Yield, technological quality and water footprints of wheat under Mediterranean climate conditions: A field experiment to evaluate the effects of irrigation and nitrogen fertilization strategies

Alexandra Tomaz[a,b,*5] José Ferro Palma [a], Tiago Ramos [a], Maria Natividade Costa [a], Elizabete Rosa[a], Marta Santos [c], Luís Boteta[c], José Dores [a], Manuel Patanita[a,b]

[a] Escola Superior Agraria, Instituto Politécnico de Beja, R. Pedro Soares S/N, 7800-295 Beja, Portugal
[b] GeoBioTec, Nova School of Science and Technology, Campus da Caparica, 2829-516 Caparica, Portugal
[c] Centro Operativo e de Tecnologia de Regadio, Quinta da Saúde, Apartado 354, 7800-999 Beja, Portugal

ARTICLE I NFO
ABSTRACT
Handling Editor: Dr Z Xiying

Keywords:
Wheat
Water footprint
Irrigation water productivity
Nitrogen fertilization
Factor analysis
Multivariate linear regression

The evaluation of the role of different agronomic strategies in achieving sustainable wheat yields under variable Mediterranean climate conditions may involve the use of resource-use indicators that combine productivity and environmental impact. A two-seasons field experiment was conducted in South Portugal to study the effect of water regimes and nitrogen fertilization on wheat yield, grain quality and water use evaluated with water productivity and water footprint indicators. The water regime treatments were full irrigation, supplemental irrigation, and rainfed. Nitrogen fertilizer treatments, including conventional and enhanced efficiency fertilizers (EEF) were distinguished by N splitting and timing over the crop cycle. Contrasting meteorological variables in the two years caused distinct wheat productive responses. Although leading to lower grain yields, supplemental irrigation guaranteed a water productivity similar to full irrigation. The use of EEFs in which 50% of the total nitrogen was applied at the booting phase had a positive significant effect on grain protein content and on dough rheologic properties, indicating that late nitrogen applications benefit the technological quality of wheat. The average total water footprints estimated for the two seasons showed no relevant differences but the partition of the green, blue and grey components in irrigated wheat varied, with an increased importance of blue water consumptive use in the second year of the experiment. In fact, the ratio blue water footprint/green water footprint increased from 0.40 to 2.00 due to higher irrigation requirements. High grey water footprint in rainfed wheat was mostly influenced by lower yields in 2018-2019, and by an advantageous rainfall distribution during the 2017-2018 season. No significant reduction in grey water footprint was observed when using EEFs. A multivariate statistical approach through factor analysis (FA) and multivariate linear regression (MLR) was used to examine the data structure and correlation. FA resulted in three-factor models of yield and water use, yield components and wheat quality, in the first season. In the second, drier, season, variables most related with irrigation water use were clustered in one detached factor. The stepwise MLR pointed to a good prediction capability of water footprints from NDVI measured with proximal sensors at booting, anthesis, maturation and/ or tillering.

1. Introduction

Inter-annual and seasonal rainfall patterns variability and frequent occurrence of heat stress periods are features of the Mediterranean climate and often promote situations of water deficit in the most water sensitive stages of wheat (*Triticum aestivum* L.) growth cycle leading to significant reductions in productivity (Makinen et al., 2018). This unfavorable distribution tends to accentuate with climate change (Trnka et al., 2011), contributing to the unpredictability of productive responses, to the instability of a sector already weakened by income gaps and fluctuations and, ultimately, to the increase in the intensity of water and fertilizer use in order to achieve higher yields (Castellanos et al., 2016). Portugal is an importer of wheat. In 2018, the Portuguese wheat production was only 0.05% of the EU-28 total harvested production (EUROSTAT, 2020). This trade deficit is difficult to overcome given the less than optimal market conditions and the increasing attractiveness to farmers of other crops that are more productive under the Mediterra- nean climate that prevails in mainland Portugal, especially in the Southern regions. The need to reverse the downward trend in cereal production that has occurred in recent decades, led the Portuguese Government to establish a national strategy to promote the development of the Portuguese cereal production (MAFDR, 2018). This policy iden- tifies, among other priority measures, the need to improve the resource-efficiency, through the adoption of more efficient irrigation and fertilization management practices.

Corresponding author at: Escola Superior Agraéria, Instituto Politéecnico de Beja, R. Pedro Soares S/N, 7800-295 Beja, Portugal. *E-mail address:* atomaz@ipbeja.pt (A. Tomaz).

Wheat sensitivity to water deficits and high temperatures varies through its growth cycle. Wheat response to water stress is more con- spicuous from stem-elongation to grain-filling (Zhang and Oweis, 1999); During stem elongation and booting, it can affect the potential grain number per unit area (Alghory and Yazar, 2018); at the reproductive stages of anthesis and grain filling, the photosynthesis rate can be significantly affected, therefore reducing the amount of assimilates available to the grains (Porter and Gawith, 1999; Barnabás et al., 2008; Prasad and Maduraimuthu, 2014). Water stress combined with nitrogen (N) deficiency can lead to the reduction in the number of grains per unit area, grain yield and N use efficiency (NUE), particularly if they occur around anthesis (Plaut et al., 2004; Albrizio et al., 2010; Liu et al., 2018). Furthermore, N content is widely considered as the main factor pro- moting protein storage and wheat grain quality (Blandino et al., 2015; Yu et al., 2018). In order to face these constraints, adapted agronomic practices have the potential to stabilize and/or increase wheat yields in Mediterranean areas, ensuring higher Water Use Efficiency (WUE), NUE, and grain quality (Ali Fallahi et al., 2008; Chen et al., 2008; Tomaz et al., 2017a; Ul-Allah et al., 2018; Oliveira et al., 2019; Patanita et al., 2019) This practices include supplemental irrigation (Oweis, 1997; Zhang et al., 1999; Zeleke and Nendel, 2016; Liu et al., 2018) combined with alternative N fertilization techniques, such as time-adjusted application or prolonged bioavailability through Enhanced Efficiency Fertilizers (EEFs). Nitrogen EEFs can be classified as: slow-release fer- tilizers, obtained as condensation products of urea and urea aldehydes; controlled-release fertilizers, that contain a conventional fertilizer whose nutrient release in the soil is regulated by sulfur or/and polymer coatings; stabilized fertilizers, which are modified during the production process with a nitrification inhibitor or an urease inhibitor (Trenkel, 1997).

The use of efficiency and/or productivity indicators of water and nutrients used by crops under different water regimes has been the subject of several studies (Howell, 2001; Katerji et al., 2008; Zwart et al., 2010; Pereira et al., 2012; Zhang et al., 2017; Tomaz et al., 2018). Water Productivity values, expressed as the ratio between the product obtained (grain yield) and the input use (crop evapotranspiration, in the case of Crop Water Productivity (WP_C), and volume of irrigation water, in the case of Irrigation Water Productivity (WP_I)), are indicators to evaluate the impact of different options on resource productivity and on farm results (Levidow et al., 2014; Fernaández et al., 2020).

Moreover, the assessment of the impact of Human consumption on freshwater resources incorporated in industrial and/or agricultural processes, called "Virtual water", has been carried out using the Water Footprint (WF) concept (Hoekstra, 2003). The water footprint is a tool to calculate the water virtually embedded in commodities, representative of the volume of water needed to produce goods and services (Hoekstra et al., 2011). At the crop level, it can be a quantifiable indicator for measuring the water applied by irrigation, the water stored in the soil, fractions consumed by the crop, and the potentially contaminated water as a result of the adopted agronomical practices (Hoekstra et al., 2011; Mekonnen and Hoekstra, 2011). Therefore, three components are considered in the water footprint: (i) the green water footprint (WF_{Green}) representing the volume of water resulting from precipitation that does not runoff or recharge aquifers, being consumed by the crop during its growth; (ii) the blue water footprint (WF_{Blue}) representing the consumptive volume of surface and groundwater that is used in irriga- tion; (iii) the grey water footprint (WF_{Grey}) representing the volume of water that is necessary to assimilate the polluting load which, in the case of agriculture, is an indicator of the degree of water contamination associated with the leaching of chemicals used in the productive process (Hoekstra et al., 2011). The consumptive WF per unit of product (green and blue components) can be interpreted as the inverse of water pro- ductivity and as such is relevant in discussions about resource efficiency (Hoekstra, 2017). This standpoint is a basis to explore the water foot- prints of crop production based, not only in large spatial and temporal scales, as it has been largely conducted (Zeng et al., 2012; Ababaei and Etedali, 2014; Ercin and Hoekstra, 2016; Liu et al., 2017; Garofalo et al., 2019; Elbeltagi et al., 2020), but also at the field level (Nogueira et al., 2012; Qin et al., 2016; Xinchun et al., 2018). Some constraints in WF accounting related to data quality and accuracy and/or feasibility for comparisons between regions with different climates have been re- ported, which constitutes an impairment for its use as a reliable indi- cator of agricultural water use (Huang et al., 2019; Laan et al., 2019; Liu et al., 2017). Expanding water footprint estimates from on-field mea- surements in different agri-environmental conditions can improve its benchmarking, making this integrated indicator of crop water use a valuable tool for improving water productivity and for resources man- agement (Hoekstra, 2017; Elbeltagi et al., 2020; Pardo et al., 2020), as well as for delineating strategic policies regarding wheat production in water-scarce regions as is the case of Southern Portugal.

Taking the above into consideration, the object of this study was to contribute to the adoption of more efficient irrigation and fertilization practices and to the economic and environmental sustainability of wheat production under Mediterranean climatic conditions. For this purpose we aimed to: (i) evaluate the effects of different irrigation and nitrogen fertilization strategies on wheat yield, water productivity and techno- logical quality, (ii) apply the water footprint indicators to a field experiment, widening the base of results from the application of this methodology to field studies (iii) examine data structure and relation- ships between wheat grain yield, water use indicators, grain techno- logical traits, and NDVI measurements with proximal sensors through multivariate statistical techniques.

2. Materials and methods

2.1. Study design and site description

The study took place during two seasons, 2017-2018 and 2018-2019, in Beja, South Portugal. It consisted of two trials with the wheat cultivar 'Antequera', classified as 'Improver' by the milling in- dustry (ANPOC, 2017), in a split-plot design with the main plots being the water regime treatments and the subplots the N fertilization treat- ments, with four replications. Water regime treatments where: Rainfed (R0); Full irrigation with 100% of crop evapotranspiration (ETc) throughout the cycle (R1); Supplemental irrigation with 100% of ETc only at four stages (R2). The four stages considered were: Beginning of stem extension; Booting; Heading or inflorescence emergence; Grain filling. The fertilization treatments, with a total rate of 180 kg N ha $^{-1}$ were distinguished by type of fertilizer used at sowing, splitting (% of N total) and timing (phenological stage) treatments. The nitrogen fertil- izers included conventional and enhanced efficiency fertilizers (EEF), namely: N1 and N2 - Conventional fertilizer; N3 and N4 - Stabilized fertilizer (with nitrification inhibitor); N5 and N6 - Controlled-release fertilizer (polymer coating); N7 and N8 - Stabilized fertilizer (with urease inhibitor); each pair distinguished by N splitting and timing over the crop cycle (Table 1). In the N fertilization treatments numbered with even numbers, topdressing N fertilization was applied with urea and ammonium nitrate, respectively, at tillering, and at stem extension stage plus booting stage to ensure the 180 Kg ha $^{-1}$ rate of N fertilization. To ensure equal phosphorus (P) and potassium (K) rates in all treatments binary P-K fertilizer was applied at sowing.

Table 1

Nitrogen fertilizer type and name, splitting (% of N total) and timing (pheno- logical stage) treatments through the wheat cycle.

Treatment (N type/ splitting/ timing)	Type of fertilizer at sowing	% of N total applied at phenological stages			
		Sowing	Tillering	Stem extension	Booting
N1	Conventional	25	50		25
N2		25	25	25	25
N3	Stabilized, with	100			
N4	nitrification inhibitor	50			50
N5	Controlled	100			
N6	release, with polymer coating	50			50
N7	Stabilized, with	100			
N8	urease inhibitor	50			50
Top dressing N fertilizer	-	-	Urea	Ammonium nitrate	

Sowing was carried out on 22 December 2017 and 30 December 2018, in the first and second seasons, respectively. In 2017-2018, har- vest took place on 18 July in the rainfed treatment, since plants were more advanced in maturation, and on 25 July in the irrigated treat- ments. In 2018-2019, harvest of all treatments occurred on 26 June.

