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Yield Response and Leaf Gas Exchange of Sicilian Wheat Landraces

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Abstract: Wheat landraces are traditional varieties that have evolved over generations in response to local environments and farming practices and therefore exhibit remarkable adaptability to challenging climatic conditions and low-input farming systems. While the suitability of Mediterranean landraces to non-optimal climatic conditions during anthesis and grain ripening stage have been previously assessed, the role of photosynthesis efficiency and stomatal control on this resilience remains unexplored. This study aims to evaluate the relationship between grain yield and the post-anthesis flag leaf gas exchanges of Sicilian wheat landraces under irrigated and rainfed conditions and to compare these traits to modern durum (*Triticum turgidum* subsp. *durum*) and bread wheat (*T. aestivum*) varieties. Results indicate that wheat landraces respond to water availability similarly to modern varieties, reducing stomatal conductance by 26.8% and net photosynthesis by 18.1% under rainfed conditions, resulting in 10.6% lower grain yield compared to irrigated conditions. However, some landraces demonstrate comparable or even higher flag leaf net photosynthesis rates and lower transpiration levels, leading to higher yields in both rainfed and irrigated conditions, confirming their value as a source of gene pool for wheat breeding programs in drought-prone Mediterranean regions.

Keywords: grain yield; net assimilation rate; leaf transpiration; stomatal conductance; instant water use efficiency; Mediterranean

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1. Introduction

Wheat landraces are traditional varieties that have evolved over many generations in response to the local environmental conditions and the selective pressure of the local farming system, leading to a high genetic diversity and local adaptation, unlike modern commercial varieties, which are bred for high uniformity and often consist of individual pure lines with low genetic variability [1,2]. These landraces have been selected under low-input farming systems, which has led to the conservation of traits that increase the suitability to under-optimal environmental and climatic conditions [3,4]. Among these traits are higher plant height, which increases the competitiveness against weeds [5,6], and the low susceptibility to drought, especially in landraces selected in semi-arid areas, mainly due to the deep root system [7–10] or reducing their cycle length to anthesis and therefore performing the grain filling phase under more favorable conditions [4].

During the last century, wheat landrace adoption by farmers decreased in favor of high-yielding commercial varieties, and therefore, the in situ and ex situ conservation of their gene pool is entrusted to custodian farmers and gene banks, respectively [2,11].

The gene pool of landraces is useful for wheat breeding programs that aim to improve the grain quality and resilience towards biotics (pathogens and pests) and abiotic stresses of modern wheat varieties [4,12,13].

Moreover there is a growing interest in these wheat landraces related to their appreciable technological features and sensory and nutraceutical properties, such as high fiber content, antioxidants, vitamins, and minerals [14,15].

Mediterranean wheat landraces could provide genetic traits to enhance grain yield in an environment characterized by non-optimal climatic conditions during the grain filling stage. Grain filling, and consequently grain yield, is sustained both by transient photosynthesis after anthesis and by the translocation of stored reserves accumulated before anthesis [16]. If the climatic condition during the grain filling phase is non-optimal, such as in the Mediterranean climates, where hot and dry conditions prevail in late spring, grain filling is mainly sustained by the translocation of stored reserves, since photosynthesis declines due to stomatal response [9,16]. Modern varieties have been found to have a higher photosynthesis rate than local landraces in favorable climatic conditions and high nitrogen input [17] and their grain yield has been found to be positively correlated with photosynthesis rate at different phenological stages [17–19].

Considering the broader spectra of climatic and agronomic conditions, modern varieties have not shown a higher rate of photosynthesis per unit leaf area than the open-pollinated populations or landraces from which they are derived [20]; in these cases, grain yield increased mainly as a result of improved harvest index [20,21] or as a result of higher total photosynthesis during the life of the plant due to the increase in leaf area, daily duration of photosynthesis, or leaf area duration [20].

Wheat grain yield is affected by limiting soil water availability. In this condition, the photosynthesis rate is reduced by the plant response to lower stomatal conductance with the aim of reducing water transpiration [19,22–26]. Sicilian wheat landraces have demonstrated to be particularly adapted to non-optimal climatic conditions during anthesis and grain ripening stage and low-input agronomical practices [27,28], while the role of photosynthesis efficiency or stomatal conductance in achieving these results has yet to be assessed.

The aim of the present work is to evaluate the relationship between grain yield and the post-anthesis flag leaf gas exchanges of Sicilian wheat landraces under irrigated and rainfed conditions and compare these traits to modern durum (*Triticum turgidum* subsp. *durum*) and bread wheat (*T. aestivum*) varieties.

2. Materials and Methods

2.1. Field Trial

The field trial was carried out at the experimental farm of the University of Catania (37°24′ N., 15°03′ E., 10 m a.s.l.), in a representative area of Sicilian cereal farming, in a typical Xerofluvent soil with a preponderantly clayey texture, whose characteristics are listed in Table 1.

Table 1. Soil characteristics of the field site in the top layer (0–50 cm).

Soil Characteristics	Unit	Value	Method
Sand	%	49.3	Gattorta [29]
Loam	%	22.4	Gattorta [29]
Clay	%	28.3	Gattorta [29]
pH		8.6	In water solution
Total calcareous	%	15.2	Gas-volumetric [30]
Organic matter	%	1.4	Walkley and Black [30]
Total N	‰	1	Kjeldahl [30]
P_2O_5 availability	ppm	5	Ferrari [30]
K_2O availability	ppm	245	Dirks and Scheffer [30]
Bulk density	g cm^{-3}	1.1	
Field capacity at −0.03 MPa	%	27	
Wilting point at −1.5 MPa	%	11	

The experimental design was a split-plot design with three replicates. The irrigation was the experimental factor assigned to the main plots and had two levels: rainfed and 100% of maximum crop evapotranspiration (ETm) restoration during the period from the end of anthesis until the full seed ripening. The sub-plot factor was the genotype, with seventeen categories: twelve Sicilian landraces of durum wheat ("Bidì", "Castiglione Glabro", "Giustalisa", "Margherito", "Perciasacchi", "Realforte", "Ruscia", "Russello", "Russello Ibleo", "Timilia", "Tripolino", "Urria"), one landrace of bread wheat ("Maiorca"), one old variety of durum wheat ("Senatore Cappelli"), two commercial varieties of durum wheat ("Mongibello" and "Core"), and one commercial variety of soft wheat ("Bologna"). The durum wheat landraces were selected to provide an extensive representation of the genetic and morphological diversity among Sicilian durum wheat landraces [1,31]. Only one bread wheat landrace has been selected for this study because of the low diffusion and low productivity of bread wheat in the semi-arid Mediterranean regions [32]. Both durum wheat modern commercial varieties are well-adapted to the local environmental conditions and are proved to be high-yielding [33,34], while the bread wheat "Bologna" has been selected as a widespread Italian variety, despite its low suitability for the local conditions.

The sub-plot size was 1.25 × 8 m^2. Irrigation was provided by a sprinkler irrigation system. Daily ETm was calculated according to:

$$ETm = ET0 \times Kc$$

where ET0 is reference evapotranspiration (mm) and Kc is the crop coefficient for wheat according to [35]. Irrigation started on 3 May 2020 the first year and on 2 May 2021 the second year.

Sowing was carried out on 8 January 2020 during the first year and on 13 January 2021 during the second year with a target sowing density of 400 plants m^{-2}.

