-2433.2
P < 0.001
0
10
20
30
40
50
TKW

Fig. 4