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ORIGINAL PAPER

Response of commercial classes of wheat to contrasting irrigation regimes

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Abstract

A 3-year experiment was established in which four wheat classes were evaluated including soft, medium hard, hard and durum wheat with the objective to determine which class is more efficient in water use under reduced irrigation. The experiments were established during three growing seasons (2016–2018). The amount of water applied were: 26, 34 and 54 cm distributed in 2, 3 and 5 irrigations, respectively. Eighteen genotypes from each wheat class were evaluated in an alpha lattice design with three replicates. Phenological data, yield and yield components were analyzed. Yield in the two-irrigation regime ranged from 3974 to 5436, 4453 to 6909 under three and 6177 to 9107 kg ha^{-1} under five. Correlation analysis showed that with two irrigations there is a greater association of grain yield with thousand kernel weight (TKW), but under three and five irrigations, grain yield was associated to a greater degree with kernel number per unit area (KNO). When analyzing the grain yield, it was observed that under reduced irrigation (2 and 3 irrigations), bread wheats were superior to durum wheats regardless of the class. Under five irrigations, durum wheats showed the highest yield (8303 kg ha^{-1}); however, they were only significantly superior (Tukey ≤ 0.05) to the hard wheats (7721 kg ha^{-1}). In general, the tested wheats showed higher water efficiency (considered as water productivity) under reduced irrigation than under normal irrigation. The lowest losses in water productivity when going from two to five irrigations were observed in durum wheats (0.17 kg m^{-3}) and the highest losses in the hard wheats (0.38 kg m^{-3}).

Keywords Classes of wheat · Restricted irrigation · Water productivity · Yield · Efficient use of water

Abbreviations

D	Durum wheat
H	Hard wheat
MH	Medium-hard wheat
S	Soft wheat
D2I	Durum wheat two irrigations
D3I	Durum wheat three irrigations
D5I	Durum wheat five irrigations
H2I	Hard wheat two irrigations
H3I	Hard wheat three irrigations
H5I	Hard wheat five irrigations
MH2I	Medium-hard wheat two irrigations
MH3I	Medium-hard wheat three irrigations
MH5I	Medium-hard wheat five irrigations
S2I	Soft wheat two irrigations
S3I	Soft wheat three irrigations
S5I	Soft wheat five irrigations
HD	Heading days
MD	Maturity days
PH	Plant height
GY	Grain yield
Bio	Biomass

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HI	Harvest index
KNO	Kernels per square meter
SM2	Spikes per square meter
TKW	Thousand kernel weight
TRB	Biological yield of 100 stems from the plot
TRG	Yield in grams of 100 stems from the plot
IS	Irrigation schedules
CWP	Crop water productivity
WC	Wheat classes
WP	Water productivity
WUE	Water use efficiency

Introduction

The world population of 7.8 billion in 2020 will increase to more than 9 billion by 2050 and likely peak at approximately 11 billion by the end of the century (Randive et al. 2021). Improving yield potential and closing the yield gap are important to achieve global food security (Senapati and Semenov 2020). It has been predicted that food production needs to increase by about 70% between 2007 and 2050 to feed an estimated > 9 billion people (Reynolds et al. 2011). Rising temperatures and the incidence of drought associated with global warming pose serious threats to food security (Lobell et al. 2013). New wheat cultivars better adapted for future climatic conditions will therefore be required (Semenov et al. 2014). It has found that unless steps are taken to mitigate climate change, up to 60% of the current wheat-growing areas worldwide could experience simultaneously, severe and prolonged droughts by the end of the century (Trnka et al. 2019). Accordingly, understanding and improving plant survival and growth under restricted water availability are of central significance in contemporary plant science. This challenge will probably be further compounded by reduced water availability and increased temperatures due to global warming (Saha et al. 2018). Water is a key input among all the inputs; however, water for irrigation is a scarce resource; therefore, efficient utilization of irrigation water is essential. Optimum use of irrigation water permits better utilization of all other production factors and leads to increased yield per unit area and time (Kumar et al. 2019). Flood irrigation, the conventional method of irrigation can be highly inefficient where flow rates are inadequate to complete the irrigation quickly (a couple of hours). The inefficiency is due to deep drainage below the rootzone. Flood irrigation also causes temporary waterlogging, with adverse effects on crops like wheat, maize and legumes (Yadav et al. 2013). To overcome these situations, pressurized irrigation systems (PISs) are the best option (Firouzabadi et al. 2021). The main types of PISs available are sprinkler irrigation and drip irrigation (surface and subsurface). Drip and sprinkler irrigation systems are much more water-efficient than conventional basin irrigation practices. These have a conveyance efficiency of 100% and an application efficiency of 70–90%, while the corresponding figures for basin irrigation are 40–70% and 60–70%, respectively (Singh et al. 2020). In an arid region of China, were compared rice yields in flood and non-flood systems. Non-flood systems included (i) drip irrigation frequencies with plastic mulch and (ii) furrow irrigation with and without plastic mulch. Yields were typically greater in the flood system across all treatments, but in non-flood system water use efficiency was 2.5 times greater when compared with the flood system (He et al. 2016). In a wheat study, comparing drip irrigation tubes with 60 and 75 cm spacing with the furrow irrigation prevalent in Hamedan province, Iran, and investigates the effects of the former form of irrigation on the productivity of wheat crops with various cropping layouts. The mean irrigation water productivity obtained for drip and furrow irrigation treatments were 1.74 and 1.01 kg m^{-3}, respectively. Drip irrigation caused a 33% reduction in applied irrigation water use and a 72% increase in irrigation water productivity in comparison to the furrow irrigation method (Firouzabadi et al. 2021). A 3-year field experiment was conducted to examine the effects of different irrigation methods on maize taking 525-mm border irrigation as the control, furrow and drip irrigations at three water levels were implemented. Furrow irrigation included 100% (450 mm), 80% (360 mm) and 60% (270 mm) of the recommended level, while three threshold values of soil matric potential: – 10 kPa, – 30 kPa and – 50 kPa, were used to trigger drip irrigation. The 360-mm furrow irrigation obtained a comparable grain yield and net profit with the control, but reduced water application by 31%. Drip irrigation at – 30 kPa enhanced yield by 15%, increased net profit by 23% and reduced water application by 57% (Zhang et al. 2021). The comparison between drip irrigation and conventional border irrigation method (BI) on maize was carried out to determine the effects of drip irrigation (DI, 540 mm) or conventional border irrigation method (BI, 720 mm) on maize growth, water use efficiency (WUE) as well as profitability. In comparison to conventional border irrigation, the yield of drip irrigation increased by 14.39%, as well as WUE and irrigation water use efficiency (IWUE) increased by 53.77% and 57.89%. The net return and economic benefit of drip irrigation was 1998.87 and 756.58 USD$ hm^{-1} higher than that of BI. Drip irrigation increased net return and benefit/cost ratio by 60.90% and 22.88% compared with BI. These results demonstrate that the drip irrigation can effectively improve the growth, yield, WUE and economic benefit of maize in northwest China (Liu et al. 2023). In a simulation study to explore the use of drip and surface irrigation decision support systems to select among furrow, border and drip irrigation systems for cotton, considering water saving and economic priorities. Simulation of drip irrigation was performed with MIRRIG model (Pedras and Pereira 2009), and furrow and border irrigation alternatives were designed and ranked with the SADREG model (Gonçalves & Pereira 2009). The results showed that the comparison between surface and drip irrigation systems, despite low cost, drip alternatives may lead to 28–35% water saving relative to improved graded furrows, and increase water productivity from 0.43 to 0.61 kg m^{-3}, surface irrigation provides higher farm returns. Drip irrigation is selected only when high priority is assigned to water saving. Deficit irrigation does not change this pattern of results. Apparently, adopting drip irrigation requires appropriate economic incentives to farmers, changes in the structure of production costs and increased value of production (Darouich et al. 2014).