The trial followed organic management. The fertilization was performed before sowing and just before the stem elongation phase, applying in total 80 kg ha^{-1} of N as organic fertilizer in pellet form with 7% of N and 13% of P_2O_5. Harvesting was carried out at physiological maturity (when the grain moisture content approaches 12%) on 6 July 2020 during the first year and on 2 July 2021 during the second year, collecting all the aboveground biomass in the experimental plots using a self-propelled combine harvester. The grain yield was calculated relating the grain dry weight to the unit area (Mg ha^{-1}).

2.2. Measurements

Physiological measurements were carried out weekly from anthesis until full ripening, reaching a total of 5 dates of measurement in 2020 and 4 in 2021 during an interval of ±2 h from midday, avoiding cloud conditions when the photosynthetic photon flux was highly variable or below 1200 μmol m^{-2} s^{-1}, on the flag leaf of two plants in each experimental plot. The physiological measurements were performed using the LCi-SD Portable Photosynthesis system (ADC BioScientific Ltd., Hoddesdon, UK), which measures net photosynthesis rate (A, μmol CO_2 m^{-2} s^{-1}), transpiration rate (E, mmol H_2O m^{-2} s^{-1}) and stomatal conductance (gs, mol H_2O m^{-2} s^{-1}) on the basis of CO_2 and H_2O gas exchange. Instantaneous water use efficiency (iWUE μmol CO_2 mol^{-1} H_2O) was calculated as the ratio of net photosynthesis and transpiration. Meteorological data (maximum temperature, mean temperature, minimum temperature, precipitation, solar incident radiation, maximum humidity, minimum humidity, mean wind speed) were measured hourly by a weather station connected to a data logger (CR10, Campbell Scientific, Logan, UT, USA), located 50 m from the experimental field.

2.3. Statistical Analysis

The data were subjected to an analysis of variance (four-way ANOVA) to assess the effect of genotype, irrigation, days after sowing (DAS), and the interactions genotype × irrigation, genotype × DAS, irrigation × DAS, and genotype × irrigation × DAS on net photosynthesis rate, transpiration rate, stomatal conductance, and instantaneous water use efficiency. The effect of genotype, irrigation, and year and the interactions genotype × irrigation on grain yield were assessed through a three-way ANOVA.

The year of the trial was considered as a random factor in the four-way and three-way ANOVA.

The Shapiro–Wilk test was used to test residuals for normality. The Bartlett test was used to test homoscedasticity.

Fisher's least square difference (LSD) procedure at a 95% confidence level was performed to compare pairwise the genotype and the genotype × irrigation interaction means. Correlation between variables was studied with the Pearson's product-moment correlation test. All analyses were performed using the R CRAN software version 4.4.0 [36].

3. Results

3.1. Meteorological Trend

Thermal trends, precipitation, and reference evapotranspiration were typical of the semiarid Mediterranean environment during the duration of the experiment.

Mean air temperatures throughout growing seasons were slightly lower in 2020 than 2021; the monthly average daily mean temperature was 14.88 °C and 15.06 °C in 2020 and 2021, respectively, the monthly average daily minimum temperature was 9.28 °C and 9.48 °C in 2020 and 2021, respectively, lower than the long-term average of 10 °C, the monthly average daily maximum temperature was 20.98 °C and 21.11 °C in 2020 and 2021, respectively, both higher than the long-term average of 20.5 °C, although reference evapotranspiration was higher during the 2020 growing season (707.4 mm) than the 2021 growing season (660.1 mm), and both were higher than the long-term average (643.8 mm). Precipitation was higher during the period starting from October 2019 to July 2020 (588 mm) than the period starting from October 2020 to July 2021 (424 mm), while the long-term average is 544.1 mm (Figure 1).

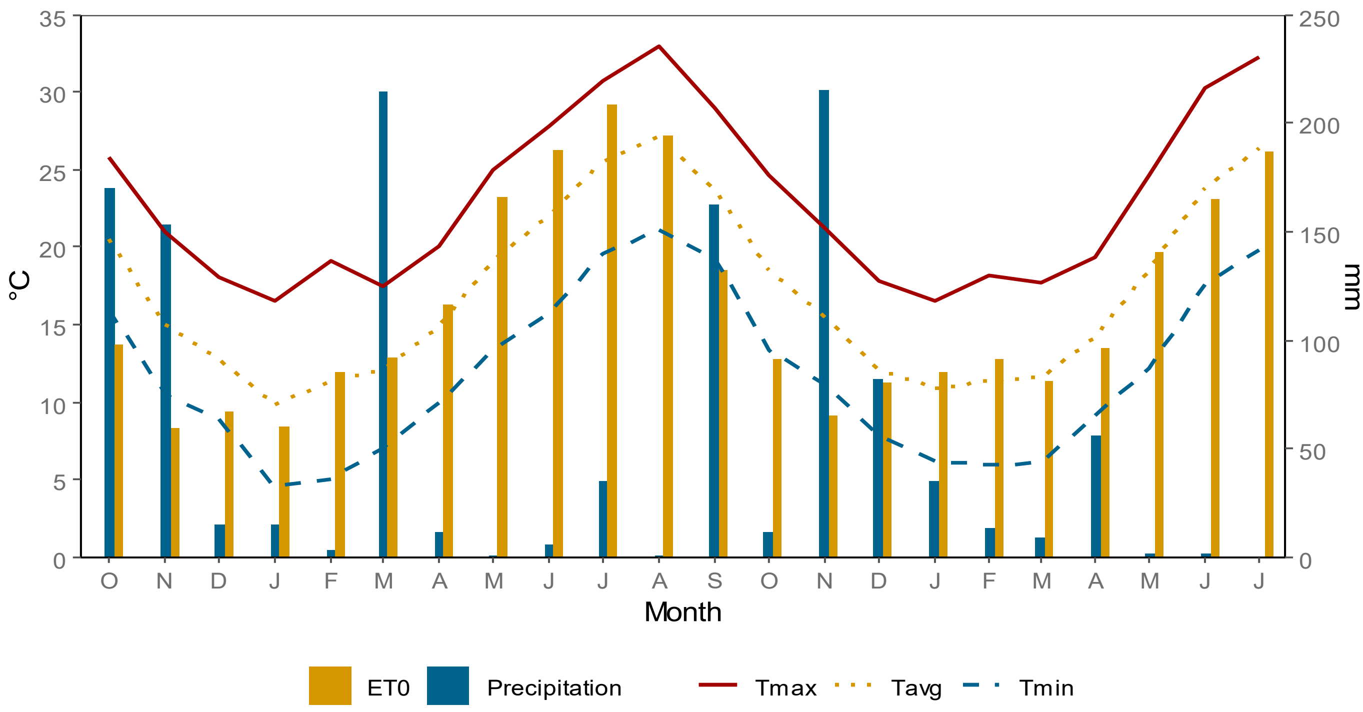

Figure 1. Meteorological variables (Tmax = month average of daily maximum temperature, Tavg = month average of daily mean temperature, Tmin = month average of daily minimum temperature, ET0 = month sum of daily reference evapotranspiration, Precipitation = monthly precipitation) from October 2019 to July 2021 at the experimental site (Catania, 37°24′ N., 15°03′ E., 10 m a.s.l.).