According to Koppen classification, the climate in the study site is temperate with hot and dry summer or Mediterranean. The long-term means for the 1981-2010 period of annual precipitation and average mean monthly temperature are, respectively, 558 mm and 16.9 °C (IPMA, 2020). Meteorological data were recorded in an automatic weather station (Fig. 1). During the 2017-2018 and 2018-2019 seasons, average mean daily temperatures were 14.3 °C and 14.6 °C, and total precipitations were 479 mm and 154 mm, respectively. Soils in the study site are predominantly Pellic Vertisols associated with Calcic Cambisols (SROA, 1970; IUSS Working Group WRB, 2014). The 0-30 cm layer of the soil profile was sampled prior to the sowing of the first trial using an open end soil probe and main physical-chemical properties were analyzed: field texture; total organic matter content (Walkley-Black method; Walkley and Black, 1934); pH (H_2O;

potentiometer); extract- able phosphorus and potassium contents (Egner-Riehm method; Egner et al., 1960). Soils presented fine texture, very low organic matter content (0.5-0.7%), slightly alkaline reaction (7.6-8.0), low to medium extractable phosphorus (27-77 mg P_2O_5 kg $_-{}^{1}$), and medium to high extractable potassium (64-189 mg K_2O kg $_-{}^{1}$).

Irrigation was performed by a center-pivot system with spray-type sprinklers mounted on drop tubes. The irrigation dose and schedule were evaluated using the Irrigation Management Model for the Alentejo region (MOGRA - *Modelo de Gestao da Rega para o Alentejo* (Tomaz et al., 2017b; COTR, 2020)), that performs a daily soil water balance, based on the FAO methodology for computing crop water requirements (Allen et al., 1998), using meteorological data, crop specific information, and soil water extraction evolution. For this purpose, soil water content (SWC) was registered with non-calibrated capacitance probes (EP100G-08, EnviroPro®, Entelechy Pty Ltd.) with 86.5 cm total depth and eight sensors with a 10 cm step. Data of total precipitation, total crop evapotranspiration, and irrigation volumes during the two growing seasons are presented in Table 2.

2.2. Phenology, yield and grain technological quality evaluation

Main phenological stages in each irrigation treatment were

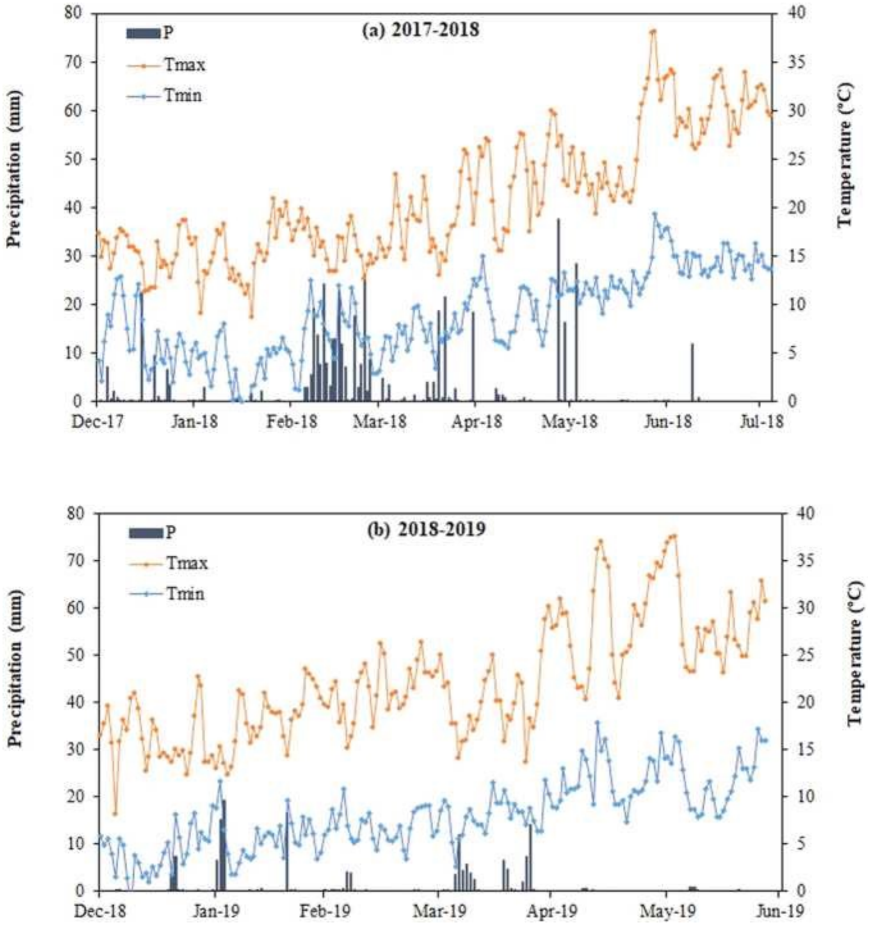

Fig. 1. Daily precipitation (P), maximum temperature (Tmax) and minimum temperature (Tmin) during (a) 2017-2018 and (b) 2018-2019.

Table 2
Main data of cumulative precipitation (P), crop evapotranspiration (ETc) and irrigation amount (I), during the 2017-2018 and 2018-2019 seasons.

Season	Irrigation treatment	P (mm)	ETc (mm)	I (mm)
2017-2018	R1	479	503	144
	R2		502	135
	R0		465	0
2018-2019	R1	154	485	253
	R2		484	230
	R0		433	0

registered and Normalized Difference Vegetation Index (NDVI; (Rouse et al., 1974)) was measured at tillering, stem extension, booting, head- ing, anthesis, and maturation, using a GreenSeeker hand-held sensor. Yield and yield components evaluated were the following: grain yield (Y; kg ha ^{1}), adjusted to 12% moisture and extrapolated to the hectare; 1000-grain weight (1000 GW; g), obtained by electronic counting on a seed counter (Pfeuer GmbH), according to the Portuguese norm NP517/1986; number of grains (NG; m ^{2}), determined from grain yield and 1000-grain weight (g).

The following indicators of yield-water use were determined (Zwart and Bastiaanssen, 2004; Pereira et al., 2012; Fernéandez et al., 2020):

(i) Crop Water Productivity (*WPc*; kg m ^{3}), computed using:

WP
ETa
(1)

Where *ETa* is the seasonal actual crop evapotranspiration expressed in m^3 ha ^{1}.

(ii) Irrigation Water Productivity (WP_I; kg m 3) using:

$$WP_I = \frac{Y}{I} \quad (2)$$

Where I is the seasonal irrigation expressed in m^3 ha 1.

The grain quality parameters studied were: hectoliter weight (or test weight) (HW; kg hL 1), using a grain analysis meter; grain protein content (GPC; %), according to the Portuguese norm NP988/2000, analyzed by NIT-Near-Infrared Transmittance Spectrophotometry (Infratec™ 1241). The alveographic parameters of the flour (P, tenacity; L, extensibility; W, dough strength) were evaluated using a Chopin alveograph (AlveoLab Graph) following the norm ISO 27971:2008.

2.3. Water footprints

The total water footprint (WF; m^3 t 1) of a given product or pro- duction system corresponds to the sum:

$$WF = WF_{Green} + WF_{Blue} + WF_{Grey} \quad (3)$$

Each of the components was calculated as follows:

(i) Green Water Footprint (WF_{Green}; m^3 t 1):

$$WF_{Green} = \frac{ET_{Green}}{Y} \quad (4)$$

where ET_{Green} is the green component in crop water use (m^3 ha 1), calculated as the minimum between crop evapotranspi- ration (ETa) and effective precipitation (P_{eff}) (Hoekstra et al., 2011), and Y is the crop yield expressed in tons per hectare (t ha 1).

(ii) Blue Water Footprint (WF_{Blue} m^3 t 1):

$$WF_{Blue} = \frac{ET_{Blue}}{Y} \quad (5)$$

where ET_{Blue} is the amount of irrigation water that is available for plant uptake (m3 ha 1), defined by Aldaya et al. (2010) as the minimum of the irrigation requirement (IR) and the effective irrigation (Ieff). If Peff is equal or higher than the crop water re- quirements (CWR), IR is 0, otherwise it is equal to the difference between CWR and Peff.

(iii) Grey Water Footprint (WFGrey; m3 t 1):

Appl-a

WFGrey = ‘"“y"1000 (6)

Where Appl is the chemical application rate, in this case the N applica- tion rate, a is the leaching-runoff fraction, i.e., the fraction of applied N that reaches the freshwater bodies, cmax is the maximum acceptable concentration of the contaminant in the aquatic environment (kg m 3) and cnat is the natural concentration of N in the aquatic environment (kg m 3). Although it may be expected that reduced N leaching is a feature of EEFs and/or rainfed cropping systems, in the absence of data collected in situ or consistent information with respect to diffuse sources of water pollution in Portuguese agricultural systems, we used a value of a = 10% for nitrogen fertilizers (Hoekstra et al., 2011; Franke et al., 2013). In the literature we can find different values of cmax and cnat leading to dis- parities in the WFGrey assessments that could prevent this indicator to provide a consistent value for water quality and being a tool for sound policy supporting in the water sector (Mekonnen and Hoekstra, 2015; Liu et al., 2017). We followed the recommendation to use local infor- mation whenever available (Hoekstra et al., 2011) and, for the ambient water quality standard, cmax, we used 50 mg N-NO3 L \ the maximum allowable value concerning the protection of waters against pollution caused by nitrates from agricultural sources according to European (EEC, 1991) and Portuguese legislation (Decree-Law 236/98 On water quality assessment, 1998). In the case of cnat for N, many previous studies assumed the value 0 due to lack of data but this assumption leads to an underestimation of WFGrey (Liu et al., 2017) which we prevented by using the value 0.1 mg N-NO3 L 1 from Franke et al. (2013).

2.4. Statistical analyses

For the statistical analyses of data (Statistica 7; StatSoft, Inc.), two- way Analyses of Variance (ANOVA) were performed for the effects of irrigation and nitrogen strategies. The ANOVA were conducted sepa- rately for each growing season. Differences between means were compared using Tukey′s test ($p < 0.05$). Factor Analyses (FA) for each season were conducted to explore the data structure, to describe how the original p variables depend on a small number k of latent variables or factors ($k<p$), thus reducing correlated observed variables into a small number of independent variables (Hardle and Simar, 2015). The aim was to examine, for each season, latent (unobserved) common charac- teristics of the studied variables, related with wheat grain yield, tech- nological quality and/or water use. The factors were extracted using the Principal Components Analysis (PCA) method and the matrix of factor loadings was submitted to varimax rotation to yield a factor structure simpler to interpret (Jagadamma et al., 2008). Factors were retained when presenting eigenvalues > 1, a contribution for the proportion of variance > 10% and at least two observed variables contribution with absolute factor loadings > 0.40. Variables with large in absolute value factor loadings are more likely to represent a common factor. Although there are no established or clear rules that help decide what is a ‘‘large″ factor loading (Mallarino et al., 1999; Jagadamma et al., 2008), vari- ables were considered highly correlated whenever factor loadings were > 0.50 and moderately correlated when loadings were > 0.40 (Lee et al., 2005; Jagadamma et al., 2008). If the variables are properly selected, by studying the result of a factor analysis it is possible to make a fairly justified choice of the independent variables which can be included in a subsequent regression analysis (Ferrari et al., 1957). For each season, NDVI measurements and water footprints values were selected to perform stepwise multiple linear regressions (MLR) in order to examine the relationship between the NDVI measurements as inde- pendent variables and green, blue or grey water footprint indicators as response (dependent) variables. For these analyses, the standard selec- tion procedure to identify a single subset of independent variables was used by adding or deleting a variable at each step according to a given criterion stated on terms of the F statistic, in this case, F-to-enter = 1 and F-to remove = 0 (Neter et al., 1983). In a MLR model, Multiple R^2 measures the proportionate reduction of total variation in the response variable associated with the use of the set of selected independent var- iables. Higher R^2 values mean a good model fit for the data. Since R^2 often can be made high by including a large number of independent variables, a modified measure is also used, the Adjusted R^2, which rec- ognizes the number of independent variables in the model (Neter et al., 1983). */)* are the standardized regression coefficients of the independent variables, used to facilitate comparisons when different units are involved (Neter et al., 1983; Monaco and Sali, 2018).