Scheduling irrigation is very critical for obtaining optimal crop yields. Irrigation scheduling involves the timing of irrigation and the amount of water applied. There are different methods of irrigation scheduling, viz., critical crop growth stage approach, soil moisture depletion approach, irrigation based on atmospheric evaporativity, etc., which may be adopted for optimizing the timing of irrigation (Singh et al. 2014). Limited irrigation, with an amount less than the crop water requirement, has been recognized as a viable water-saving technique in preparation for future water-shortage scenarios (Zhao et al. 2019). Several researchers have reported the water use efficiency (WUE) under limited irrigation. In maize, for example, 50% of the evapotranspiration requirement reduced grain yield by 4.78 t ha^{-1} for the conventional hybrid when compared to 100% of the evapotranspiration requirement (Zhao et al. 2019). In barley, five irrigation treatments were performed over 3 years: no deficit (ND) (control), and four with different volumes of available irrigation water, corresponding to 100%, 90%, 80% and 70% of barley net irrigation requirement. Yield decreased with deficit and ND was the treatment that achieved the highest average yield (9049 kg ha^{-1}). While the average yield decreased by 19.4% and 29.9% regarding to ND, the highest average irrigation water productivity was for 80% and 70% (average 3.63 kg m^{-3}), as these treatments reduced the average amount of irrigation water by 39.1% and 46.7%, respectively (Pardo et al. 2020). Wheat was evaluated two levels of irrigation included the local conventional irrigation amount, 2400 m^3 ha^{-1} (high: I2), and the local conventional irrigation amount reduced by 20%, 1920 m^3 ha^{-1} (low: I1). Grain yield was 2.4–4.3% greater with I1 compared to I2, but grain yield was not significantly different between irrigation levels (Guo et al. 2019).

Thus, to improve crop production while conserving water, it is important to explore alternative irrigation strategies. Water is a scarce resource in the Bajío region (Mexico area, states of Guanajuato, Michoacán and Jalisco). Due to overexploitation of the aquifer in the Bajío with more than 16,000 active wells, which results in a 3–6 m year^{-1} drop in water table and increases the cost of electrical energy used to extract water, the underground hydraulic balance shows a deficit of more than 900 million m^3 (Ledesma et al. 2010).

However, this area possesses the potential to increase crop production while maximize the water use efficiency. This can be accomplished by employing alternative strategies and research priorities that consider the changing climatic conditions and aim to save available water. Strategies that have a potential to increase water use efficiency such as identifying wheat genotypes with higher water use efficiency are important (Liwani et al. 2019). In this area, Martínez et al. (2020) reported the effect of the water deficit on the yield of wheat genotypes applying different water volumes distributed in different number of irrigations. In their research, they evaluated four irrigation schedules two (0 and 35), three (0, 35 and 70), four (0, 35, 70 and 105) and five (0, 35, 70, 105 and 125 days after the sowing). They found that the reductions in the number of irrigations of 4, 3 and 2 decreased the grain yield by 14.4, 37.6 and 76.8%, respectively. However, they identified a genotype (Temporalera M87) that only reduced its yield by 50% when going from five to two irrigations. This genotype could be used as a parent to increase the efficiency in the use of water from the germplasm of the region. The associated traits on WUE could be used as a selection criterion in breeding wheat for limited water conditions. Adoption of superior WUE genotypes could directly reduce water consumption by 20%, further contributing to the reduced cost of cultivation (USD 42.6 ha^{-1}) to farmers. Pearson correlation identified grain yield ($r=0.99$), above ground biomass ($r=0.46$), harvest index ($r=0.86$), thousand grain weight ($r=0.52$) and chlorophyll meter reading ($r=0.46$) at post-anthesis as significant traits contributing to higher WUE (Meena et al. 2019).

To face the challenges of increasing water use efficiency in wheat-growing areas, it is very important to identify water stress tolerant wheat genotypes (Liwani et al. 2019). Due to the water crisis in the Bajío, México, the severe effect of water stress on wheat yields and the limitation of water use across the region, it is imperative to conserve water by identifying the wheat genotypes with highest water use efficiency. In order to identify a suitable wheat class to cultivate in this area for production under normal and reduced irrigation, the objective of this study was to compare the relative tolerance of durum and bread wheat genotypes (three classes: soft, medium hard and hard) to reduced irrigation.

Materials and methods

This study was carried out in the Bajío Experimental Field belonging to the National Institute of Forestry, Agricultural and Livestock Research (INIFAP), located in Celaya, Guanajuato, México, at 20° 32′ North Latitude, 100° 48′ West Longitude and 1752 m above sea level; the annual precipitation and average temperature are 578 mm and 19.8 °C, respectively. The research was carried out in three agricultural cycles 2015–2016, 2016–2017 and 2017–2018, the sowing date in all cases was December 1 of each year.

Genetic material

According to the characteristics of gluten in Mexico, five classes of wheat are recognized: Group 1 (strong gluten): it is intended for the mechanized bakery industry and mixes with soft wheat, its *W* value is $\geq 300 * 10^{-4}$ J. Group 2 (medium-strong gluten): it is intended for the handmade bread industry and for mixtures with soft wheat, its W value is between 200 y 300 $*10^{-4}$ J. Group 3 (soft gluten): it is intended for the biscuit industry for the preparation of tortillas, fritters, etc., its W value is less than $200*10^{-4}$ J. Group 4 (tenacious gluten): it is intended for the pastry, biscuit industry and for the preparation of donuts (is independent of the W value, although soft wheats are more representative). Group 5 (crystalline grain): it is mainly intended for the pasta and macaroni industry, but it can also be used in mixtures for bakery products (DOF 1984). The most used classes by area sown are groups 1, 2, 3 and 5, which were considered in this study. A total of 72 genotypes were evaluated (Online Resource 1) including 54 bread wheats (*Triticum aestivum* L.) of which 18 are soft wheats, 18 medium-hard wheats, 18 hard wheats, in addition 18 durum wheats (*Triticum durum* Desf.) were studied.