3.2. Analysis of Variance

The main effects (genotype, irrigation, days after sowing) had a significant effect on net photosynthesis rate, transpiration rate, stomatal conductance, and iWUE. The interaction genotype × irrigation had no significant effect on any variable. The interaction genotype × DAS had a significant effect on net photosynthesis rate, transpiration rate, stomatal conductance, and iWUE. The interactions irrigation × DAS and genotype × irrigation × DAS had a significant effect only on transpiration rate (Table 2). Grain yield was significantly affected by genotype and irrigation. The year, considered as a random factor, had a significant effect on net photosynthesis rate, transpiration rate, stomatal conductance, iWUE, and grain yield. The residual distribution was non-significantly different from the normal distribution for all the variables according to the Shapiro–Wilk test and the variance of all the variables was significantly homogeneous according to the Bartlett test.

Table 2. Four-way ANOVA for main effects (Genotype, Irrigation, DAS = days after sowing, Year) and interaction (Genotype × Irrigation, Genotype × DAS, Irrigation × DAS, Genotype × Irrigation × DAS) on net photosynthesis rate (A), transpiration rate (E), stomatal conductance (gs), instantaneous water use efficiency (IWUE). Three-way ANOVA for main effects (Genotype, Irrigation, Year) and interaction (Genotype × Irrigation) on grain yield. The *p*-value is reported. Irrigation and genotypes are the between-factor effects.

Surce of Variation	A	E	gs	iWUE	Grain Yield
Genotype	2.39×10^{-13}	3.77×10^{-8}	3.59×10^{-12}	1.53×10^{-6}	5.46×10^{-12}
Irrigation	$<10^{-15}$	3.68×10^{-15}	$<10^{-15}$	2.52×10^{-6}	3.13×10^{-4}
DAS	$<10^{-15}$	$<10^{-15}$	$<10^{-15}$	$<10^{-15}$	-
Year	$<10^{-15}$	$<10^{-15}$	$<10^{-15}$	3.59×10^{-5}	$<10^{-15}$
Genotype × Irrigation	0.29	0.48	0.13	0.52	0.99
Genotype × DAS	8.99×10^{-12}	4.83×10^{-7}	5.72×10^{-12}	7.45×10^{-5}	-
Irrigation × DAS	0.62	1.27×10^{-6}	0.59	0.29	-
Genotype × Irrigation × DAS	0.67	0.01766	0.12	0.30	-

3.3. Grain Yield

Irrigation input led to an increase in grain yield in 2020 and a stronger increment in 2021. Among the ancient populations, Margherito reached the highest grain yield during both years (3.1 Mg ha^{-1} in rainfed conditions and 3.4 Mg ha^{-1} in irrigated conditions), exceeding the productivity of the modern commercial varieties of durum wheat (Mongibello and Core) (Figure 2). The soft wheat variety Bologna had the lowest yield both in 2020 and 2021 due to its low suitability to the semiarid Mediterranean environment, due to the long growing season.

Grain yields were higher in 2020 than in 2021 (3.1 and 2.2 Mg ha^{-1}, respectively) due to the higher precipitation during the period of October–May, before the differentiation of the irrigation factor. The difference in precipitation between the first and the second year led to a higher effect of irrigation on grain yield during the second year; the mean increase in grain yield due to irrigation was 5.06% in 2020 and 16.2% in 2021.

3.4. Leaf Gas Exchange

Irrigation caused an increase of 28.9% and 24.6% in stomatal conductance in 2020 and 2021, respectively (from 0.14 mol m^{-2} s^{-1} to 0.19 mol m^{-2} s^{-1} in 2020 and from 0.09 mol m^{-2} s^{-1} to 0.12 mol m^{-2} s^{-1} in 2021), which led to 17.4% and 18.8% increase in net assimilation rates in 2020 and 2021, respectively (from 10.6 µmol m^{-2} s^{-1} to 12.9 µmol m^{-2} s^{-1} in 2020 and from 8.4 µmol m^{-2} s^{-1} to 12.2 µmol m^{-2} s^{-1} in 2021). Transpiration rate increased by 18.8% and 4.1% in 2020 and 2021 under irrigated condition compared to rainfed condition (from 3.09 mmol m^{-2} s^{-1} to 3.79 mmol m^{-2} s^{-1} in 2020 and from 2.29 mmol m^{-2} s^{-1} to 2.40 mmol m^{-2} s^{-1} in 2021).

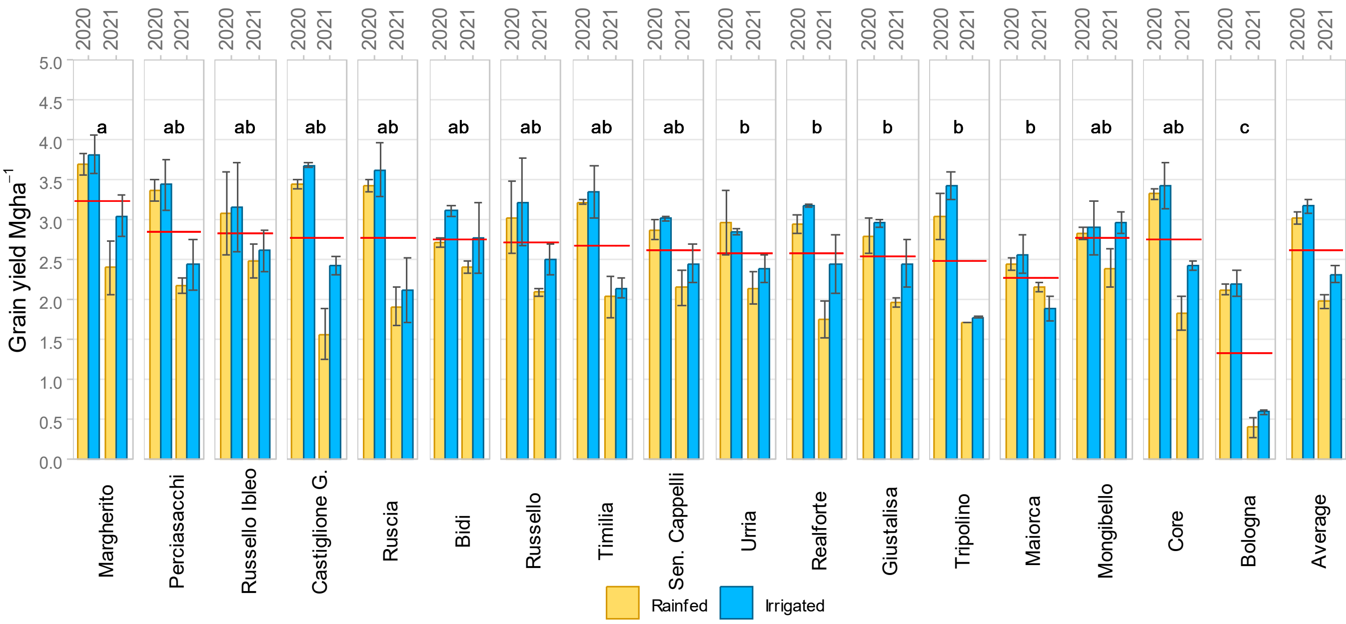

Figure 2. Grain yield (Mg ha^{-1}) during 2020 and 2021 cropping seasons under two irrigation levels (rainfed and irrigated) for twelve ancient Sicilian populations of durum wheat ("Bidì", "Castiglione Glabro", "Giustalisa", "Margherito", "Perciasacchi", "Realforte", "Ruscia", "Russello", "Russello Ibleo", "Timilia", "Tripolino", "Urria"), one ancient Sicilian population of bread wheat ("Maiorca"), one old variety of durum wheat ("Senatore Cappelli"), two modern commercial varieties of durum wheat ("Mongibello" and "Core"), and one modern commercial variety of soft wheat ("Bologna"). The red lines represent the average grain yield for each genotype. Grain yield LSD = 0.770 Mg ha^{-1}. Letters indicate significant differences between genotype means using Fisher's LSD post hoc test.