3. Results and discussion

3.1. Phenology and biomass monitoring

The temporal variation of the maximum and minimum temperatures, as well as the total amount of rainfall over the wheat growth cycles under study was quite different (Fig. 1), promoting different water re- quirements (Table 2). In 2017-2018 the distribution of precipitation, particularly in the spring months (March to May), was more favorable as it coincided with some of the critical stages of wheat regarding water requirements, like booting and flowering.

The contrasting meteorological variables in the two years influenced the crop phenological cycle (Fig. 2). Higher temperatures in February 2019, promoted an anticipation of tillering and booting (Fig. 2b). Overall, the 2018-2019 crop cycle was approximately one month shorter than in 2017-2018, but reduction was higher from sowing to anthesis (—17 days) than in the remaining growing season (—12 days from anthesis to harvest). Thus, the increase in evaporative demand of the atmosphere due to higher temperatures was counterbalanced by the reductions in the length of the phenological cycle.

The NDVI, an indicator of chlorophyll concentration and canopy leaf area, was used for the dynamic monitoring of the biomass change during the two growth seasons (Duan et al., 2017) (Fig. 3). In 2017-2018, no significative differences were found in NDVI values measured in the three water regimes at any stage of the growing cycle (Fig. 3a; Table S1). The highest values were measured at the booting stage, varying from 0.823 in R1 to 0.853 in R0, and the lowest were registered at maturation,

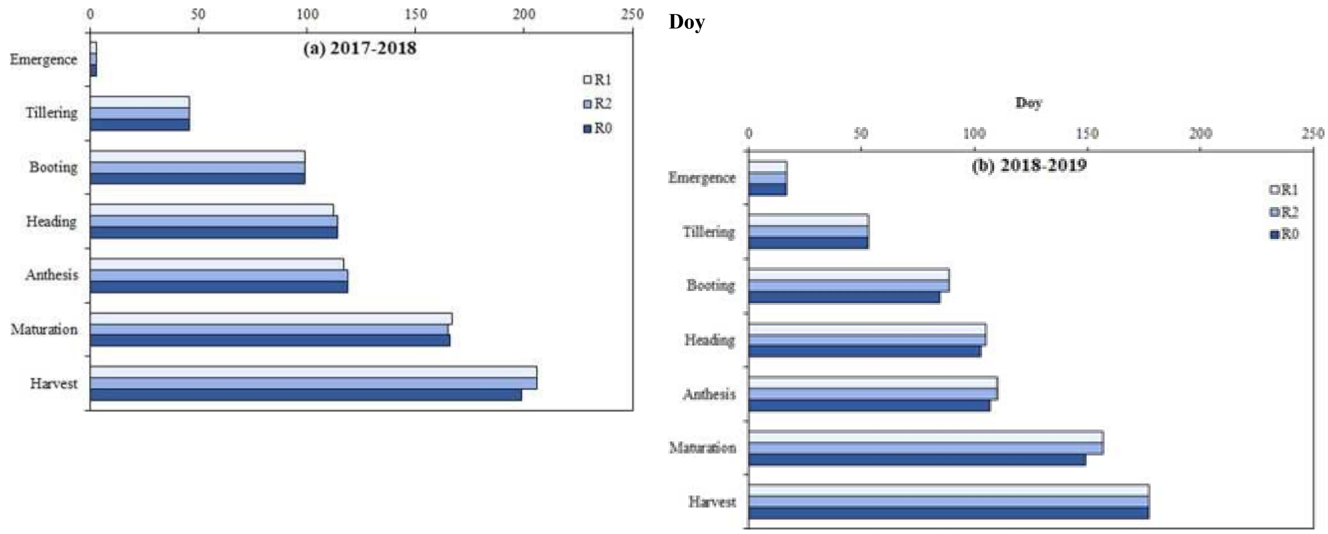

Fig. 2. Day of the year (Doy) for the beginning of wheat phenological stages in the irrigation treatments during (a) 2017-2018 and (b) 2018-2019 seasons. R0 - Rainfed; R1 - Full irrigation; R2 - Supplemental irrigation at the stages beginning of stem extension, booting, heading, and grain filling.

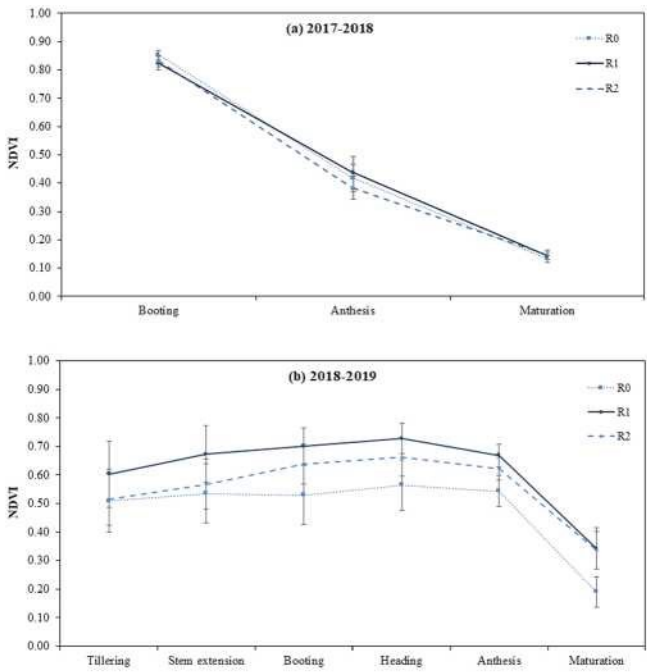

Fig. 3. Normalized Difference Vegetation Index (NDVI) measurements at different growth stages during **(a)** 2017-2018 and **(b)** 2018-2019 seasons. Dots represent the average of measurements performed in the three irrigation treatments and whiskers represent the standard deviation (n = 32). R0 - Rainfed; R1 - Full irrigation; R2 - Supplemental irrigation at the stages beginning of stem extension, booting, heading, and grain filling.

averaging 0.141. In the case of N fertilization, NDVI values measured at booting were significatively higher in the N3 and N5 treatments (0.846), denoting a positive effect in the biomass of plants when stabilized or controlled-release fertilizers are applied (Table S1). At the maturation phase, NDVI was higher in the N4 treatment (0.147), indicating higher chlorophyll content, thus, some delay in maturation, probably due to the late application of N at the booting stage. In 2018-2019, NDVI values differed significantly for different water regimes in every stage, except tillering ($NDVI_{Till}$), with the highest values measured at booting ($NDVI_{Boot}$) and heading ($NDVI_{Head}$) in the full irrigation treatments (0.701 and 0.728, respectively), and in the supplemental irrigation treatments (0.638 and 0.662, respectively) (Fig. 3b; Table S1). These results were, in general, below reference values in the literature where $NDVI_{Boot}$ in irrigated wheat ranged from 0.80 to 0.88 (Aparicio et al., 2000; Clay et al., 2012), and $NDVI_{Head}$ reached 0.91 (Duan et al., 2017). The differences regarding values in the literature are even more pro- nounced in the advanced stages of the cycle since, even in irrigated plants, the $NDVI_{Mat}$ values measured (0.337 and 0.342, in R1 and R2, respectively) were considerably lower than those reported by Aparicio et al. (2000) (0.50) or Naser et al. (2020) (0.58). These values indicate the effect of the high temperatures experienced during the final growing stages, which induced a more rapid plant senescence. Nitrogen fertil- izers type, splitting and timing influenced NDVI values, except at the anthesis phase (Table S1). The highest values were registered in the treatments with EEFs totally applied at sowing, N3, N5 and N7, at the booting stage (0.689, 0.678, and 0.688, respectively) and at the heading stage (0.706, 0.689, and 0.701, respectively), pointing to a positive in- fluence of N gradual bio-availability in the development of wheat biomass.

3.2. *Grain yield and water use*

The results of grain yield and its components reflected the effect of temperatures and the quantity and distribution of rainfall recorded in each year, especially during April and early May (Table 3). Higher temperatures and lack of precipitation caused an increase in 2018-2019 irrigation requirements of approximately 1.7 times compared to the previous year. In 2017-2018, with more abundant and better distributed rainfall in periods of higher crop demand, there was a statistically sig- nificant effect of water regime both in the number of grains per m^2 (NG) and 1000-grains weight (1000 GW), showing an inverse compensation effect between these yield components that lead to no statistical differ- ences in grain yield, Y (7286 kg ha ^{1} in R1, 6932 kg ha ^{1} in R2 and 7083 kg ha ^{1} in R0). The occurrence of precipitation during the stages of heading and initial grain filling attenuated the differences between water regimes, an effect which is even more pronounced when soils present a high water storage capacity as is the case of Vertisols. In 2018-2019, a shorter cycle and a shorter time for biomass accumula- tion, resulted in lower yields in general. The average yield obtained in 2018-2019 was about 38% lower than the previous year. Although no significant differences were observed in 1000GW between water regimes, there was a significantly higher NG in the irrigated treatments (13,338 per m^2 in R1 and 12,695 per m^2 in R2) when compared to the rainfed (6480 per m^2). Also, the effect of irrigation on productivity had statistical significance, with the R1 treatment presenting the highest yield values (5570 kg ha ^{1}), followed by the R2 (4956 kg ha ^{1}) and R0 (2629 kg ha ^{1}). In a study on the interactive effects of water and nitrogen on the productive responses of durum wheat (*Triticum durum* Desf.) grown in a Mediterranean environment Albrizio et al. (2010) found similar results with the crop response being mostly influenced by nitrogen fertilization as a consequence of the occurrence of abundant rainfall during the experiment period. In 2017-2018, the N1 and N2 fertilization treatments (distinguished by different fractioning with a conventional N fertilizer) showed the highest NG (16,158 per m^2 and 16, 145 per m^2, respectively); N1 and N2 were also the nitrogen fertilizer treatments with the highest Y (respectively, 7378 kg ha ^{1} and 7337 Kg ha ^{1}), WP_C (1.62 kgm ^{3} in N1 and 1.60 kgm ^{3} in N2) and WP_i (5.28 kg m ^{3} in N1 and 5.35 kg m ^{3} in N2). This set of results indicates that gradual N release fertilizers had no distinctive effect on wheat productivity, as found by Maharjan et al. (2014) or Blandino et al. (2015). Probably because of N availability until advanced stages, the N4 treatment showed the highest 1000GW in both years (46.69g and 42.61g, in 2017-2018 and 2018-2019, respectively). In 2018-2019, the N7 treatment had the highest NG (12,065 grains per m^2), Y (4899 kg ha ^{1}) and WP_j (2.50 kg m ^{3}).

Rainfed wheat used soil stored water more efficiently (WP_C of 1.77 kg m ^{3} in 2017/2018 and 1.86 kg m ^{3} in 2018/2019). Further- more, the WP_C of the two irrigated treatments did not differ statistically in any of the agricultural years (1.4-1.5kgm“^{3}, in 2017-2018; 1.3-1.4 kg m ^{3}, in 2018-2019), indicating that the supplemental irri- gation strategy (R2) adjusted so that the water supplies coincide with the crop critical stages, although leading to lower grain yields, gua- rantees an efficiency in the use of water similar to full irrigation (R1). The agronomic practice of supplemental irrigation applied at the crop most sensitive periods to drought and heat stress is already commonly adopted in the Mediterranean area and in many world regions on low value crops aiming to minimize yield variation and maintain production to an economically acceptable level (Daccache et al., 2014). Overall, average WPc were, in any water regime for both seasons, higher than some of the reported in reference literature, namely, 0.47 kg m ^{3} (Chapagain and Hoekstra, 2004), 0.39 kg m ^{3} (Liu et al., 2007) or 0.64 kg m ^{3} to 1.82 kg m ^{3} (Zwart et al., 2010), obtained for wheat yields in Turkey and France, respectively. In fact, the average values observed in R0 approached the potential value estimated by Liu et al. (2007) for Portugal (1.85 kg m ^{3}) corresponding to a potential yield of approximately 9000 kg ha ^{1}. When analyzing the average values of WP_I, the results show that in 2017-2018, with reduced irrigation re- quirements due to a very beneficial distribution of rainfall during Spring and the subsequent attainment of high yields, wheat presented a high WP_j of 5.10 kg m ^{3}. In 2018-2019, the average values of WP_j decreased

Table 3

Effect of irrigation and nitrogen fertilization type/splitting/timing on number of grains per m^2 (NG), 1000-grains weight (1000 GW), yield (Y), crop water productivity (WPC), and Irrigation water productivity (WPI) in 2017-2018 and 2018-2019.