Experimental management

This group of materials was evaluated in three irrigation schedules (IS): two, three and five irrigations at (0–55, 0–45–75 and 0–35–65–85 and 105 days after sowing). The irrigations were given by flooding using the sluice method. The applied irrigation sheets were 26 cm (14 + 12) for the two-irrigation schedule, 34 cm (14 + 10 + 10) for the three-irrigation schedule and 54 cm (14 + 10 + 10 + 10 + 10) for the five-irrigation schedule.

All plots were fertilized with the 240–60-00 formula, half the nitrogen and all the P_2O_5 at sowing and the rest of the nitrogen in the first irrigation. The fertilizer sources were urea (CO $(NH_2)_2$) with 46% of N and triple calcium superphosphate (Ca $(H_2PO_4)_2$) with 46% of P_2O_5. The narrow-leaved weeds were controlled with Topik 24EC® at 28 days after planting irrigation and the broad-leaved weeds with Esteron 47® at 34 days. The harvest was carried out with a combine adapted for experimental plots when the grain reached a moisture content between 12 and 14%.

Measurement of traits

The phenotypic characters measured were: (1) plant height (PH), measured in centimeters from the soil surface to the tip of the terminal spikelet; (2) heading days (HD), number of days from sowing until 50% of the ears were exposed; (3) maturity days (MD), from sowing to the moment when 50% of the peduncles of the plants turned yellowish; (4) harvest index (HI), equal to TRG/TRB, where TRG = yield in grams of 100 stems from the plot and TRB = biological yield of 100 stems from the plot; (5) grain yield (GY), in grams per plot and it was transformed to kg ha^{-1}; (6) biomass (Bio), in t per ha, calculated as (GY/1000)/HI; (7) spikes per square meter (SM2) = (Bio * 100)/(TRG/100); (8) 1000 grain weight (TKW) in g; (9) kernels per square meter (KNO) = (GY/10)/(TKW/1000).

Statistical analysis

A principal component analysis was carried out using the FactoMIneR packages (to perform the analysis) and factoextra (to obtain the visualization based on ggplot2), both packages can be run with software R, version 4.1.1 (R Core Team 2021).

With the data obtained in each irrigation schedule, the combined variance analysis for grain yield was performed. For this analysis, the model used to explain the behavior of any type of wheat in the different environments (years and irrigation schedules) of evaluation is:

$$
\begin{aligned}
Y_{ijkln} = & \mu + a_j + (r_k)a_j + (b_l)r_{kj} + \varepsilon A_{jkl} + is_n + a_j is_n \\
& + \varepsilon B_{nkl} + wt_i + a_j wt_i + is_n wt_i + a_j is_n wt_i + \varepsilon_{ijk\,\mathrm{ln}}
\end{aligned}
$$

where Y_{ijkln} = mean behavior of the wheat type "*i*" in block "*l*," of the repetition "*k*," in the irrigation schedules "*n*," in year "*j*;" μ = general mean across all environments; a_j = effect of year "*j*"; (r_k) a_j = effect of repetition "*k*" within year "*j*;" (b_l) rk_{aj} = effect of block "*l*" within repetition "*k*," in year "*j*;" $\varepsilon A_{jkl} = A$ error; is_n = effect of the irrigation; schedule "*n*;" wt_i = effect of wheat type "*i*;" $\varepsilon B_{jkl} = B$ error; $a_j is_n$ = effect of the interaction of the irrigation schedule "*n*" in year "*j*;" $a_j wt_i$ = effect of the interaction of the wheat type "*i*" in year "*j*;" $\mathrm{is_n wt_i}$ = effect of the interaction of the wheat type "*i*" in the irrigation schedule "*n*;" $a_j is_n wt_i$ = effect of the interaction of the wheat type "*i*" in the irrigation schedule "*n*" in year "*j*;" ε_{ijkln} = combined experimental error.

The interactions with the grain yield variable that were statistically significant were analyzed by means of orthogonal contrasts using SAS version 9.3 routines (SAS Institute 2018).

Water productivity

To determine the productivity of irrigation water, the expression used was Productivity = Quantity of product/Unit of water (Ríos et al. 2016). Productivity is the relationship between the unit of result and the unit of input. In this case the term "water productivity" was used exclusively to denote the quantity or value of the product over the volume or value of the water consumed.

Results

For ten traits of wheat, principal component analysis (PCA) was carried out. According to the correlation matrix values presented in Online Resource 2, the first two main components represent 69.8% of the total variation (PC1 50.9% and PC2 18.9%). According to the eigenvectors analysis results shown in Online Resource 3, the first major component has a higher degree of association with Bio, GY and MD variables. On the *Y* axis, the second component showed a greater association with HI and HD variables. The principal components graph is shown in Fig. 1, where the irrigation schedules are differentiated by colors and shapes, and the vectors (red arrows) indicate the behavior of the variables. As was already mentioned, PC1 (50.9%) was positively associated with the variables biomass (Bio), yield (GY) and days to maturity (MD), so the highest values in these variables are presented in the schedule of five irrigations (on the right side of the biplot). PC2 (18.9%) was positively associated with days to heading (HD) and negatively associated with harvest index (HI). The results observed in PC2 show that genotypes with high values of this component have the longest cycles and the lower harvest index. The vectors explain the behavior of the variables in the irrigation schedules; thus, it is observed in the graph that almost all the variables are in the side of the five irrigations, which indicates that they had a greater expression in this treatment.

Associations of variables considering the wheat classes

Table 1 and Online Resource 4 show that the variables associated with grain yield over different wheat classes are not fixed, but are modified according to the availability of water, so the yield components are particular to each class in each irrigation schedule.

In the two-irrigation schedule, grain yield was positively correlated with Bio, KNO and HI in the soft wheats; in the three irrigations was correlated with KNO and HI, and in the five irrigations with Bio, SM2 and KNO, which indicates that HI is an important component of GY under water restriction, but not when there is sufficient water availability; rather, under normal irrigation SM2 is an important component of yield, but not under water restriction. GY is negatively correlated with HD and MD under restricted irrigation, but this correlation is lost in normal irrigation. So the association between GY and KNO increases with the number of irrigations.