Among ancient landraces, "Realforte", "Margherito", and "Bidi" had higher than average stomatal conductance in 2020 both under rainfed and irrigated conditions (Figure 3). During 2021, the aforementioned landraces had stomatal conductance values close to average or slightly above (Figure 3). "Russello" showed higher than average stomatal conductance under irrigated condition during 2020 and 2021, but the values were lower or close to average under rainfed condition.

High stomatal conductance led to higher than average transpiration and net assimilation rates; "Realforte", "Bidi", and "Margherito" had the highest net assimilation and transpiration rates in 2020 under rainfed and irrigated conditions (Figures 4 and 5).

The modern commercial bread wheat variety "Bologna" showed the highest net photosynthesis rate under irrigated condition considering the two-year average, while under rainfed condition, it showed a net photosynthesis rate higher than the average of the genotypes (Figure 4). Among the modern durum wheat varieties, "Core" showed higher than average net assimilation and transpiration rate in 2020 under irrigated and rainfed conditions, while the values were close to average in 2021.

The ancient landraces "Realforte", "Margherito", "Bidi", and "Russello Ibleo" had the highest iWUE values under irrigated conditions in both years. "Russello Ibleo" reached 4.1 and 3.9 µmol CO_2 mol^{-1} H_2O during the 2021 growing season under irrigated and rainfed condition, respectively, despite having a net photosyentesis rate just above average, due to the low transpiration rate.

The average iWUE among ancient landraces was higher than the average among modern varieties under rainfed conditions and lower than the average among modern varieties under irrigated conditions.

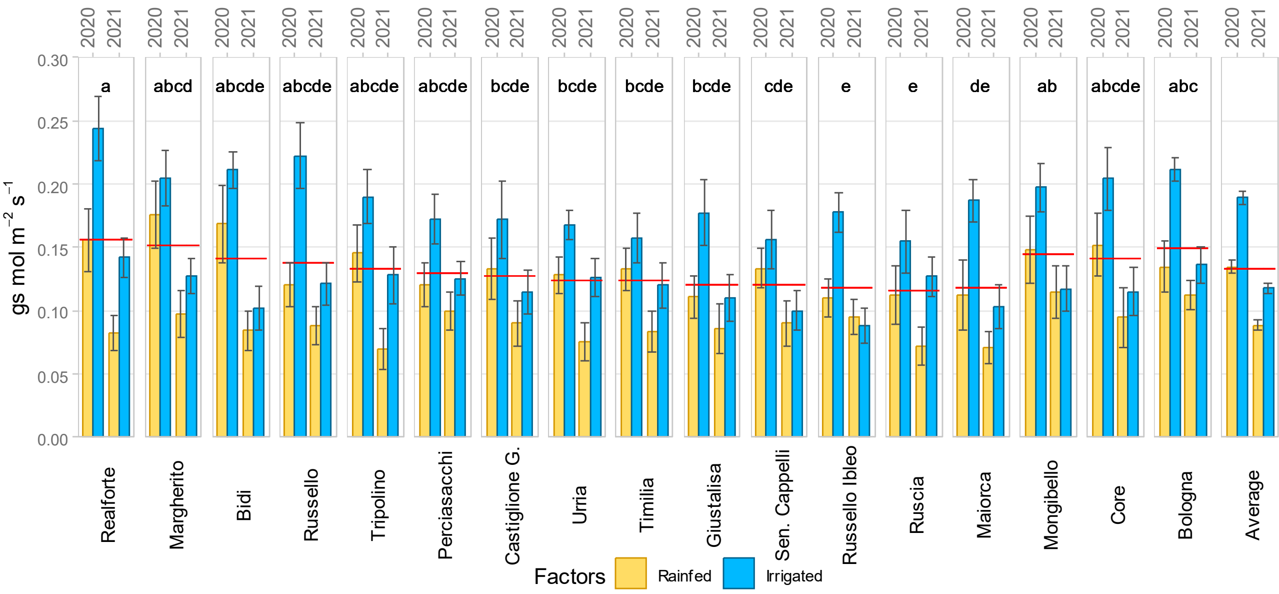

Figure 3. Stomatal conductance (gs, mol m^{-2} s^{-1}) during 2020 and 2021 cropping seasons under two irrigation levels (rainfed and irrigated) for twelve ancient Sicilian populations of durum wheat ("Bidì", "Castiglione Glabro", "Giustalisa", "Margherito", "Perciasacchi", "Realforte", "Ruscia", "Russello", "Russello Ibleo", "Timilia", "Tripolino", "Urria"), one ancient Sicilian population of bread wheat ("Maiorca"), one old variety of durum wheat ("Senatore Cappelli"), two modern commercial varieties of durum wheat ("Mongibello" and "Core"), and one modern commercial variety of soft wheat ("Bologna"). The red lines represent the average value for each genotype. Letters indicate significant differences between genotype means using Fisher's LSD post hoc test.

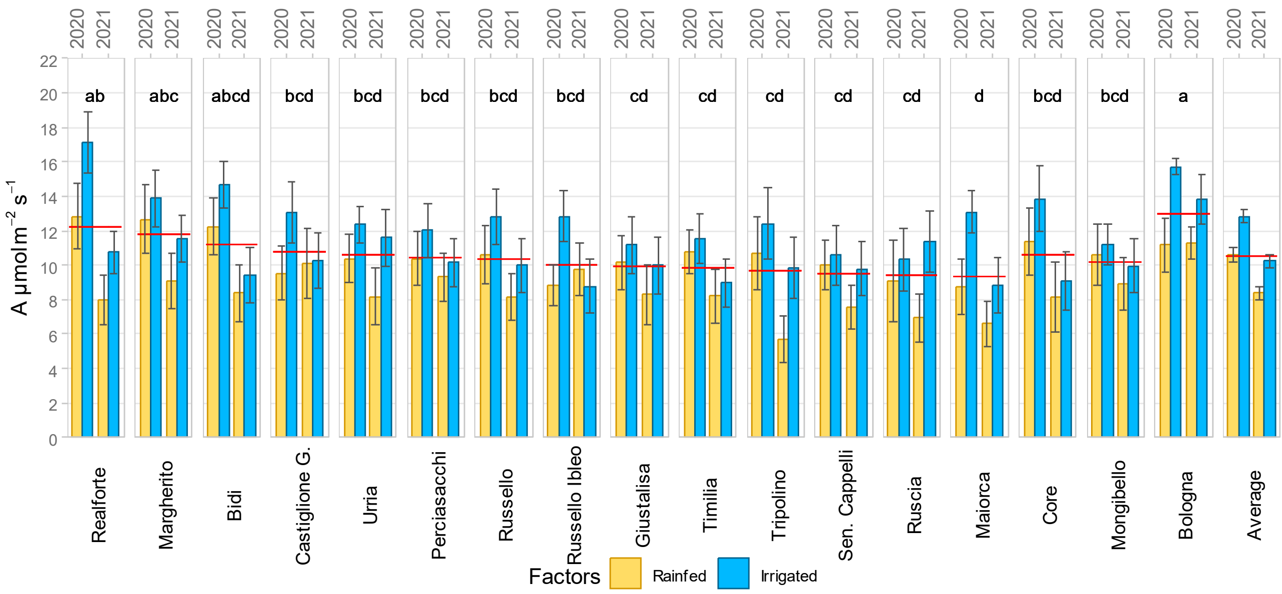

Figure 4. Net assimilation rate (A, µmol m^{-2} s^{-1}) during 2020 and 2021 cropping seasons under two irrigation levels (rainfed and irrigated) for twelve ancient Sicilian populations of durum wheat ("Bidì", "Castiglione Glabro", "Giustalisa", "Margherito", "Perciasacchi", "Realforte", "Ruscia", "Russello", "Russello Ibleo", "Timilia", "Tripolino", "Urria"), one ancient Sicilian population of bread wheat ("Maiorca"), one old variety of durum wheat ("Senatore Cappelli"), two modern commercial varieties of durum wheat ("Mongibello" and "Core"), and one modern commercial variety of soft wheat ("Bologna"). The red lines represent the average value for each genotype. Letters indicate significant differences between genotype means using Fisher's LSD post hoc test.