Source of variation	NG (m^{-2}) 2017/18	2018/19	1000 GW (g) 2017/18	2018/19	Y (kg ha^{-1}) 2017/18	2018/19	WPC (kg m^{-3}) 2017/18	2018/19	WPI (kg m^{-3}) 2017/18	2018/19
Irrigation	*	*	*	*ns*	*ns*	*	*	*	*ns*	*ns*
R1	15814 **ab**	13338 **a**	47.57 **a**	42.07	7286	5570 **a**	1.48 **b**	1.42 **b**	5.06	2.20
R2	14583 **b**	12695 **a**	46.14 **b**	39.18	6932	4956 **b**	1.42 **b**	1.34 **b**	5.14	2.16
R0	16182 **a**	6480 **b**	43.82 **c**	40.33	7083	2609 **c**	1.77 **a**	1.86 **a**		
N type/splitting/timing	*	*	*	*	*	*	*	*ns*	*	*
N1	16158 **a**	10959 **ab**	45.72 **ab**	38.95 **c**	7378 **a**	4226 **b**	1.62 **a**	1.50	5.28 **ab**	2.09 **b**
N2	16145 **a**	11435 **ab**	45.51 **ab**	38.52 **c**	7337 **a**	4333 **ab**	1.60 **a**	1.53	5.35 **a**	2.16 **ab**
N3	15991 **ab**	10427 **ab**	45.42 **ab**	40.42 **abc**	7244 **ac**	4230 **b**	1.59 **ab**	1.53	5.16 **abc**	2.04 **b**
N4	15236 **bc**	10817 **ab**	46.69 **a**	42.61 **a**	7091 **abc**	4587 **ab**	1.55 **abc**	1.60	5.09 **abc**	2.31 **ab**
N5	15091 **c**	10183 **b**	45.13 **b**	39.52 **bc**	6793 **c**	4039 **b**	1.49 **c**	1.46	4.82 **c**	1.95 **b**
N6	15138 **bc**	10254 **b**	46.33 **ab**	42.02 **ab**	6999 **abc**	4313 **ab**	1.53 **abc**	1.52	5.09 **abc**	2.15 **ab**
N7	15219 **bc**	12065 **a**	45.27 **b**	40.38 **abc**	6873 **bc**	4899 **a**	1.51 **bc**	1.69	4.93 **bc**	2.50 **a**
N8	15242 **bc**	10561 **ab**	46.66 **a**	41.77 **ab**	7089 **abc**	4399 **ab**	1.55 **abc**	1.51	5.06 **abc**	2.24 **ab**
Interaction	*ns*	*ns*	*ns*	*ns*	*ns*	*ns*	*ns*	*ns*	*ns*	*ns*

Different letters indicate statistically significant differences ($p < 0.05$) by the Tukey test; *- significance for $p < 0.05$; *ns* - no significance for $p < 0.05$. R0 - Rainfed; R1 - Full irrigation; R2 - Supplemental irrigation at the stages beginning of stem extension, booting, heading, and grain filling. N1 and N2 - classic fertilizer; N3 and N4 - fertilizer with nitrification inhibitor; N5 and N6 - controlled-release fertilizer; N7 and N8 - fertilizer with urease inhibitor. Each pair is distinguished by N splitting over the crop cycle.

Table 4

Effect of irrigation and nitrogen fertilization type/splitting/timing on grain hectoliter weight (HW), grain protein content (GPC), and on flour alveographic parameters dough balance (P/L) and dough strength (W) in 2017-2018 and 2018-2019.

Source of variation	HW (kg hL^{-1}) 2017/18	2018/19	GPC (%) 2017/18	2018/19	P/L 2017/18	2018/19	W (10^{-4} J) 2017/18	2018/19
Irrigation	*ns*	*	*ns*	*	*ns*	*	ns	ns
R1	81.1	79.1 **b**	12.4	14.8 **a**	1.04	1.04 **c**	279	336
R2	81.0	79.1 **b**	12.7	12.4 **c**	1.07	1.21 **b**	280	349
R0	81.3	82.4 **a**	13.2	14.0 **b**	0.95	1.82 **a**	302	328
N type/splitting/timing	*ns*	*ns*	*	*	*	*	*	*
N1	81.6	80.3	12.5 **cd**	14.6 **a**	1.02 **ab**	1.21 **b**	284 **bcd**	340 **bc**
N2	81.6	80.4	13.0 **bd**	14.7 **a**	1.04 **ab**	1.17 **b**	304 **ab**	349 **ab**
N3	80.9	80.1	12.3 **de**	13.5 **b**	1.12 **a**	1.69 **a**	276 **cde**	305 **d**
N4	81.2	81.2	13.6 **a**	15.1 **a**	0.87 **b**	1.14 **b**	301 **ab**	370 **ab**
N5	81.2	79.2	12.0 **de**	13.6 **b**	1.03 **ab**	1.58 **a**	262 **de**	314 **cd**
N6	80.8	80.6	13.5 **ab**	15.1 **a**	0.97 **ab**	1.24 **b**	294 **abc**	375 **a**
N7	80.8	79.9	12.0 **e**	13.4 **b**	1.14 **a**	1.64 **a**	257 **e**	300 **d**
N8	81.1	80.1	13.5 **ab**	15.0 **a**	0.97 **ab**	1.20 **b**	316 **a**	350 **ab**
Interaction	*ns*	*ns*	*	*ns*	*ns*	*	*	*

Different letters indicate statistically significant differences ($p < 0.05$) by the Tukey test; * - significance for $p < 0.05$; *ns* - no significance for $p < 0.05$. R0 - Rainfed R1 - Full irrigation; R2 - Supplemental irrigation at the stages beginning of stem extension, booting, heading, and grain filling. N1 and N2 - classic fertilizer; N3 and N4 - fertilizer with nitrification inhibitor; N5 and N6 - controlled-release fertilizer; N7 and N8 - fertilizer with urease inhibitor. Each pair is distinguished by N splitting over the crop cycle.

to 2.18 kg m ^{3}. The differences between R1 and R2 had no statistical significance in both years of the experiment, a confirmation that irrigation applied at the beginning of stem extension, booting, anthesis and grain filling is used equally efficiently by the crop, while using smaller volumes of irrigation water. These results were in accordance to previous findings of this research team in a study during a very dry year, in which the same wheat cultivar showed higher efficiency in the use of irrigation water under a supplemental irrigation management strategy (Oliveira et al., 2019). No interaction water regime x N splitting/timing occurred in grain yield, yield components and water productivity.

on hectoliter weight (HW), which seems to indicate that this grain quality trait is mainly linked to genetic factors (Borghi et al., 1997). Only in the year 2018-2019, the significantly higher value obtained in R0 stood out (82.4 kg hL ^{1}), which may be related with the lower number of grains obtained in this water regime. The grain protein content (GPC) is mainly influenced by the environmental conditions of each location and each year and by the dose and fractionation of N fertilization (Blandino et al., 2015) and the results showed that this was the factor that most influenced GPC: the treatments that led to higher levels of GPC

were those corresponding to the application of EEFs in which 50% of the total nitrogen was applied at the booting stage (N4, N6 and N8), which evidences that late nitrogen applications benefit this grain quality quality parameter. The higher average GPC in 2018/2019 in the N treatments, 14.4%, was related to lower grain yield. R1 treatment showed a higher

3.3. Grain technological

The effect of irrigation and N fertilization type/splitting/timing on grain quality traits differed in the two years of the experiment, which indicates that, as reported by Lªopez-Bellido et al. (2001), the variability of the Mediterranean climate also leads to irregular wheat quality (Table 4). In general, there was no significant effect of the studied factors significant GPC of 14.8%, while the lower value occurred in R2 (12.4%). In 2017-2018 there was no significant effect of the water regime. The absence of this effect was certainly linked to the Spring rainfall, which attenuated the differences obtained under different water regimes. The

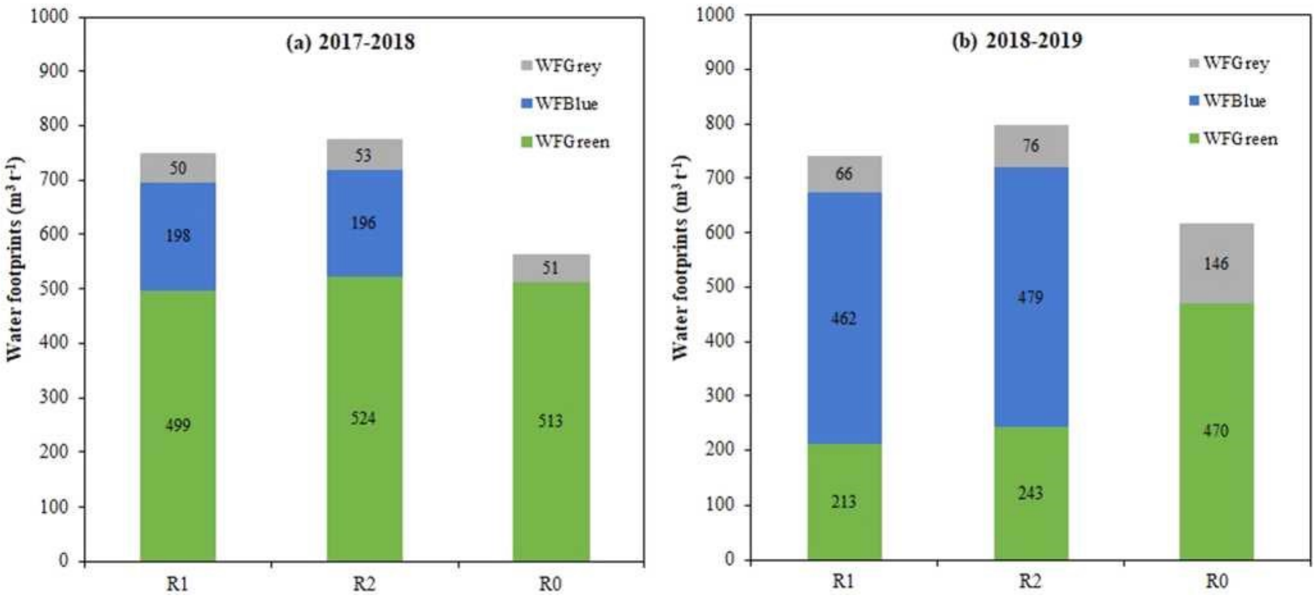

Fig. 4. Green (WF_{Green}), Blue (WF_{Blue}) and Grey (WF_{Grey}) compositions of total water footprints under different water regimes in the **(a)** 2017-2018 and **(b)** 2018-2019 seasons. R1 - Full irrigation; R2 - Supplemental irrigation at the stages beginning of stem extension, booting, heading, and grain filling; R0 - Rainfed.

Table 5

Factor loadings, communalities, eigenvalues, percentage of variance and cumulative percentage of total variance in a three-factor model for 15 variables during the 2017-2018 wheat season.