Fig. 1 Plot of the first two principal components from analysis of 72 genotypes evaluated in three irrigation schedules

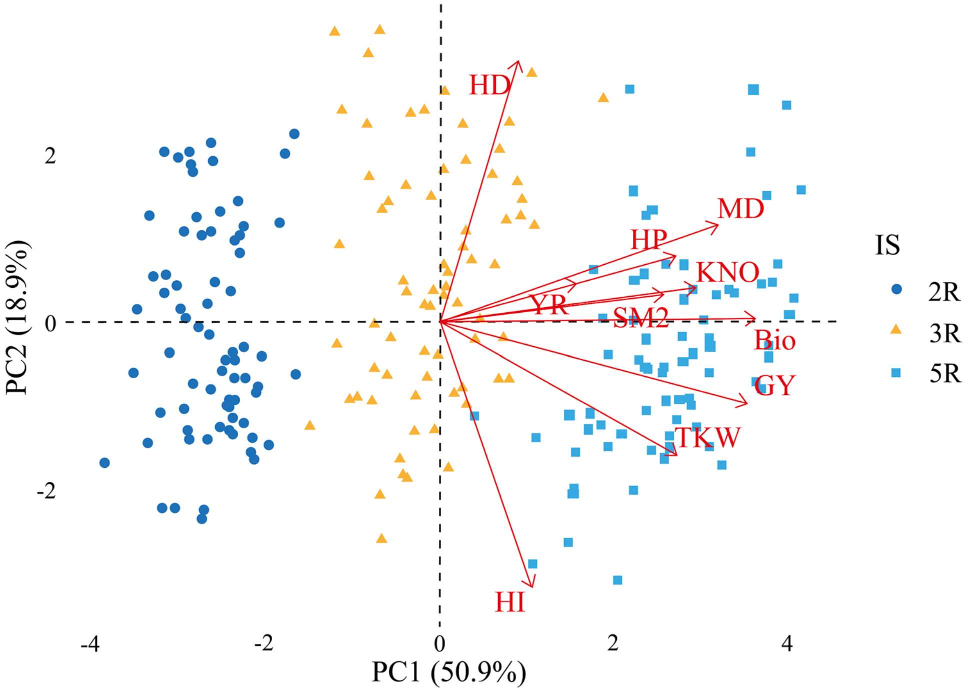

Table 1 Correlations of the estimated variables with grain yield by wheat classes

TREAT	Bio	HI	SM2	TKW	KNO	MD	HD	PH
S2I	0.74**	0.53*	NC	NC	0.58**	−0.52*	−0.58**	NC
S3I	NC	0.49*	NC	NC	0.59**	−0.63**	−0.50*	NC
S5I	0.79**	NC	0.64**	NC	0.72**	NC	NC	NC
MH2I	0.55**	0.60**	NC	0.50*	NC	−0.54*	−0.52*	NC
MH3I	NC	NC	NC	NC	NC	−0.51*	NC	NC
MH5I	0.48*	NC	NC	NC	0.60**	NC	NC	NC
H2I	0.77**	0.67**	NC	0.73**	NC	−0.64**	−0.75**	NC
H3I	0.57**	0.51*	NC	0.50*	NC	−0.71**	−0.66**	NC
H5I	0.51*	0.56**	NC	0.56**	NC	NC	−0.58**	NC
D2I	0.68**	NC	NC	0.53*	NC	−0.50*	NC	NC
D3I	0.80**	0.58**	0.56*	0.49*	0.50*	−0.63**	−0.55*	NC
D5I	0.72**	0.64**	0.47*	NC	0.57**	NC	NC	NC

Bio biomass, *HI* harvest index, *SM2* spikes per square meter, *TKW* thousand kernel weight, KNO kernels per square meter, *MD* maturity days, *HD* heading days, *PH* Plant height. *2I* two irrigations, *3I* three irrigations, *5I* five irrigations. *D* durum wheat, *S* soft wheat, *H* hard wheat, *MH* medium-hard wheat. *NC* nocorrelated

GY positively correlated with HI, Bio and TKW in the medium-strength gluten wheats under two irrigations; under three irrigations, it does not correlate positively with any variable; under five irrigations was positively correlated with Bio and KNO. GY was negatively correlated with HD and MD with two irrigations, in three irrigations with MD and with five irrigations there was not negative correlation.

In the hard gluten group with two, three and five irrigations, GY was positively correlated with Bio, HI and thousand kernel weight. This indicates that thousand kernel weight and Bio were important components of GY under water restriction and normal irrigation, whereas KNO was not an important component for this class of wheat in any of the irrigated conditions tested. GY was negatively correlated with HD and MD in restricted irrigation, but under five irrigations, the negative correlation was only with HD.

Under the schedule of two irrigations for durum wheat GY was positively correlated with Bio, thousand kernel weight and negatively with MD, in the three irrigation schedules was positively correlated with Bio, HI, SM2, thousand kernel weight and KNO and negatively with MD and HD; in the five irrigations, it was positively correlated with Bio, HI, SM2 and KNO, that is, the grain weight is relevant for the grain yield of durum wheats only under restricted irrigation, while KNO increases its relevance with the increasing in the number of irrigations. It is significant to note that, when there was a water shortage, GY in durum wheat was inversely correlated with MD, but as water availability rises, this correlation disappears and was absent in five irrigations, whereas the HI exhibited a positive correlation with grain yield as the number of irrigations rises.

Effect of irrigation schedules on the morphophysiological characteristics of commercial classes of wheat

In the 10 characters that were evaluated, highly significant differences between years and irrigation schedules were found with the analyses of variance over years (Online Resource 5 and 6). Eight characters showed highly significant differences between wheat types; plant height was significant, and Bio was not significant. The interaction years by irrigation schedules was highly significant in the 10 characters evaluated. The interaction year by wheat type was highly significant in six traits, and not significant in the HP, GY, HI and SM2 traits. The interaction schedules of irrigation by wheat classes were highly significant in the characters HP, YR, Bio, GY, KNO and HI and not significant in HD, MD, TKW and SM2. The triple interaction was highly significant in five characters HP, YR, TKW, KNO and HP and significant in GY.

The year 2016 (Online Resource 7) had the best environmental conditions (cooler average temperatures) for the development of wheat and therefore it led to the highest grain yield, surpassing the years 2017 and 2018 with 9.4 and 27.4%, respectively (Table 2). The year 2016 also registered a higher HP, HD y KNO, but it was surpassed in MD y TKW by the year 2018.