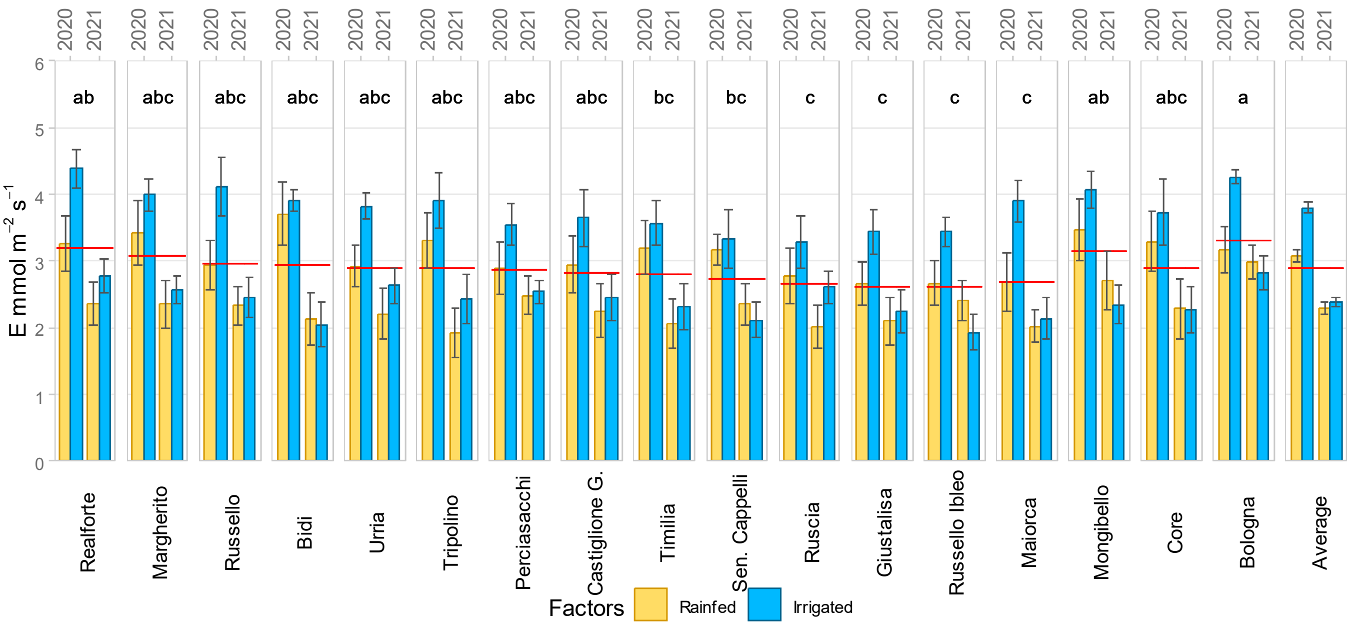

Figure 5. Transpiration rate (E, mmol m^{-2} s^{-1}) during 2020 and 2021 cropping seasons under two irrigation levels (rainfed and irrigated) for twelve ancient Sicilian populations of durum wheat ("Bidì", "Castiglione Glabro", "Giustalisa", "Margherito", "Perciasacchi", "Realforte", "Ruscia", "Russello", "Russello Ibleo", "Timilia", "Tripolino", "Urria"), one ancient Sicilian population of bread wheat ("Maiorca"), one old variety of durum wheat ("Senatore Cappelli"), two modern commercial varieties of durum wheat ("Mongibello" and "Core"), and one modern commercial variety of soft wheat ("Bologna"). The red lines represent the average value for each genotype. Letters indicate significant differences between genotype means using Fisher's LSD post hoc test. The effect of irrigation on iWUE was not statistically significant (Table 1); nevertheless, the highest iWUE values were achieved under irrigated conditions (Figure 6). IWUE values were higher in 2021 than in 2020 due to the lower transpiration rates.

The relationship between net assimilation rate and grain yield has been studied for 16 genotypes (Figure 7), with the exclusion of "Bologna", whose grain yield values were outside the interquartile range. Net assimilation rate and grain yield results were significantly correlated (p-value = 3.20×10^{-9}) with a Pearson's product-moment correlation coefficient of 0.659 (Figure 8).

A strong positive correlation has also been observed between grain yield and transpiration rate and between grain yield and stomatal conductance. Among gas exchange variables, net assimilation rate, transpiration rate, and stomatal conductance were pairwise correlated, while instant water use efficiency was not significantly correlated with net photosynthesis rate and stomatal conductance and was negatively correlated with transpiration rate (Figure 8).

Stomatal conductance decreased during the period from anthesis until full ripening under both rainfed and irrigated conditions due to leaf senescence (Figures 9 and 10). The decrease in stomatal conductance was faster in rainfed condition where soil moisture was depleted. Late ripening varieties ("Bidi", "Bologna", "Margherito", "Timilia", "Urria") maintained a higher stomatal conductance during the late ripening stage under irrigated conditions.

The trend in stomatal conductance also affected the net assimilation rate trend, which showed a sharp decrease approaching the full ripening stage (Figures 11 and 12). In irrigated condition, net assimilation rate stayed high until full ripening stage in late ripening varieties ("Bidi", "Bologna", "Margherito", "Timilia", "Urria").