Variable	Factor 1	Factor 2	Factor 3	Communality
Y	**0.942598**	-0.158402	0.108491	0.925352
NG	-0.010249	**0.918389**	0.086721	0.851064
1000GW	0.210958	**-0.777215**	0.019590	0.648949
WP_C	*0.460222*	0.286729	0.363881	0.426427
WPj	**0.908122**	0.187714	0.051117	0.862534
WForeen	**-0.943750**	0.149837	-0.112602	0.925794
WFBIUC	**-0.912148**	-0.167643	-0.058543	0.863545
WF(3rcy	**-0.943750**	0.149837	-0.112602	0.925794
HW	0.243853	0.362825	-0.012226	0.191256
GPC	0.205154	0.038492	**0.893993**	0.842792
W	0.217370	0.052430	**0.862740**	0.794318
P/L	0.111008	-0.007004	**-0.820768**	0.686032
NDVIsoot	*0.402040*	0.165855	0.112054	0.201700
NDVlAnth	**0.538953**	-0.212105	0.359003	0.464341
NDVlMat	0.191411	-0.119590	0.158045	0.075918

Eigenvalues	5.751203	2.435820	2.037392	
% total variance	38.34135	16.23880	13.58261	
% Cumulative variance	38.34135	54.58015	68.16277	

Y - Yield; NG - Number of grains per m^2; 1000 GW - 1000 grain weight; WP_C - Crop water productivity; WP_I - Irrigation water productivity; WF_{Green} - Green water footprint; WF_{Blue} - Blue water footprint; WF_{Grey} - Grey water footprint; HW - Hectoliter weight; GPC - Grain protein conten; W - dough strength; P/L - dough balance; $NDVI_{Boot}$ - NDVI measurement at booting; $NDVI_{Anth}$ - NDVI measurement at anthesis; $NDVI_{Mat}$ - NDVI measurement at maturation. **Bold values** -absolute loading > 0.50 in the three-factor model. *Italic values* - absolute loadings > 0.40.

flour rheological properties, strength (W) and tenacity/extensibility ratio (P/L) were also mainly influenced by nitrogen fertilization. This factor clearly influenced the dough balance in 2017–2018, as P/L values were lower and closer to the values required by the milling industry for a balanced wheat, namely in the range 0.50 – 1.00 (Bordes et al., 2008), when 50% of the total nitrogen was applied at the booting stage (0.87 in N4, 0.97 in N6 and 0.97 in N8). It is also worth noting that the P/L values were, in general, and especially in 2018–2019, high, corresponding to very strong and moderately extensible dough, which is likely related to the characteristics of the grain in this cultivar. In 2017–2018, values of W above 300 × 10^ 4 J, characteristic of good quality wheat (Bordes et al., 2008), were obtained in the treatments with N fractioning and late application. In 2018–2019, W values were higher than 350 × 10^ 4 J, characteristic of strong improving wheats (Bordes et al., 2008), valued by the milling industry, occurred in the same N treatments. These results indicate the advantage of this strategy to promote the technological quality of the grain. The W values were in direct relation with GPC, which is in accordance with the results by Lo´pez-Bellido et al. (2001) that found a significant correlation between variations in W and GPC when analyzing the bread-making quality of hard red spring wheat under rainfed Mediterranean conditions.

3.4. Water footprints

The average total water footprints (WF) estimated for the two wheat seasons showed no relevant differences (694.3 m3 t^ 1 in 2017–2018 and 717.6 m3 t^ 1 in 2018–2019) but the partition of the three components of water footprint in irrigated wheat varied due to the increase in the relative importance of blue water consumption in the second year of the experiment (Fig. 4). The total WF obtained for both seasons were approximately 2.5 times smaller than the crop benchmark reported by Mekonnen and Hoekstra (2011) (1827 m3 t^ 1) which includes wheat crops of humid climates. As a result of the amount and beneficial dis-tribution of rainfall in 2017–2018, there were no significant statistical differences between the values of WFGreen of the three irrigation re-gimes, although the R2 value was approximately 25 m3 t^ 1 higher than the R1 value (Table S2). In 2018–2019, when a differentiation between water regimes took place, the WFGreen value was significantly higher in the rainfed treatment (470.3 m3 t^ 1). Overall, the magnitude of the WFGreen indicator decreases with the increase in the amount of irrigation applied and its value is influenced by climatic conditions. In 2018–2019, WFGreen in the R1 treatment was 212.8 m3 t^ 1, while the reference value for wheat reported by Mekonnen and Hoekstra (2011), in their global

Table 6
Factor loadings, communalities, eigenvalues, percentage of variance and cumulative percentage of total variance in a three-factor model for 18 variables during the 2018-2019 wheat season.

Variable	Factor 1	Factor 2	Factor 3	Communality
Y	**0.908839**	-0.293512	0.243573	0.971465
NG	**0.886140**	-0.231228	0.248235	0.900331
1000GW	0.070544	-0.334020	0.000777	0.116547
WP_C	-0.202201	0.288698	**0.646669**	0.542413
WPi	0.226379	0.015262	**0.940345**	0.935729
WForeen	**-0.904175**	0.287877	-0.086632	0.907910
WFsiue	-0.212182	0.024437	**-0.941484**	0.932011
WFftey	**-0.904175**	0.287877	-0.086632	0.907910
HW	**-0.635715**	0.036323	*0.407988*	0.571908
GPC	0.102424	**-0.872945**	-0.014622	0.772737
W	-0.130541	**-0.803296**	-0.046729	0.664509
P/L	*-0.454909*	**0.779438**	0.037758	0.815891
NDVITÍU	**0.508966**	0.265359	-0.166971	0.357341

NDVIstem	**0.734439**	0.356673	0.096200	0.675872
NDVIsoot	**0.911534**	0.208469	0.005510	0.874385
NDVIuead	**0.920071**	0.139141	0.030434	0.866816
NDVIAnth	**0.784458**	-0.301734	0.103351	0.717099
NDVIMat	**0.507471**	**-0.607483**	-0.066741	0.631017
Eigenvalues	7.807338	3.160729	2.338918	
% total variance	43.37410	17.55961	12.99399	
% Cumulative variance	43.37410	60.93371	73.92770	

Y - Yield; NG - Number of grains per m^2; 1000 GW - 1000 grain weight; WP_C - Crop water productivity; WP_I - Irrigation water productivity; WF_{Green} - Green water footprint; WF_{Blue} - Blue water footprint; WF_{Grey} - Grey water footprint; HW - Hectoliter weight; GPC - Grain protein conten; W - dough strength; P/L - dough balance; $NDVI_{Till}$ - NDVI measurement at tillering; $NDVI_{Stem}$ - NDVI measurement at stem extension; $NDVI_{Boot}$ - NDVI measurement at booting; $NDVI_{Head}$ - NDVI measurement at heading; $NDVI_{Anth}$ - NDVI measurement at anthesis; $NDVI_{Mat}$ - NDVI measurement at maturation. **Bold values** -absolute loading > 0.50 in the three-factor model. *Italic values* - absolute loadings > 0.40.

Table 7
Results of the stepwise multiple linear regression between NDVI measurements and water footprints in 2017-2018.

Dependent variable	Independent variables	Coefficient	Standard error		t-value	p > |t|	Summary statistics of the regression model
WF_{Green}	Intercept	853.216	110.248		7.739	0.000	F(2,93) = 17.110
	$NDVI_{Boot}$	-235.027	128.491	-0.169	-1.829	0.071	Prob > F = 0.000
	$NDVI_{Anth}$	-315.650	56.965	-0.512	-5.541	0.000	Multiple R^2 = 0.358
	$NDVI_{Mat}$	-104.144	197.523	-0.047	-0.527	0.599	Adjusted R^2 = 0.337
WF_{Blue}	Intercept	463.068	51.330		9.021	0.000	F(2,61) = 12.795
	$NDVI_{Boot}$	-260.007	59.823	-0.484	-4.346	0.000	Prob > F = 0.000
	$NDVI_{Anth}$	-54.844	26.522	-0.231	-2.068	0.043	Multiple R^2 = 0.390
	$NDVI_{Mat}$	-184.518	91.963	-0.214	-2.006	0.049	Adjusted R^2 = 0.360
WF_{Grey}	Intercept	85.020	10.986		7.739	0.000	F(2,93) = 17.110
	$NDVI_{Boot}$	-23.420	12.804	-0.169	-1.829	0.071	Prob > F = 0.000
	$NDVI_{Anth}$	-31.454	5.676	-0.512	-5.541	0.000	Multiple R^2 = 0.358
	$NDVI_{Mat}$	-10.378	19.682	-0.0467	-0.527	0.599	Adjusted R^2 = 0.337

j) - standardized regression coefficients. $NDVI_{Boot}$ - NDVI measurement at booting; NDVIAmi, - NDVI measurement at anthesis; $NDVI_{Mat}$ - NDVI measurement at maturation. Bold values are; WF_{Green} - Green water footprint; WF_{Blue} - Blue water footprint; WF_{Grey} - Grey water footprint.

assessment of the water footprint for the period 1996-2005, is 1277 $m^3 t^1$, therefore, there should be caution when comparing this indicator across areas with different climates (Pardo et al., 2020). WF_{Blue} values in 2017- 2018 (198.4 $m^3 t^1$ in R1 and 196.0 $m^3 t^1$ in R2, respectively) are of the order of magnitude of the reference value 140 $m^3 t^1$ of Southern Europe obtained by (Mekonnen and Hoekstra, 2011) and are lower than the season WF_{Green} values. Contrary, in the next year, blue water was the primary water source for wheat growth (Fig. 4b), with WF_{Blue} reaching 478.8 $m^3 t^1$ in the R2 treatment, a value that is 40% higher than the benchmarks of the crop (324 $m^3 t^1$) or of the region (Southern Europe) (Mekonnen and Hoekstra, 2011). The ratio WF_{Blue}/WF_{Green} was of approximately 0.40 and 2.00 in 2017-2018 and 2018- 2019, respectively, showing that blue water use is of higher relevance in semi-arid environments in general and, particularly, in dry years in regions with Mediterranean climate, where the achievement of sustainable crop yields is dependent on irrigation. Within the same re- gion, WF_{Blue} of a given crop may vary widely according to irrigation conditions, from no irrigation to full irrigation and from highly efficient to non-efficient systems. Recent studies have highlighted that in deter- mining the blue component of the water footprint it is also necessary to account for the extra consumption of water that is often applied to compensate non-uniform irrigation distribution, percolation and runoff losses due to low efficiency of the irrigation systems or salts leaching fractions (Ababaei and Etedali, 2014; Castellanos et al., 2016; Al-Muaini et al., 2019). Another important consideration is that blue water foot- print is directly related to the carbon footprint whenever pressurized irrigation systems are used and, therefore, this indicator implies an impact of irrigated agriculture on global warming (Pardo et al., 2020). No significant differences were found for WF_{Grey} among water regimes in the first season, but a significant effect was found for N fertilization, with the lowest values observed in the conventional fertilizer treat- ments, N1 and N2. These results were complementary of the results presented in Section 3.2. for grain yield and water use (Table 3). Therefore, under Mediterranean environment, the wheat grey footprint related to nitrogen, under the occurrence of advantageous rainfall amount and distribution during the growing cycle, was mostly influ- enced by nitrogen fertilization with no benefit resulting from the use of the so called “enhanced efficiency” N fertilizers. Contrary to what could be expected in rainfed conditions, where N leaching is lower, thereby more likely to remain longer in the soil, significant higher WF_{Grey} was observed in the R0 treatment in 2018-2019 (145.5 $m^3 t^1$). This result primarily reflects the low yields of rainfed plants, under less optimal rainfall distribution and temperatures, but also the calculation of WF_{Grey} using the same leaching fraction for rainfed and irrigated treatments. Nevertheless, values of grey water footprint obtained for all treatments were lower than the reference value for WF_{Grey} of wheat (207 $m^3 t^1$)

Table 8
Results of the stepwise multiple linear regression between NDVI measurements and water footprints in 2018-2019.