The comparison of means between irrigation schedules showed significant differences in the agronomic characters measured, grain yield and its components (Table 3). Irrigation levels affected plant height. The genotypes under the two-irrigation treatment registered plants significantly shorter (Tukey ≤ 0.05) than the plants under three and five irrigations. The reduction in the number of irrigations from five to three and two irrigations only reduced the cycle to heading in one to two days, but days to maturity was reduced in five and eleven days, respectively (Tukey ≤ 0.05). The grain yield under the five irrigations was superior by 34.3 and 71.6% compared to the three and two irrigations, respectively. The reduction in the number of irrigations affected in a greater proportion to thousand kernel weight than kernel per square meter: 22.7 and 36.4%, against 8.6 and 24.7% for the schedules of three and two irrigations, respectively. Like in the case of grain yield, the accumulation of biomass was higher (62.6 and 24.2%) when increasing the number of irrigations, but not in the case of harvest index, where two irrigations exceeded three irrigations, but both were surpassed by five irrigation schedules (Tukey ≤ 0.05).

Durum wheats exhibited the lowest plant height (Table 4) but registered a longer cycle to heading and maturity than bread wheats (Tukey ≤ 0.05). In terms of grain yield, on the other hand, soft wheats obtained the highest yield, surpassing (Tukey ≤ 0.05) the other wheat classes. When the data from normal and restricted irrigation were averaged, thousand kernel weight was the component that contributed the most to grain yield of the soft wheats, since they obtained the highest thousand kernel weight and the lowest values of kernel per square meter (Tukey ≤ 0.05). The two upper groups (soft and medium hard) had different strategies to express the highest yields, soft wheats genotypes produced fewer kernel per square meter than medium-hard wheats but were substantially higher in thousand kernel weight. The mean of the restricted and normal irrigation treatments suggests a greater association between grain yield with harvest index than with kernel per square meter and biomass.

Table 2 Effect of the sowing year on the yield, its components and physiological characteristics of wheat evaluated in two-irrigation schedules in the Bajío Experimental Station, Celaya, Guanajuato, Mexico, in the years 2016 to 2018

Year	PH	HD	MD	GY	TKW	KNO	HI	Bio	SM2
2016	90 a	90 a	133 b	6911 a	43 b	16,399 a	0.40 a	17.3 a	435 b
2017	88 b	79 c	125 c	6318 b	39 c	16,016 b	0.36 b	17.2 a	483 a
2018	87 c	83 b	134 a	5431 c	45 a	11,979 c	0.40 a	13.9 b	332 c
HSD	0.75	0.52	0.33	95.4	0.65	276	0.006	0.30	11.5

PH plant height, *HD* heading days, *MD* maturity days, *GY* grain yield, *TKW* thousand kernel weight, *KNO* kernel per square meter, *HI* harvest index, *Bio* biomass, *SM2* spikes per square meter, *HSD* Tukey's honest significant difference at 0.05; means with the same letters are not statistically different (Tukey, 0.05)

Table 3 Effect of the irrigation schedule on the yield, its components and agronomic characters of the wheat evaluated in the Bajío Experimental Station Celaya, Gto., Mexico, during the years 2016 to 2018

IS	PH	HD	MD	GY	TKW	KNO	HI	Bio	SM2
2	83 c	83 c	124.7 c	4673 c	36.5 c	13,071 c	0.38 b	12.3 c	369 c
3	90 b	84 b	130.7 b	5969 b	40.6 b	15,015 b	0.37 c	16.1 b	420 b
5	92 a	85 a	135.8 a	8018 a	49.8 a	16,308 a	0.41 a	20.0 a	461 a
HSD	0.8	0.5	0.3	97	0.6	279	0.006	0.3	11.6

IS irrigation schedules, PH plant height, *HD* heading days, *MD* maturity days, *GY* grain yield, *TKW* thousand kernel weight, *KNO* kernel per square meter, *HI* harvest index, *Bio* biomass, *SM2* spikes per square meter, *HSD* Tukey's honest significant difference at 0.05; means with the same letters are not statistically different (Tukey, 0.05)

Table 4 Yield, its components and physiological characters of wheat classes evaluated in the Bajío Experimental Field, Celaya, Guanajuato, México, in the years 2016 to 2018 under normal and restricted irrigation

WC	PH	HD	MD	GY	TKW	KNO	HI	Bio	SM2
D	87.7 b	90.3 a	132.9 a	6104 b	43 b	14,216 c	0.37 c	16.4 a	388 c
S	88.3 ab	80.7 c	129.0 c	6381 a	44 a	14,484 c	0.40 a	15.9 b	427 ab
H	88.7 a	82.8 b	129.7 b	6111 b	41 c	14,957 b	0.39 b	16.1 ab	418 b
MH	88.5 ab	82.1 b	130.0 b	6283 a	41 c	15,535 a	0.39 b	16.2 ab	433 a
HSD	0.9	0.7	0.4	121	0.82	353	0.007	0.39	14.5

WC wheat classes, *D* durum, *S* soft, *H* hard, *MH* medium hard, *PH* plant height, *HD* heading days, *MD* maturity days, *GY* grain yield, *TKW* thousand kernel weight, *KNO* kernel per square meter, *HI* harvest index, *Bio* biomass, *SM2* spikes per square meter, *HSD* Tukey's honest significant difference at 0.05; means with the same letters are not statistically different (Tukey, 0.05)

Table 5 Analysis of the interaction of irrigation schedules and types of wheat with grain yield variable

Treatment comparison	Difference in yield means (kg ha^{-1})		
	Two$^{\alpha}$	Three	Five
Between soft and medium hard	104 n.s.	283**	243**
Between soft and hard	105 n.s.	367**	472**
Between soft y durum	520**	870**	78 n.s.
Between medium hard and hard	1 n.s.	84 n.s.	229**
Between medium hard and durum	416**	588**	−243 n.s
Between hard and durum	415**	504**	−393**

$^{\alpha}$Irrigations number

Effect of irrigation schedules on grain yield of wheat classes

The analysis of the highly significant interaction between the wheat classes with irrigation schedules showed that under the two-irrigation schedule, bread wheats (soft, medium hard and hard) were superior to durum wheats and did not present significant differences between them (Table 5). Again, under the three-irrigation schedule, bread wheats were superior to durum wheats, but soft wheats were significantly superior to hard and medium-hard wheats. There were no significant differences between these two classes. In the five-irrigation schedule, durum wheats obtained their highest grain yield; however, they only significantly outperformed to hard wheats. Soft wheats registered highly significant differences with hard and medium-hard wheats.