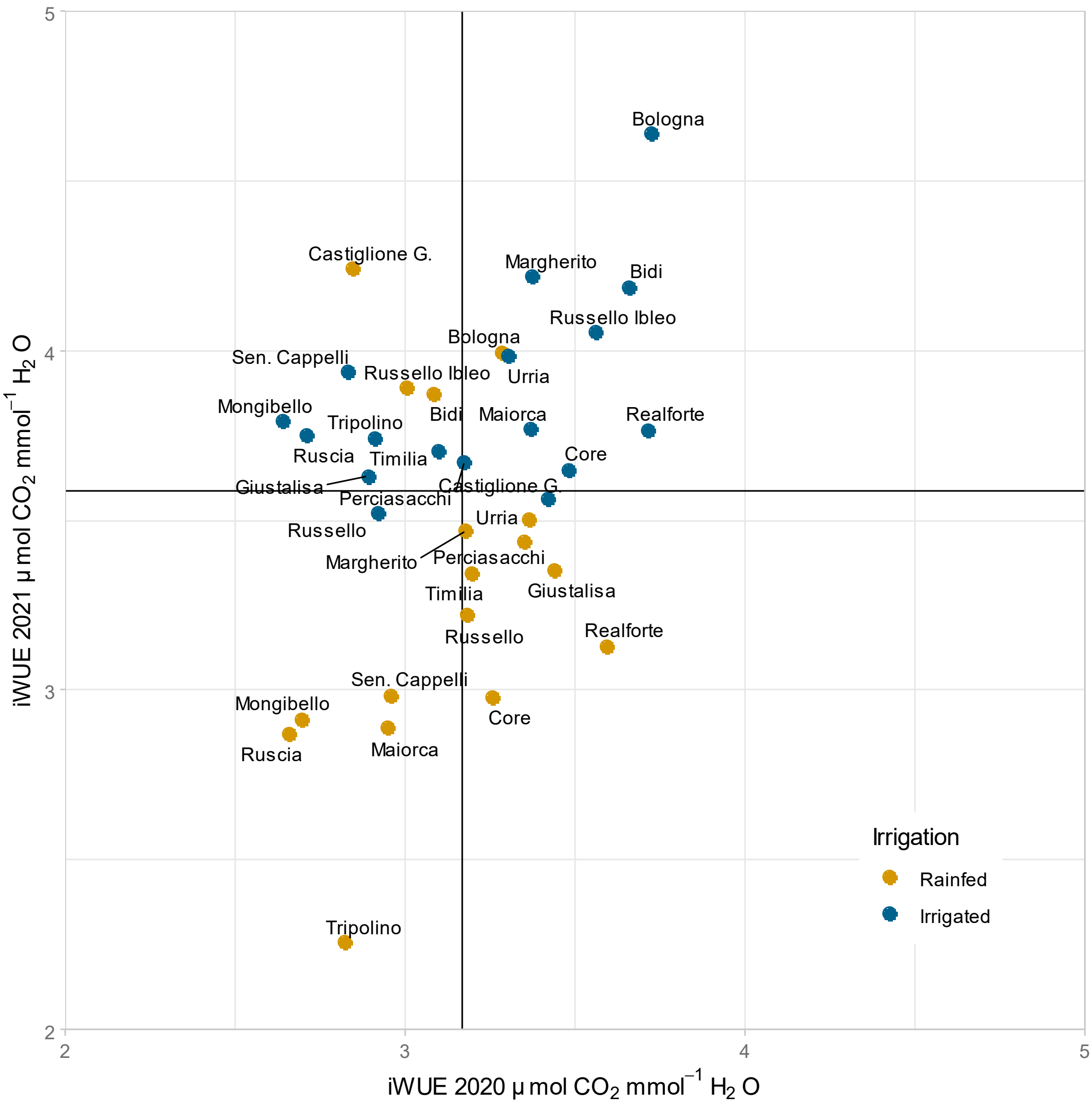

Figure 6. Instantaneous water use efficiency (µmol CO_2 $mmol^{-1}$ H_2O) during 2020 and 2021 cropping seasons under two irrigation levels (rainfed and irrigated) for twelve ancient Sicilian populations of durum wheat ("Bidì", "Castiglione Glabro", "Giustalisa", "Margherito", "Perciasacchi", "Realforte", "Ruscia", "Russello", "Russello Ibleo", "Timilia", "Tripolino", "Urria"), one ancient Sicilian population of bread wheat ("Maiorca"), one old variety of durum wheat ("Senatore Cappelli"), two modern commercial varieties of durum wheat ("Mongibello" and "Core"), and one modern commercial variety of soft wheat ("Bologna"). The continuous black lines represent the mean iWUE values for 2020 and 2021.

A similar trend was observed for the transpiration rate (Figures 13 and 14), which decreased during the period from anthesis until full ripening due to the decreasing stomatal conductance in response to leaf senescence and soil moisture depletion in rainfed condition. The decrease in transpiration rate during late ripening was lower compared to the decrease in stomatal conductance due to the rising vapor pressure deficit, which has a positive effect on leaf transpiration.

The IWUE trend was mainly affected by phenological stage and poorly affected by the irrigation factor (Figures 15 and 16). The lowest values of iWUE were reached at full ripening stage.

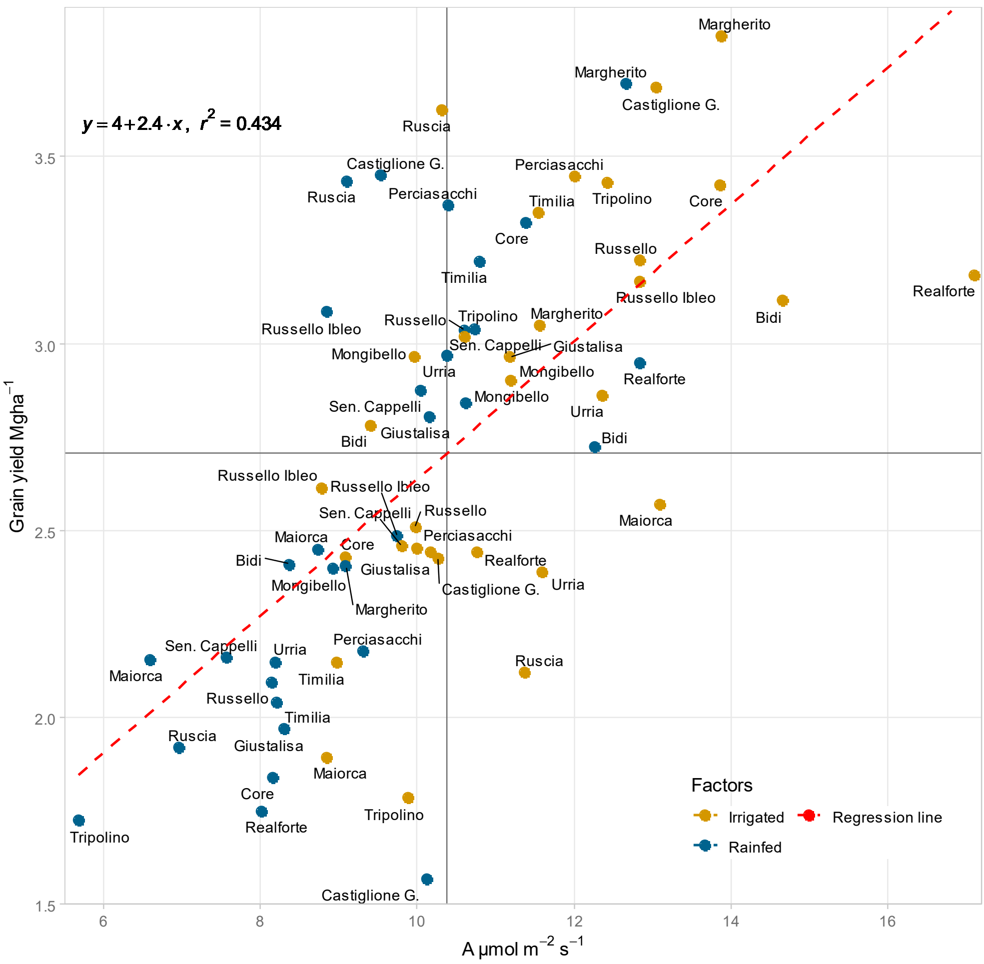

Figure 7. Variation of grain yield (Mg ha^{-1}) in relation to the net assimilation rate (A, μmol m^{-2} s^{-1}) during 2020 and 2021 cropping seasons under two irrigation levels (rainfed and irrigated) for twelve ancient Sicilian populations of durum wheat ("Bidì", "Castiglione Glabro", "Giustalisa", "Margherito", "Perciasacchi", "Realforte", "Ruscia", "Russello", "Russello Ibleo", "Timilia", "Tripolino", "Urria"), one ancient Sicilian population of bread wheat ("Maiorca"), one old variety of durum wheat ("Senatore Cappelli"), and two modern commercial varieties of durum wheat ("Mongibello" and "Core"). The dashed red line represents the linear regression. The continuous black lines represent the mean values for grain yield and net assimilation rate.