Dependent variable	Independent variables	Coefficient	Standard error		t-value	p>|t|	Summary Statistics of the regression model
WF_{Green}	Intercept	1157.008	63.243		18.295	0.000	$F(5,90) = 56.839$
	NDVI$_{Till}$	40.175	71.517	0.034	0.562	0.576	Prob > F = 0.000
	NDVI$_{Stem}$	159.500	120.608	0.133	1.322	0.189	Multiple R^2 = 0.793
	NDVI$_{Boot}$	-647.236	240.284	-0.516	-2.694	0.008	Adjusted R^2 = 0.779
	NDVI$_{Head}$	-188.740	242.717	-0.136	-0.778	0.439	
	NDVI$_{Anth}$	-510.816	170.889	-0.258	-2.989	0.004	
	NDVI$_{Mat}$	-435.150	96.925	-0.304	-4.490	0.000	
WF_{Blue}	Intercept	812.740	78.199		10.393	0.000	$F(5,58) = 5.879$
	NDVI$_{Till}$	282.986	88.428	0.417	3.200	0.002	Prob > F = 0.000
	NDVI$_{Stem}$	-78.440	149.129	-0.114	-0.526	0.601	Multiple R^2 = 0.382
	NDVI$_{Boot}$	160.204	297.105	0.223	0.539	0.592	Adjusted R^2 = 0.317
	NDVI$_{Head}$	-347.828	300.113	-0.438	-1.159	0.251	
	NDVI$_{Anth}$	-660.133	211.300	-0.581	-3.124	0.003	
	NDVI$_{Mat}$	278.764	119.845	0.340	2.326	0.024	
WF_{Grey}	Intercept	357.939	19.565		18.295	0.000	$F(5,90) = 56.839$
	NDVI$_{Till}$	12.429	22.125	0.034	0.562	0.576	Prob > F = 0.000
	NDVI$_{Stem}$	49.344	37.312	0.133	1.322	0.189	Multiple R^2 = 0.793
	NDVI$_{Boot}$	-200.233	74.336	-0.516	-2.694	0.008	Adjusted R^2 = 0.779
	NDVI$_{Head}$	-58.390	75.088	-0.136	-0.778	0.439	
	NDVI$_{Anth}$	-158.029	52.867	-0.258	-2.989	0.004	
	NDVI$_{Mat}$	-134.621	29.985	-0.304	-4.490	0.000	

j) - standardized regression coefficients. $NDVI_{TiB}$ - NDVI measurement at tillering; $NDVI_{Stem}$ - NDVI measurement at stem extension; $NDVI_{Boot}$ - NDVI measurement at booting; $NDVI_{Head}$ - NDVI measurement at heading; $NDVI_{Anth}$ - NDVI measurement at anthesis; $NDVI_{Mat}$ - NDVI measurement at maturation. Bold values are; WF_{Green} - Green water footprint; WF_{Blue} - Blue water footprint; WF_{Grey} - Grey water footprint.

reported by Mekonnen and Hoekstra (2011). The assessment of WF_{Grey} related to nitrogen is affected by disparities in the selected quality standards and the leaching-runoff rate considered for its computation (Liu et al., 2017). These limitations in WF_{Grey} calculations must be taken into consideration when comparing results from different studies. As reported by Laan et al., (2019), the application of water footprint ac- counting is mostly done at large scales, but the estimation of crop- and region-specific water footprints for up-scaling is dependent on accurate and representative in-field measurements.

3.5. Factor analysis and Multiple linear regression

The relationships observed among specific clusters of variables were translated into three-factor models for both seasons (Tables 5 and 6). In 2017- 2018, the three factors explained 68.2% of total variance and presented communality values generally high for all the variables. Factor 1, explained 38.3% of the variance and presented high positive loadings (> 0.50) of Y (0.94), WP_I (0.91), and $NDVI_{Anth}$ (0.54). High negative loadings in Factor 1 *(<* — 0.50) belonged to WF_{Green} (—0.94), WF_{Blue} (—0.91) and WF_{Grey} (—0.94), and moderate positive factor loadings belonged to WP_C (0.46) and $NDVI_{Boot}$, (0.40). Thereby, Factor 1 describes yield and water use (including water productivity and water footprint indicators) given the high weights of Y, WP and WF. Factor 2 was responsible for explaining 16.2% of the total variance and repre- sented a latent variable of yield components, since it was mainly influ- ence by NG (0.92) and 1000 GW (—0.78). Lastly, Factor 3 accounted with 13.6% of total variance and presented high positive correlations with GPC (0.89) and W (0.86), and negative correlation with P/L (—0.82), therefore, corresponding to a grain quality factor. In 2018- 2019, the data were mainly determined by three factors that captured 73.9% of the total variance, overall presenting high commu- nalities (Table 6). The factors presented the following structure: Factor 1 (accounting for 43.4% of total variance) was highly correlated with Y (0.91), NG (0.89), WF_{Green} (-0.90), WF_{Grey} (-0.90), HW (-0.64), $NDVI_{Till}$ (0.51), $NDVI_{Stem}$ (0.73), $NDVI_{Boot}$ (0.91), $NDVI_{Head}$ (0.92), $NDVI_{Anth}$ (0.78), and $NDVI_{Mat}$ (—0.51), therefore, denoted a yield and water footprint latent variable; Factor 2, accounting for 17.6% of total variance, was a grain quality factor with high loadings of GPC (—0.87), W (—0.80), P/L (0.78), and $NDVI_{Mat}$ (—0.61); Factor 3, which explained 13.0% of total variance, was positively correlated with WP_C (0.65), WP_I (0.94), and WF_{Blue} (—0.94), representing a latent variable of irrigation water productivity. Although with some similarities, the comparison of the factor models obtained for the two seasons points to a shift in the contribution of the yield-water use variables. While the latent variables obtained in 2017-2018 may somewhat be described as of “classical” structure, drawing out the separation between yield and water use pa- rameters, yield components and wheat quality characteristics (Lee et al., 2005; Leilah and Al-Khateeb, 2005), in 2018-2019, variables most related with blue water use were clustered in one detached factor, which was probably related to a determining influence of the environmental conditions that lead to the differentiation in irrigation requirements and crop responses for this season. Furthermore, measures of biomass progress (NDVI) from tillering to anthesis strongly participated the yield related latent variable, highlighting that under dryer conditions, there is consistent correlation between NDVI measured at early growing and anthesis stages and grain yield (Naser et al., 2020).

FA was conducted to combine the homogenous variables together thereby reducing the number of variables to be considered for further investigation. Based on this assumption, multiple linear regression analysis (MLR), using the standard stepwise procedure, were performed to identify a set of NDVI measurements at different stages of the growing cycle that could act as predictors of wheat WF. Specifically, NDVI var- iables in each season were selected to examine its prediction capability of correlated water footprints. The results of the MLR for the 2017-2018 season indicated that there was no collective significant effect between the three NDVI variables ($NDVI_{Boot}$, $NDVI_{Anth}$ and $NDVI_{Mat}$) and water footprint green (WF_{Green}) or grey (WF_{Grey}) (Table 7). $NDVI_{Anth}$ signifi- cantly predicted WF_{Green} (p = — 0.512, p < 0.000) but neither $NDVI_{Boot}$ nor $NDVI_{Mat}$ were significant predictors. These variables explained 35.8% of the variance (R^2 = 0.358; F(2,93) = 17.110; p < 0.000). $NDVI_{Boot}$ significantly predicted WF_{Blue} (p = —0.484, p < 0.000), as well as $NDVI_{Anth}$ (p = -0.231, p < 0.043) and $NDVI_{Mat}$ (p = -0.214, p < 0.049), explaining 39.0% of the variance (R^2 = 0.390; F(2,61) = 12.795; p < 0.000). $NDVI_{Boot}$ and $NDVI_{Mat}$ were not predictors of WF_{Grey} while $NDVI_{Anth}$ significantly predicted this indicator (P = — 0.512, p < 0.000) explaining 35.8% of the variance (R^2 = 0.358; F(2,93) = 17.110; p < 0.000). Since no collective significant effect was found between the NDVI records and green and grey water footprints values in the first season, these relationships may be fairly explained using simple regressions. In the case of the 2018-2019 data, the results of MLR were as follow (Table 8): a collective significant effect was found between NDVI measurements and WF_{Green} (F(5, 90) = 56.839, p < 0.000, R^2 = 0.793), with significant predictors in $NDVI_{Boot}$ (p = -0.516, p < 0.008), $NDVI_{Anth}$ (P = -0.258, p < 0.004) and $NDVI_{Mat}$ (p = -0.304, p < 0.000); $NDVI_{Till}$, $NDVI_{Anth}$ and $NDVI_{Mat}$ (respectively, p = —0.427 and p = 0.002, p = — 0.581 and p = 0.003, p = —0.340 and p = 0.024) significantly predicted WF_{Blue}, explaining 38.2% of the variance (R^2 = 0.382; F(5,58) = 5.879; p < 0.000); $NDVI_{Boot}$ (p = -0.526, p < 0.008), $NDVI_{Anth}$ (p = -0.258, p < 0.004) and $NDVI_{Mat}$ (p = —0.304, p < 0.000) measurements significantly pre- dicted WF_{Grey} (F(5, 90) = 56.839, p < 0.000, R^2 = 0.793). The MLR models were in accordance with the Factor models for the two years of the study, whose results grouped, in general, water footprint indicators and NDVI measurements in the same latent factors. Equal β and Multiple R^2 values found for the MLR of green and grey water footprints reflect a strong correlation between the NDVI values at different stages, espe- cially in 2018-2019.

4. Conclusions

Contrasting weather patterns typical of the Mediterranean climate lead to distinct wheat productive responses. The results of our study indicate that the occurrence of precipitation during the stages of heading and initial grain filling attenuated the differences between water regimes and the crop response was mostly influenced by nitrogen fertil- ization. Smaller amount of precipitation, combined with higher average maximum temperatures, during the wheat growth is cause for shorter time for biomass accumulation and, therefore, lower yields. The sup- plemental irrigation strategy adjusted so that the water supplies coin- cided with the critical stages of the crop, although leading to lower grain yields, guaranteed crop water productivity and irrigation water pro- ductivity similar to full irrigation. Different effects of water regimes observed for the two years under study show that the influence of the Mediterranean climate irregularity is determinant, not only for yield variability, but also for grain quality. The application of enhanced effi- cient N fertilizers in which 50% of the total nitrogen was applied at the booting stage had a positive significant effect on grain protein content and in the values of the alveograph, indicating that late nitrogen ap- plications benefit the technological quality of wheat.

The average total water footprints estimated for the two seasons showed no relevant differences but the partition of the green, blue and grey components in irrigated wheat varied, with an increase in the blue water consumptive use in the second year of the experiment due to higher irrigation requirements. In fact, the ratio WF_{Blue}/WF_{Green} was 5 times higher in the drier season which clearly shows that blue water use is most relevant in semi-arid environments in general and in dry years in regions with Mediterranean climate, where the achievement of sus- tainable crop yields is dependent on irrigation. The wheat WF_{Grey}, related to nitrogen, under the occurrence of advantageous rainfall amount and distribution during wheat growing, was mostly influenced by N fertilization. Furthermore, no benefit resulted from the use of ni- trogen EEFs although it should be taken into account that the same leaching rate was used for the various types of nitrogen fertilizers.

The multivariate statistical analysis performed with factor analysis resulted in a combination of homogenous variables in three-factor models obtained for each season. The latent variables found in 2017-2018 were related to yield and water use relations, yield com- ponents and wheat quality parameters. In 2018-2019, indicators of blue water use were clustered in one detached factor, probably expressing the determining influence of the environmental conditions that lead to the differentiation in irrigation requirements for this season.

The stepwise multivariate linear regression analysis allowed for the establishment of significant relationships between biomass develop- ment, measured with NDVI proximal sensors at the stages of tillering, booting, anthesis and maturation, and water footprints indicators of green and blue consumptive water, as well as grey water that is neces- sary to assimilate the nitrogen load from mineral fertilization. The re- sults of the study pointed to a good prediction capability of WF_{Blue} using multiple linear regressions with NDVI registered at booting, anthesis, maturation and /or tillering, and of WF_{Green} and WF_{Grey} using multiple linear relations with the NDVI registered at booting, anthesis and maturation.

Funding

This research was supported by the Project INTERATrigo (Yield and quality evaluation in wheat, as a function of water-nitrogen in- teractions), funded by the European Regional Development Fund of the European Union, through the Programs COMPETE2020 and PORLisboa (grant numbers POCI-01-0145-FEDER-023262, LISBOA-01-0145- FEDER-023262), FCT (Fundaçao para a Ciência e a Tecnologia, Portugal), through national funds (PIDDAC), (grant number SAICT- POL/23262/2016). The work was also a contribution to the project GeoBioTec funded by FCT (grant number UIDP/04035/2020).

Declaration of Competing Interest

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

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.agwat.2021.107214.

References

Ababaei, B., Etedali, H.R., 2014. Estimation of water footprint components of iran′s wheat production: comparison of global and national scale estimates. Environ. Process. 1, 193-205. https://doi.org/10.1007/s40710-014-0017-7.