Wheat classes were grouped into quadrants 2, 3 and 4 as shown in Fig. 2. The medium-hard and soft wheats were situated in quadrant II, which corresponded to the wheats that yielded higher than average under both irrigation schedules. As previously noted, these wheat classes respond similarly in the two-irrigation schedule, however under three-irrigation schedule soft wheats yield more (Tukey ≤ 0.05). The medium-hard wheats, located in quadrant III, generated yields that were higher than the average with just two irrigations, but less so with three. Finally, in quadrant IV corresponding to the wheats that yielded less than the average in both irrigation schedules, durum wheats were located. A linear regression was fitted with six evaluation environments; wheat types were classified by their stability performance. Therefore, the most stable and predictable wheat types were medium-hard and durum wheats based on deviations of regression.

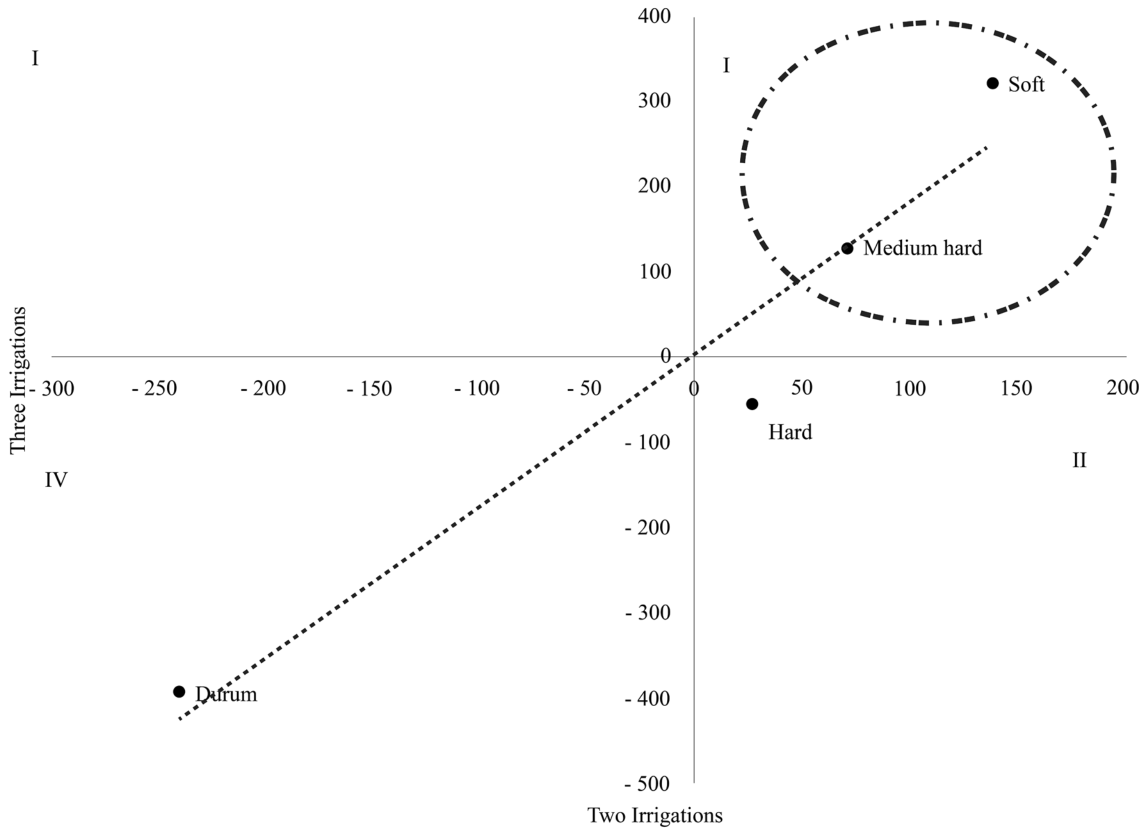

Fig. 2 Biplot of the wheat classes yield evaluated under two and three irrigations

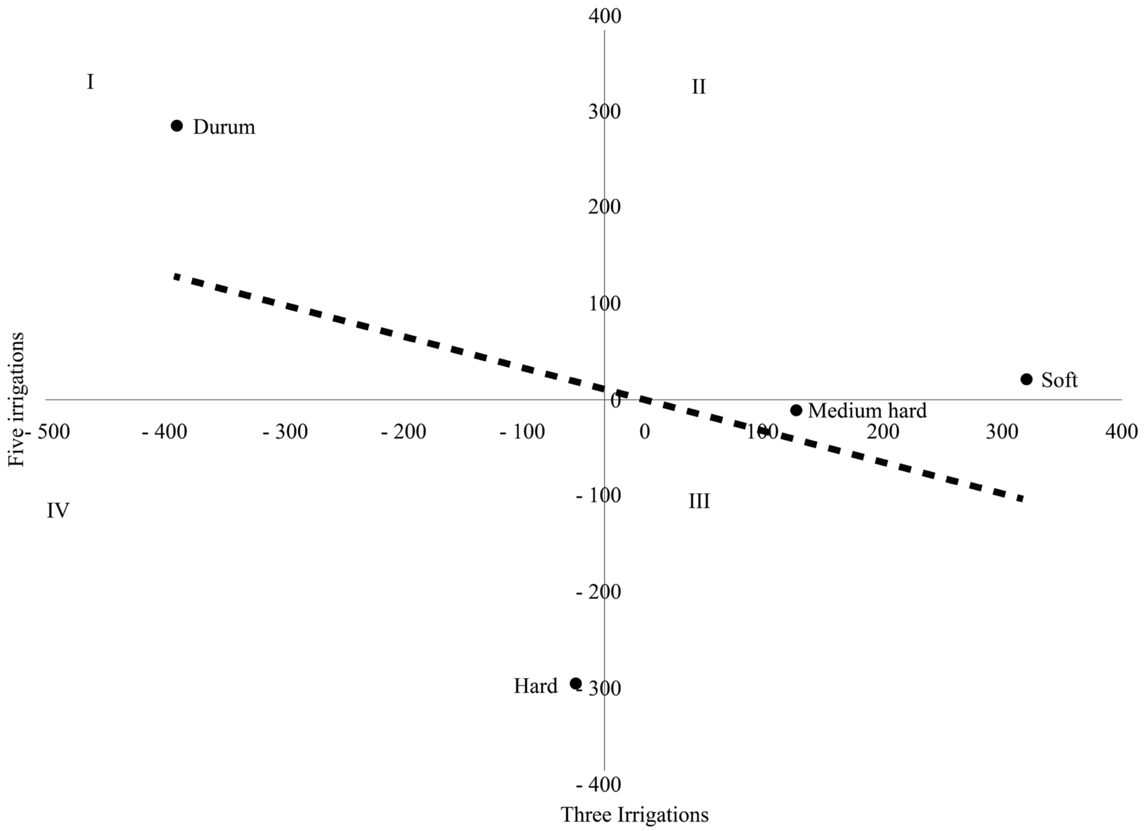

Fig. 3 Biplot of the yield of wheat classes under three and five irrigations

The graphical analysis of the interaction of the three and five irrigation schedules (Fig. 3) showed that durum wheats were located in quadrant I, they yielded more than the average in the five irrigation schedules, even under this schedule them outperformed hard wheat (Tukey ≤ 0.05). Once again, soft wheats were in quadrant II, that is, they obtained higher than average yields in both irrigation schedules. Medium-hard wheats were in quadrant III, exceeding the average yield under the three-irrigation schedule, but not under the five irrigations. Hard wheats, on the other hand, obtained lower yield than the average in both irrigation schedules. The most stable genotypes in these environments were the medium hard class and the most unstable were the hard and durum classes.