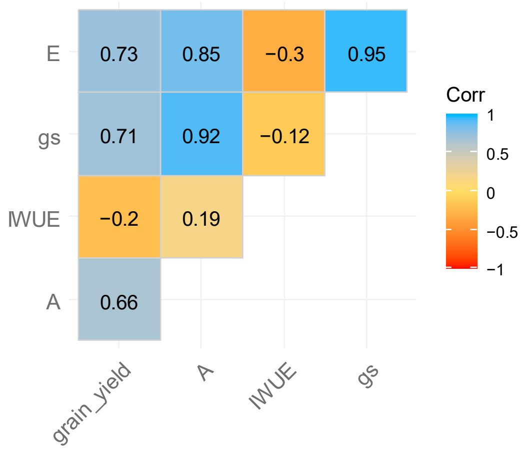

Figure 8. Pearson correlation matrix of the measured variables (grain yield, A = net assimilation rate, IWUE = instant water use efficiency, gs = stomatal conductance, E = transpiration rate).

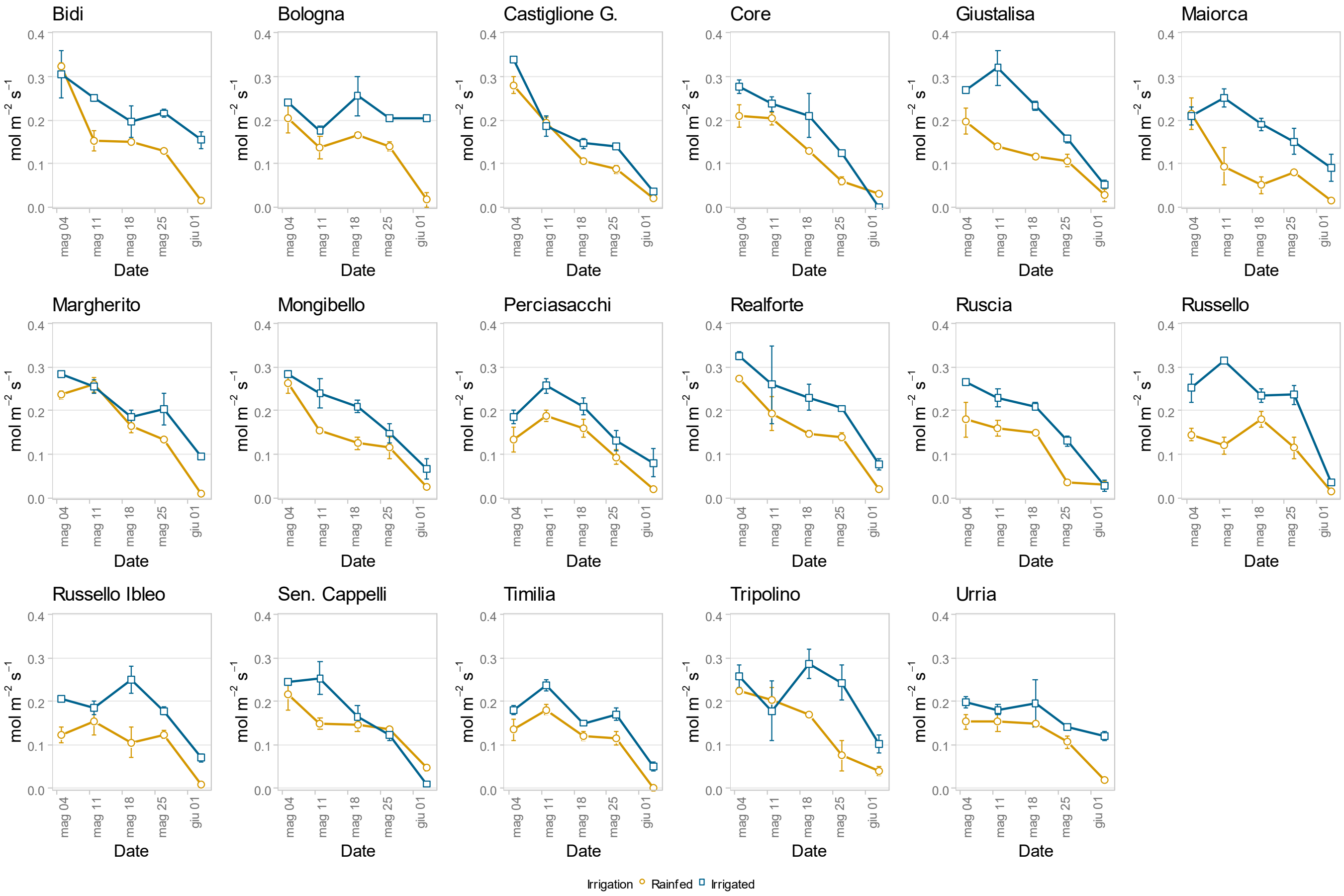

Figure 9. Stomatal conductance (mol m^{-2} s^{-1}) during 2020 cropping seasons under two irrigation levels (rainfed and irrigated) for 17 wheat genotypes.