Al-Muaini, A., Sallam, O.M., Green, S., Kennedy, L., Kemp, P., Clothier, B., 2019. The blue and grey water footprints of date production in the saline and hyper-arid deserts of United Arab Emirates. Irrig. Sci. 37, 657-667. https://doi.org/10.1007/s00271- 019-00642-6.

Albrizio, R., Todorovic, M., Matic, T., Stellacci, A.M., 2010. Comparing the interactive effects of water and nitrogen on durum wheat and barley grown in a Mediterranean environment. Field Crops Res. 115, 179-190. https://doi.org/10.1016/j. fcr.2009.11.003.

Aldaya, M.M., Martínez-Santos, P., Llamas, M.R., 2010. Incorporating the water footprint and virtual water into policy: reflections from the mancha occidental region, Spain. Water Resour. Manag. 24, 941-958. https://doi.org/10.1007/s11269-009-9480-8.

Alghory, A., Yazar, A., 2018. Evaluation of net return and grain quality characteristics of wheat for various irrigation strategies under the Mediterranean climatic conditions. Agric. Water Manag. 203, 395-404. https://doi.org/10.1016/j.agwat.2018.03.033.

Ali Fallahi, H., Nasseri, A., Siadat, A., 2008. Wheat yield components are positively influenced by nitrogen application under moisture deficit environments. Int. J. Agric. Biol. 10, 1560-8530. http://www.fspublishers.org/published_papers/43592_. pdf.

Allen, R.G., Pereira, L.S., Raes, D., Smith, M., 1998. Crop evapotranspiration - Guidelines for computing crop water requirements (FAO Irrigation and drainage paper No. 56). FAO, Rome. http://www.fao.org/3/x0490e/x0490e00.htm.

ANPOC, 2017. LVR (Lista de Variedades Recomendadas) Lista de variedades recomendadas de trigo mole. Apoio ' decisão das sementeiras 2017/18. http://www .vidarural.pt/wp-content/uploads/sites/5/2017/10/Variedades-de-Trigo-Mole.pdf.

Aparicio, N., Villegas, D., Casadesús, J., Araus, J., Royo, C., 2000. Spectral vegetation indices as nondestructive tools for determining durum wheat yield. Agron. J. 92. https://doi.org/10.2134/agronj2000.92183x.

Barnabas, B., Jager, K., Fehér, A., 2008. The effect of drought and heat stress on reproductive processes in cereals. Plant, Cell Environ. 31, 11-38. https://doi.org/ 10.1111/j.1365-3040.2007.01727.x.

Blandino, M., Marinaccio, F., Vaccino, P., Reyneri, A., 2015. Nitrogen fertilization strategies suitable to achieve the quality requirements of wheat for biscuit production. Agron. J. 107, 1584-1594. https://doi.org/10.2134/agronj14.0627.

Bordes, J., Branlard, G., Oury, F.X., Charmet, G., Balfourier, F., 2008. Agronomic characteristics, grain quality and flour rheology of 372 bread wheats in a worldwide core collection. J. Cereal Sci. 48, 569-579. https://doi.org/10.1016/j. jcs.2008.05.005.

Borghi, B., Corbellini, M., Minoia, C., Palumbo, M., Di Fonzo, N., Perenzin, M., 1997. Effects of Mediterranean climate on wheat bread-making quality. Eur. J. Agron. 6, 145-154. https://doi.org/10.1016/S1161-0301(96)02040-0.

Castellanos, M.T., Cartagena, M.C., Requejo, M.I., Arce, A., Cabello, M.J., Ribas, F., Tarquis, A.M., 2016. Agronomic concepts in water footprint assessment: a case of study in a fertirrigated melon crop under semiarid conditions. Agric. Water Manag. 170, 81-90. https://doi.org/10.1016/j.agwat.2016.01.014.

Chapagain, A.K., Hoekstra, A.Y., 2004. Water footprints of nations, Value of Water Research Report Series No.16. UNESCO-IHE, Delft, the Netherlands.

Chen, D., Suter, H.C., Islam, A., Edis, R., R Freney, J., Walker, C, N., 2008. Prospects of improving efficiency of fertiliser nitrogen in Australian agriculture: a review of enhanced efficiency fertilisers. Aust. J. Soil Res. 46 https://doi.org/10.1071/ SR07197.

Clay, D., Kharel, T., Reese, C., Beck, D., Carlson, C., Clay, S., Reicks, G., 2012. Winter wheat crop reflectance and nitrogen sufficiency index values are influenced by nitrogen and water stress. Agron. J. 104, 1612-1617. https://doi.org/10.2134/ agronj2012.0216.

COTR, 2020. MOGRA - Modelo de Gestao da Rega para o Alentejo (Irrigation Management Model for Alentejo) [WWW Document]. Sistemas de Apoio a Decisao. URL http://www.cotr.pt/servicos/mogra.php. (accessed 30 September 2019).

Daccache, A., Ciurana, J.S., Diaz, J.A.R., Knox, J.W., 2014. Water and energy footprint of irrigated agriculture in the Mediterranean region. Environ. Res. Lett. 9, 124014 https://doi.org/10.1088/1748-9326/9/12/124014.

Decree-Law 236/98 On water quality assessment, 1998., Decree-Law 236/98.

Duan, T., Chapman, S.C., Guo, Y., Zheng, B., 2017. Dynamic monitoring of NDVI in wheat agronomy and breeding trials using an unmanned aerial vehicle. Field Crops Res. 210, 71-80. https://doi.org/10.1016/j.fcr.2017.05.025.

EEC, 1991. The Nitrates Directive - Council Directive concerning the protection of waters against pollution caused by nitrates from agricultural sources. https://ec.europa. eu/environment/water/water-nitrates/index_en.html.

Egner, H., Riehm, H., Domingo, W.R., 1960. Untersuchhungen uber die chemische boden: analyse als grundlage fur die beurteilung der nahrstoffzustandes der boden. II. Chemique extractions, methoden zur phosphor, und kalium-bestimmung. K. Lantbr. Ann. 26, 199-215.

Elbeltagi, A., Aslam, M., Mokhtar, A., Deb, P., Abubakar, G., Kushwaha, N.L., Venancio, L., Malik, A., Kumar, N., Deng, J., 2020. Spatial and temporal variability analysis of green and blue evapotranspiration of wheat in the Egyptian Nile Delta from 1997 to 2017. J. Hydrol. https://doi.org/10.1016/j.jhydrol.2020.125662.

Ercin, A., Hoekstra, A., 2016. European water footprint scenarios for 2050. Water 8, 226. https://doi.org/10.3390/w8060226.

EUROSTAT, 2020. Wheat and spelt by area, production and humidity [WWW Document]. URL https://ec.europa.eu/eurostat/databrowser/view/tag00047/de fault/table?lang=en. (accessed 28 October 2020).

Fernaéndez, J.E., Alcon, F., Diaz-Espejo, A., Hernandez-Santana, V., Cuevas, M.V., 2020. Water use indicators and economic analysis for on-farm irrigation decision: a case study of a super high density olive tree orchard. Agric. Water Manag. 237, 106074 https://doi.org/10.1016/j.agwat.2020.106074.

Ferrari, Th.J., Pijl, H., Venekamp, J.T.N., 1957. Factor analysis in agricultural research. Wagening. J. Life Sci. 5, 211-221. https://doi.org/10.18174/njas.v5i3.17737.

Franke, N.A., Boyacioglu, H., Hoekstra, A.Y., 2013. GreyWater Footprint Accounting: Tier 1 Supporting Guidelines. (Value of Water Research Report Series No. 65). UNESCO-IHE, Delft, the Netherlands. https://waterfootprint.org/media/downloads/ Report65-GreyWaterFootprint-Guidelines_1.pdf.

Garofalo, P., Ventrella, D., Kersebaum, K.C., Gobin, A., Trnka, M., Giglio, L., Dubrovsky, M., Castellini, M., 2019. Water footprint of winter wheat under climate change: trends and uncertainties associated to the ensemble of crop models. Sci. Total Environ. 658, 1186-1208. https://doi.org/10.1016/j.scitotenv.2018.12.279.

Hàrdle, W.K., Simar, L., 2015. Applied Multivariate Statistical Analysis, fourth edition. Springer, Heidelberg New York Dordrecht London.

Hoekstra, A.Y., 2017. Water footprint assessment: evolvement of a new research field. Water Resour. Manag. 31, 3061-3081. https://doi.org/10.1007/s11269-017-1618-5.

Hoekstra, A.Y. (Ed.), 2003. Virtual water trade: Proceedings of the International Expert Meeting on Virtual Water Trade, in: Proceedings of the International Expert Meeting on Virtual Water Trade,