Water productivity

The irrigation sheets applied were 26 (2600 m^3), 34 (3400 m^3) and 54 (5400 m^3) cm for the schedules of two, three and five irrigations, respectively. Even though the grain yield increased as the number of irrigations increased, the average water productivity decreased by 2.3 and 17.4% for the three and five irrigation schedules, respectively (Table 6). Under restricted irrigation, bread wheats are more efficient in the use of water than durum wheats, highlighting the soft wheats, which obtained water productivity values of 1.85 kg m^{-3} in both irrigation schedules. On the other hand, with normal irrigation, durum wheats are more efficient in

Table 6 Yield and water productivity of wheat types evaluated in three irrigation schedules

Wheat types	Yield (kg ha^{-1})			Water productivity (kg m^{-3})		
	Two*	Three	Five	Two	Three	Five
Durum	4434	5577	8303	1.71	1.64	1.54
Soft	4813	6290	8040	1.85	1.85	1.49
Hard	4700	5912	7721	1.81	1.74	1.43
Medium hard	4745	6097	8008	1.82	1.79	1.48

*Irrigations number

the use of water than bread wheat, surpassing the hard wheat with 110 kg m^{-3}.

Discussion

The PCA retained 69.8% of the variation (PC1 50.9% and PC2 18.9%) of the variables studied. The biplot (Fig. 1) differentiated the three irrigation schedules and demonstrated that both bread and durum wheats respond favorably to the increase in the volume of applied water. As a result, all of the phenotypic variables (whose vectors are oriented toward a schedule of five irrigations) increased their expression as the number of irrigations increased. Grain yield genotypes in two-irrigation schedule ranged from 3974 to 5436, the three from 4453 to 6909 and the five from 6177 to 9107 kg ha^{-1}. In the two-irrigation schedule, there were 14 genotypes (12, 31, 51, 42, 25, 6, 22, 60, 54, 32, 48, 62, 52 and 41) that exceeded the performance of fourteen genotypes that did not exceed the 5 t ha^{-1} in the three irrigation schedules, of which six are soft wheats, four are medium hard and four are hard wheats (Supplementary Table 1). The four lowest-yielding genotypes with three irrigation schedules were 13, 14, 44 and 64, one of them is hard wheat, and the remaining three are durum wheats. In the three-irrigation schedule, the most outstanding genotype (6, soft wheat) obtained a yield of 6907 kg ha^{-1}, this genotype surpassed the yield of genotypes 1, 43 and 10 with 0.3, 2.8 and 11.8% evaluated with five irrigations, among the genotypes with the lowest yield in this schedule two are hard wheats (10 and 43), and one is soft wheat (1) (Supplementary Table 1).

In all four wheat classes, under both water-restricted and normal irrigation conditions, biomass is the main parameter correlating with grain yield. In general, harvest index correlates with grain yield under water stress conditions in bread wheats, but not in durum wheat. In durum wheat, spikes per square meter correlates positively with grain yield in the three and five irrigation schedules and with the five irrigations in soft wheats but has no correlation with the medium-hard and hard gluten wheats. Under the two-irrigation conditions, thousand kernel weight is positively correlated with grain yield in durum and bread wheat of medium hard and hard gluten, but not with soft wheats. Kernel per square meter correlated with yield in soft wheats under restricted and normal irrigation as well as with durum wheats under three and five irrigations. However, there was no correlation with hard gluten bread wheats.

These results indicate that with normal irrigation and even with three irrigations, the association between yield and kernel per square meter is greater than with thousand kernel weight, but this does not occur when wheat is subjected to severe water stress (two-irrigation schedule). On the other hand, maturity days and heading days are negatively correlated with grain yield in the four wheat classes under stress conditions, meaning that early materials yield more under this moisture condition. Wheat (*Triticum* spp.) grain yield is determined by the weight and number of grains per unit area, of which, this last component is the one that presents the highest correlation with grain yield (Abbate 1998). Likewise, recent studies (Bastos et al. 2020) showed that kernel per square meter explains a greater variation in yield than grain weight (37 vs. 23%).

The ANOVA revealed that the years factor captured most of the variation in the variables HD, YR, KNO, HI and SM2, while irrigation schedules explained in greater proportion the variables HP, MD, Bio, GY and TKW. Highly significant differences were observed among wheat classes for evaluated traits, due to genetic differences among the evaluated genotypes (varieties and experimental lines) and effectiveness of traditional wheat breeding (Buenrostro et al. 2019). Among the interactions, the most important for its effect on variability was years by irrigation schedules for all the characters evaluated. The interaction years by wheat classes had high effects on the characters HD, MD, YR, Bio, TKW, KNO and SM2. In contrast, HP, GY and HI seem to be more affected by the interaction IS*WC. Of the total variance of the yield, the years contributed with 14.8%, the irrigation schedules with 76.0% and the wheat classes with 0.68%, of the interactions the one that contributed in the highest proportion was Years * IS with 7.5%, while the variation explained by the three first degree interactions and the triple interaction was 7.9%. Gauch and Zobel (1996) pointed out that in a multi-environmental test, the environment typically captures 80% of the variation for yield, while the genotypes and genotype-environment interaction contribute around 10% each. However, in this study, the contrast of the irrigation environments minimized the contribution of the wheat classes to the variation of the study.

The analysis of the main factors showed that the year with the best environmental conditions from sowing to heading was 2016, which allowed for the development of a cycle that was 10 and 7 days longer than in 2017 and 2018; in addition, the plant height was also higher (Tukey ≤ 0.05). The environmental conditions developed during this stage in 2016 produced a higher yield 32.1% and 34.3% higher than 2017 and 2018, respectively. In addition, the year 2016 exceeded the year 2018 (the one with the lowest performance) with 24.5%, and 36.9% more biomass and kernel per square meter, respectively. However, thousand kernel weight was more associated with the year with the lowest yield, perhaps due to a longer duration of the grain filling stage of 2018, 16.3% greater than 2016. There is evidence that lengthening the reproductive period (in this study, a longer cycle from planting to heading) may increase the number of spikelets and flowers per spike. By extending this phase, a greater amount of biomass will be obtained during the growth of the ears, which should result in an increase in the number of grains per square meter and consequently increase the grain yield (González et al. 2003; Isidro et al. 2011).

The factor that affected the yield, its components and the measured phenological and physiological characters to a greater degree was the irrigation schedules (it captured 76% of the variation). The traits most affected by the reduction from five to three and two irrigations were GY, Bio, TKW, KNO and SM2 with reductions of 71.6% and 34.6%, 62.6% and 24.2%, 36.4% and 22.7%, 24.8% and 16.4% and 24.9% and 9.8%, respectively. On the other hand, the characters affected to a lesser degree by reducing the number of irrigations were HI, HP, MD and HD with reductions from 2.4 to 10.8% with two irrigations and from 1.2 to 10.8% with three irrigation schedules. The increases in yield due to the application of a greater number of irrigations were due to a greater production of biomass that determined a greater production of spikes per square meter, kernel per square meter and thousand kernel weight. Soil moisture stress at any stage of growth decreased grain yield. When wheat was stressed at jointing, reduced grain yield resulted from fewer heads per unit area and fewer seeds per head. However, when moisture stress occurred at the flowering and dough stages, lower grain yields were caused by lighter seed weight. Stress at the flowering and dough stages also hastened maturity (Day and Intalap 1970). The results found in this study when increasing the number of irrigations were higher than those reported by Buenrostro et al. (2019) who obtained increases when going from three to four irrigations of 14.04, 15.8, 19.3 and 14.4% in grain yield, kernel per square meter, grains per spike and biomass, respectively. In addition, in this study established in the region of the Bajío, Mexico, the yields were lower in 21.2 and 3.4% for the three and four irrigation schedules. For their part, Martínez et al. (2020) evaluated four irrigation schedules 2, 3, 4 and 5 irrigations; in this study, the yields for the schedules of two, three and five irrigations were 1.8, 4.5 and 6.8 t ha^{-1}, respectively, the losses to going from five to three and two irrigations were 76.8 and 37.6%, very similar to those obtained in this study.

The analysis through years and irrigation schedules showed that soft wheats and medium hard yield more than durum ones, despite being earlier (Tukey $\leq$ 0.05). The strategy to produce higher yields was different for both wheat classes, the weight of the grain was different for soft wheats and the grains per square meter for the medium-hard wheats. Up to now, genetic gains in grain yield potential of wheat have mainly been achieved by increasing grain number per unit area (Fischer 2008). A greater association has been observed between grain yield with kernel per square meter than with thousand kernel weight, there is even a negative association between these two components (Martínez et al. 2020). However, this negative relationship is possible through genetic improvement to produce high-yield varieties with high number of grains and minimal reductions in grain weight (Griffiths et al. 2015).

Analysis of the interactions with the grain yield variable revealed that when irrigation was restricted, (2 and 3 irrigations), bread wheats are superior to durum wheats, regardless of the type of gluten. There were no differences between the bread wheats in the two-irrigation schedule, while soft wheat varieties excelled in the three-irrigation schedule (Tukey $\leq$ 0.05) to both medium-hard and hard wheats (Table 5 and Fig. 2). With five irrigations instead, the durum wheats obtained the highest yield (8303 kg ha^{-1}), however, they only significantly surpassed (Tukey $\leq$ 0.05) to hard wheats (7721 kg ha^{-1}). It is frequently assumed that durum wheat is more tolerant to stress than bread wheat. Unfortunately, few research papers compare the performance of both species side-by-side under a wide range of environments in field conditions. Differences in yield were also related to differences in water and nitrogen use efficiencies: under low-yielding conditions, bread wheat was consistently more efficient than durum wheats, which coincides with the results of this study and under high-yielding conditions durum wheats was more efficient (Marti and Slafer 2014). On the other hand, Valenzuela et al. (2018) in a study carried out in Mexico found in the general analysis across localities that durum wheats yielded more ($P \leq 0.05$) than bread wheats under normal irrigation (5.43 vs 5.21 t ha $^{-1}$), but they have the same yield in restricted irrigation (4.39 vs 4.30 t ha^{-1}).

Wheats in general show higher efficiency (considered as water productivity) under restricted irrigation than under normal irrigation. The lowest losses in water productivity when going from two to five irrigations were observed in durum wheats (0.17 kg m^{-3}) and the highest in hard wheats (0.38 kg m^{-3}). Within the bread wheats, soft wheats obtained the highest water productivity values in the three irrigation schedules, however, those that obtained the lowest losses in water productivity when going from two to five irrigations were medium-hard wheats (0.34 kg m^{-3}). With two and three irrigations, the results obtained in water productivity were higher than those observed in other studies and with five irrigations they are within the range reported by other authors. The range of crop water productivity (CWP) is very large 0.50–1.68 kg m^{-3} for wheat, 0.65–3.09 kg m^{-3} for corn and 0.33–1.48 kg/m^3 for rice (Foley et al. 2020), and thus offers tremendous opportunities for maintaining or increasing agricultural production with 20–40% less water resources (Zwart and Bastiaanssen 2004). Plants are more efficient with water when they are stressed. It is therefore tentatively concluded that to achieve optimum CWP in water short regions, it is wise to irrigate wheat and maize with less water as recommended for attaining maximized yields (Zwart and Bastiaanssen 2004).

Conclusions

T. aestivum genotypes respond differently to water restriction than *T. durum* genotypes, with soft gluten genotypes being the most yielding whose outstanding characteristics are higher HI, TKW and WP. Under optimal irrigation conditions, *T. durum* presented the highest yielding genotypes, which was mainly due to its increase in Bio, HI, TKW, KNO, and the highest WP among the four wheat classes.

The variability of genotypes included in the study allowed the identification of genotypes that with two irrigations reached grain yields greater than 5 t ha^{-1}. However, grain yield was reduced by 71.6% and 34.6%, when applying only two and three irrigations, mainly due to a reduction in grain weight. Both bread and durum wheats show higher efficiency under restricted irrigation than under normal irrigation. Bread wheats have higher water productivity in restricted irrigation, but in normal irrigation, durum wheats have higher water productivity values.

The results of this work allow recommending the cultivation of the different classes of wheat depending on the availability of water, which allows maximizing yields in any water regime.

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Author contributions ESM designed the field experiment. ESM and LLR set up the field experiment. LLR, ESM, JFBR, LAMA and SSGF contributed to the data collection of the experiments. ESM, VMT and LLLR drafted the document. AJGV performed the statistical analyses. JHE and ESM edited the document. All authors have edited, read and approved the final version of manuscript.

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Declarations

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