Value of Water Research Report Series. UNESCO-IHE, Delft, Netherlands. https://www.waterfootprint.org/media/downloads/Report12.pdf.
Hoekstra, A.Y., Chapagain, A.K., Aldaya, M.M., Mekonnen, M.M., 2011. The Water Footprint Assessment Manual: Setting the Global Standard, first ed. Routledge. https://doi.org/10.4324/9781849775526.
Howell, T.A., 2001. Enhancing water use efficiency in irrigated agriculture. Agron. J. 93, 281-289. https://doi.org/10.2134/agronj2001.932281x.
Huang, Jing, Ridoutt, B.G., Thorp, K.R., Wang, X., Lan, K., Liao, J., Tao, X., Wu, C., Huang, Jianliang, Chen, F., Scherer, L., 2019. Water-scarcity footprints and water productivities indicate unsustainable wheat production in China. Agric. Water Manag. 224, 105744 https://doi.org/10.1016/j.agwat.2019.105744.
IPMA, 2020. Climate normals - 1981-2010 - Beja [WWW Document]. URL https://www. ipma.pt/en/oclima/normais.clima/1981-2010/002/. (accessed 6 July 2019).
IUSS Working Group WRB, 2014. World Reference Base for Soil Resources 2014, Update 2015 (No. World Soil Resources Report No 106). FAO, Rome. http://www.fao. org/3/i3794en/I3794en.pdf.
Jagadamma, S., Lal, R., Hoeft, R.G., Nafziger, E.D., Adee, E.A., 2008. Nitrogen
fertilization and cropping system impacts on soil properties and their relationship to crop yield in the central Corn Belt, USA. Soil Tillage Res. 98, 120-129. https://doi.
org/10.1016/j.still.2007.10.008.
Katerji, N., Mastrorilli, M., Rana, G., 2008. Water use efficiency of crops cultivated in the Mediterranean region: Review and analysis. Eur. J. Agron. 28, 493-507. https://doi.
org/10.1016/j.eja.2007.12.003.
Laan, M. van der, Jarmain, C., Bastidas-Obando, E., Annandale, J.G., Fessehazion, M., Haarhoff, D., 2019. Are water footprints accurate enough to be useful? A case study for maize (Zea mays L.). Agric. Water Manag. 213, 512-520. https://doi.org/
10.1016/j.agwat.2018.10.026.
Lee, K.-M., Herrman, T.J., Lingenfelser, J., Jackson, D.S., 2005. Classification and prediction of maize hardness-associated properties using multivariate statistical analyses. J. Cereal Sci. 41, 85-93. https://doi.org/10.1016/j.jcs.2004.09.006.
Leilah, A.A., Al-Khateeb, S.A., 2005. Statistical analysis of wheat yield under drought conditions. J. Arid Environ. 61, 483-496. https://doi.org/10.1016/j. jaridenv.2004.10.011.
Levidow, L., Zaccaria, D., Maia, R., Vivas, E., Todorovic, M., Scardigno, A., 2014. Improving water-efficient irrigation: prospects and difficulties of innovative practices. Agric. Water Manag. 146, 84-94. https://doi.org/10.1016/j. agwat.2014.07.012.
Liu, W., Antonelli, M., Liu, X., Yang, H., 2017. Towards improvement of grey water footprint assessment: With an illustration for global maize cultivation. J. Clean. Prod. 147, 1-9. https://doi.org/10.1016/j.jclepro.2017.01.072.
Liu, W., Wang, J., Wang, C., Ma, G., Wei, Q., Lu, H., Xie, Y., Ma, D., Kang, G., 2018. Root growth, water and nitrogen use efficiencies in winter wheat under different irrigation and nitrogen regimes in North China Plain. Front. Plant Sci. 9, 1798. https://doi.org/10.3389/fpls.2018.01798.
Liu, J., Williams, J.R., Zehnder, A.J.B., Yang, H., 2007. GEPIC - modelling wheat yield and crop water productivity with high resolution on a global scale. Agric. Syst. 94,
478-493. https://doi.org/10.1016/j.agsy.2006.11.019.
Loápez-Bellido, L., Láopez-Bellido, R.J., Castillo, J.E., Loápez-Bellido, F.J., 2001. Effects of long-term tillage, crop rotation and nitrogen fertilization on bread-making quality of hard red spring wheat. Field Crops Res. 72, 197-210. https://doi.org/10.1016/
S0378-4290(01)00177-0.
MAFDR, 2018. Estrategia Nacional para a Promoção da Produção de Cereais (ENPPC) (National Strategy for the Promotion of Cereal Production). Ministáerio da Agricultura, Florestas e Desenvolvimento Rural (Portuguese Ministry of Agriculture, Forestry and Rural Development). http://www.drapal.min-agricultura.pt/drapal/i mages/servicos/noticias/2018/ENPPC.pdf.
Maharjan, B., Venterea, R., Rosen, C., 2014. Fertilizer and irrigation management effects on nitrous oxide emissions and nitrate leaching. Agron. J. 106, 703-714. https://doi.
org/10.2134/agronj2013.0179.
Makinen, H., Kaseva, J., Balek, J., Kersebaum, K., Nendel, C., Gobin, A., Olesen, J., Bindi, M., Ferrise, R., Moriondo, M., Rodriguez, A., Ruiz-Ramos, M., Takac B., P., J., Ventrella, D., Ruget G., C., F., Kahiluoto, H., 2018. Sensitivity of European wheat to extreme weather. Field Crops Res. 222, 209-217. https://doi.org/10.1016/j. fcr.2017.11.008.
Mallarino, A., Oyarzabal, E., Hinz, P., 1999. Interpreting within-field relationships between crop yields and soil and plant variables using factor analysis. Precis. Agric.
1, 15-25. https://doi.org/10.1023/A:1009940700478.
Mekonnen, M.M., Hoekstra, A.Y., 2015. Global gray water footprint and water pollution levels related to anthropogenic nitrogen loads to fresh water. Environ. Sci. Technol.
49, 12860-12868. https://doi.org/10.1021/acs.est.5b03191.
Mekonnen, M.M., Hoekstra, A.Y., 2011. The green, blue and grey water footprint of crops and derived crop products. Hydrol. Earth Syst. Sci. 15, 1577-1600. https://doi.org/
10.5194/hess-15-1577-2011.
Monaco, F., Sali, G., 2018. How water amounts and management options drive Irrigation Water Productivity of rice. A multivariate analysis based on field experiment data. Agric. Water Manag. 195, 47-57. https://doi.org/10.1016/j.agwat.2017.09.014.
Naser, M., Khosla, R., Longchamps, L., Dahal, S., 2020. Using NDVI to differentiate wheat genotypes productivity under dryland and irrigated conditions. Remote Sens. 12, 824. https://doi.org/10.3390/rs12050824.
Neter, J., Wasserman, W., Kutner, M.H., 1983. In: Irwin, Richard D. (Ed.), Applied Linear Regression Models. Inc., Homewood, Illinois.
Nogueira, A., Paço, T., Silvestre, J., Gonzalez, L., Santos, F., Pereira, L., 2012. Water Footprint Of A Super-intensive Olive Grove Under Mediterranean Climate Using Ground-based Evapotranspiration Measurements And Remote Sensing. Geophys. Res. Abstr. 14, 11301. (https://ui.adsabs.harvard.edu/abs/2012EGUGA. 1411301N/abstract}.
Oliveira, P., Patanita, M., Dores, J., Boteta, L., Palma, J.F., Patanita, M.I., Guerreiro, I., Penacho, J., Costa, M.N., Rosa, E., Tomaz, A., 2019. Combined effects of irrigation management and nitrogen fertilization on soft wheat productive responses under Mediterranean conditions. E3S Web Conf. 86, 00019. https://doi.org/10.1051/ e3sconf/20198600019.
Oweis, T., 1997. Supplemental Irrigation: A Highly Efficient Water-Use Practice.
International Center for Agricultural Research in the Dry Areas (ICARDA), Aleppo, Syria.
Pardo, J.J., Martínez-Romero, A., Láellis, B.C., Tarjuelo, J.M., Domínguez, A., 2020. Effect of the optimized regulated deficit irrigation methodology on water use in barley under semiarid conditions. Agric. Water Manag. 228, 105925 https://doi.org/
10.1016/j.agwat.2019.105925.
Patanita, M., Tomaz, A., Ramos, T., Oliveira, P., Boteta, L., Doores, J., 2019. Water regime and nitrogen management to cope with wheat yield variability under the mediterranean conditions of Southern Portugal. Plants 8, 429. https://doi.org/ 10.3390/plants8100429.
Pereira, L.S., Cordery, I., Iacovides, I., 2012. Improved indicators of water use
performance and productivity for sustainable water conservation and saving. Agric. Water Manag. 108, 39-51. https://doi.org/10.1016/j.agwat.2011.08.022.
Plaut, Z., Butow, B.J., Blumenthal, C.S., Wrigley, C.W., 2004. Transport of dry matter into developing wheat kernels and its contribution to grain yield under post-anthesis water deficit and elevated temperature. Field Crops Res. 86, 185-198. https://doi. org/10.1016/j.fcr.2003.08.005.
Porter, J.R., Gawith, M., 1999. Temperatures and the growth and development of wheat: a review. Eur. J. Agron. 10, 23-36. https://doi.org/10.1016/S1161-0301(98)00047- 1.
Prasad, P.V.V., Maduraimuthu, D., 2014. Response of floret fertility and individual grain weight of wheat to high temperature stress: Sensitive stages and thresholds for temperature and duration. Funct. Plant Biol. 41, 1261-1269. https://doi.org/
10.1071/FP14061.
Qin, L., Jin, Y., Duan, P., He, H., 2016. Field-based experimental water footprint study of sunflower growth in a semi-arid region of China: water footprint study of sunflower growth. J. Sci. Food Agric. 96, 3266-3273. https://doi.org/10.1002/jsfa.7726.
Rouse, J.W., Haas, R.H., Schell, J.A., Deering, D.W., 1974. Monitoring vegetation systems in the Great Plains with ERTS, in: NASA. Goddard Space Flight Center 3d ERTS-1 Symposium. pp. 309-317.
SROA, 1970. Carta de Solos de Portugal - Classificaçãao e caracterizaçãao morfoloágica dos solos.
Tomaz, A., Ferro Palma, J., Guerreiro, I., Patanita, M.I., Penacho, J., Doores, J., Costa, M. N., Rosa, E., Patanita, M., 2017a. An overview on the use of enhanced efficiency nitrogen fertilizers in irrigated mediterranean agriculture. BJSTR 1. https://doi.org/
10.26717/BJSTR.2017.01.000588.
Tomaz, A., Patanita, M., Guerreiro, I., Boteta, L., Palma, J.F., 2017b. Water use and productivity of maize-based cropping systems in the Alqueva region (Portugal). Cereal Res. Commun. 45, 711-721. https://doi.org/10.1556/0806.45.2017.036.
Tomaz, A., Patanita, M., Guerreiro, I., Doores, J., Boteta, L., Palma, J., 2018. Efficient use of water and nutrients in irrigated cropping systems in the Alqueva region. Span. J. Soil Sci. 8, 12-23. https://doi.org/10.3232/SJSS.2018.V8.N1.02.
Trenkel, M.E., 1997. Improving Fertilizer Use Efficiency. Controlled-Release and Stabilized Fertilizers in Agriculture. IFA, Paris.
Trnka, M., Olesen, J.E., Kersebaum, K.C., Skjelvåg, A.O., Eitzinger, J., Seguin, B., Peltonen-Sainio, P., Rotter, R., Iglesias, A., Orlandini, S., Dubrovsky, M.,
Hlavinka, P., Balek, J., Eckersten, H., Cloppet, E., Calanca, P., Gobin, A., Vucetiá, V., Nejedlik, P., Kumar, S., Lalic, B., Mestre, A., Rossi, F., Kozyra, J., Alexandrov, V., Semeradova, D., Zalud, Z.,
2011. Agroclimatic conditions in Europe under climate change. Glob. Change Biol. 17, 2298-2318. https://doi.org/10.1111/j.1365- 2486.2011.02396.x.
Ul-Allah, S., Iqbal, M., Maqsood, S., Naeem, M., Ijaz, M., Ashfaq, W., Hussain, M., 2018. Improving the performance of bread wheat genotypes by managing irrigation and nitrogen under semi-arid conditions. Arch. Agron. Soil Sci. 64, 1678-1689. https:// doi.org/10.1080/03650340.2018.1450974.
Walkley, A., Black, L.A., 1934. An examination of the Dgtjareff method for determining soil organic matter, and a proposed modification of the chromic acid titration method. Soil Sci. 37, 29-38. https://journals.lww.com/soilsci/Fulltext/19 34/01000/AN_EXAMINATION_OF_THE_DEGTJAREFF_METHOD_FOR.3.aspx.
Xinchun, C., Mengyang, W., Rui, S., La, Z., Dan, C., Guangcheng, S., Xiangping, G., Weiguang, W., Shuhai, T., 2018. Water footprint assessment for crop production based on field measurements: a

case study of irrigated paddy rice in East China. Sci. Total Environ. 610-611, 84-93. https://doi.org/10.1016/j.scitotenv.2017.08.011.
Yu, Z., Islam, S., She, M., Diepeveen, D., Zhang, Y., Tang, G., Zhang, J., Juhasz, A., Yang, R., Ma, W., 2018. Wheat grain protein accumulation and polymerization mechanisms driven by nitrogen fertilization. Plant J. 96, 1160-1177. https://doi. org/10.1111/tpj.14096.
Zeleke, K.T., Nendel, C., 2016. Analysis of options for increasing wheat (Triticum aestivum L.) yield in south-eastern Australia: the role of irrigation, cultivar choice and time of sowing. Agric. Water Manag. 166, 139-148. https://doi.org/10.1016/j. agwat.2015.12.016.
Zeng, Z., Liu, J., Koeneman, P.H., Zarate, E., Hoekstra, A.Y., 2012. Assessing water footprint at river basin level: a case study for the Heihe River Basin in northwest China. Hydrol. Earth Syst. Sci. 16, 2771-2781. https://doi.org/10.5194/hess-16- 2771-2012.
Zhang, H., Oweis, T., 1999. Water-yield relations and optimal irrigation scheduling of wheat in the Mediterranean region. Agric. Water Manag. 38, 195-211. https://doi. org/10.1016/S0378-3774(98)00069-9.
Zhang, X., Qin, W., Chen, S., Shao, L., Sun, H., 2017. Responses of yield and WUE of winter wheat to water stress during the past three decades—a case study in the North China Plain. Agric. Water Manag. 179, 47-54. https://doi.org/10.1016/j. agwat.2016.05.004.
Zhang, H., Wang, X., You, M., Liu, C., 1999. Water-yield relations and water-use efficiency of winter wheat in the North China Plain. Irrig. Sci. 19, 37-45. https://doi. org/10.1007/s002710050069.
Zwart, S., Bastiaanssen, W.G.M., 2004. Review of measured crop water productivity values for irrigated wheat, rice, cotton and maize. Agric. Water Manag. 69, 115-133. https://doi.org/10.1016/j.agwat.2004.04.007.
Zwart, S.J., Bastiaanssen, W.G.M., de Fraiture, C., Molden, D.J., 2010. A global benchmark map of water productivity for rainfed and irrigated wheat. Agric. Water Manag. 97, 1617-1627. https://doi.org/10.1016/j.agwat.2010.05.018.

This is a post-peer-review, pre-copyedit version of an article published in Agricultural Water Management. The final authenticated version is available online at https://doi.org/10.1016/j.agwat.2021.107214

The version of record Tomaz, A., Palma, J., Ramos, T., Costa, M., Rosa, E., Santos, M., Boteta, L., Dôres, J. & Patanita, M. (2021). Yield, technological quality and water footprints of wheat under Mediterranean climate conditions: A field experiment to evaluate the effects of irrigation and nitrogen fertilization strategies. Agricultural Water Management, 258, 1-14. https://doi.org/10.1016/j.agwat.2021.107214