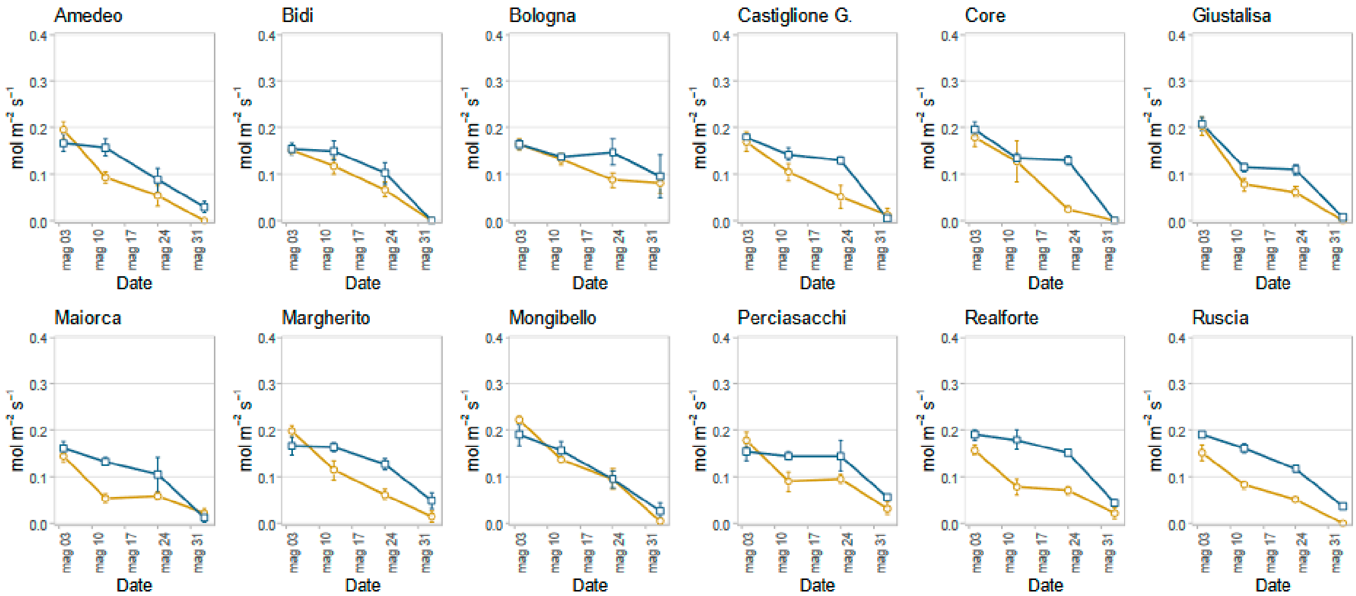

Figure 10. *Cont.*

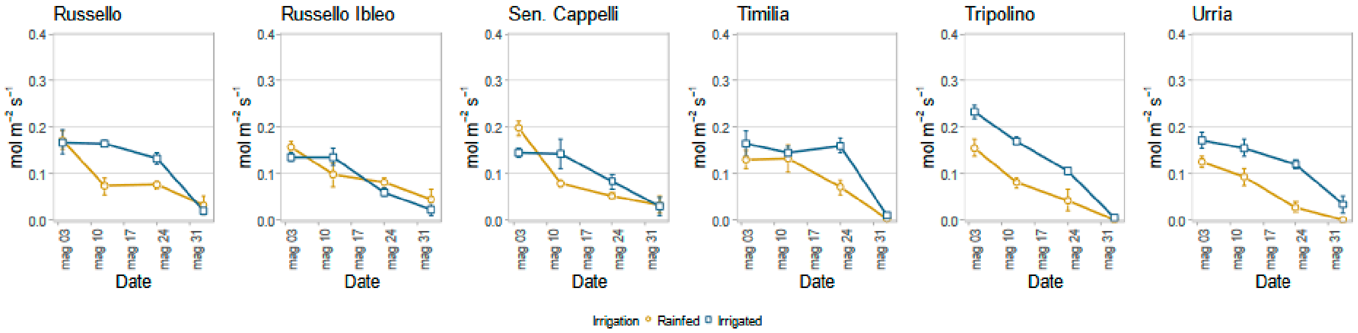

Figure 10. Stomatal conductance (mol m^{-2} s^{-1}) during 2021 cropping seasons under two irrigation levels (rainfed and irrigated) for 17 wheat genotypes.

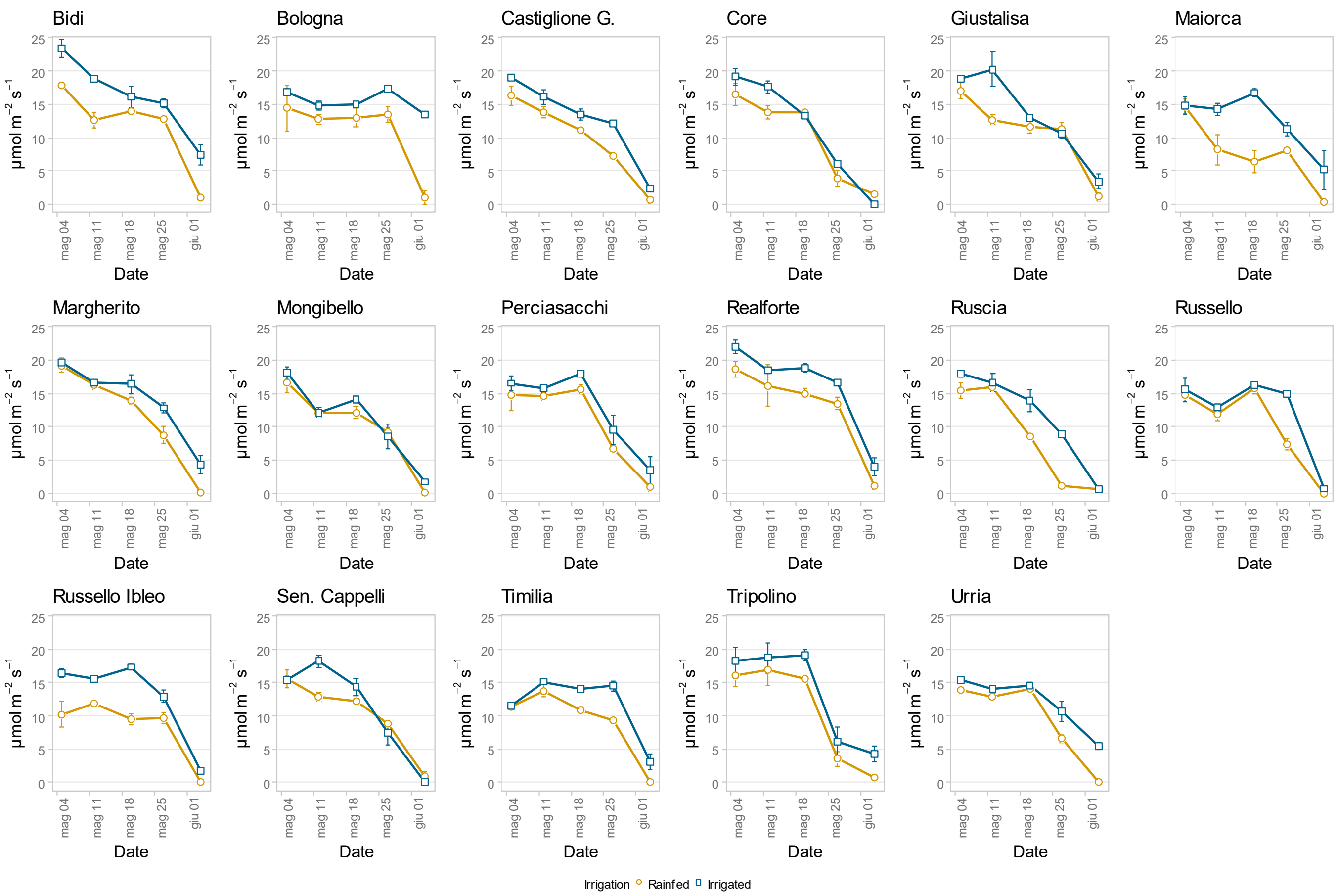

Figure 11. Net assimilation rate (µmol m^{-2} s^{-1}) during 2020 cropping seasons under two irrigation levels (rainfed and irrigated) for 17 wheat genotypes.

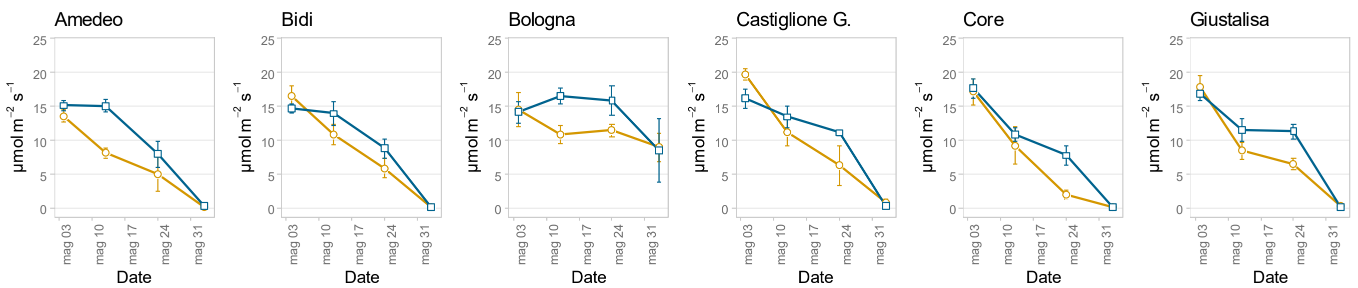

Figure 12. *Cont.*

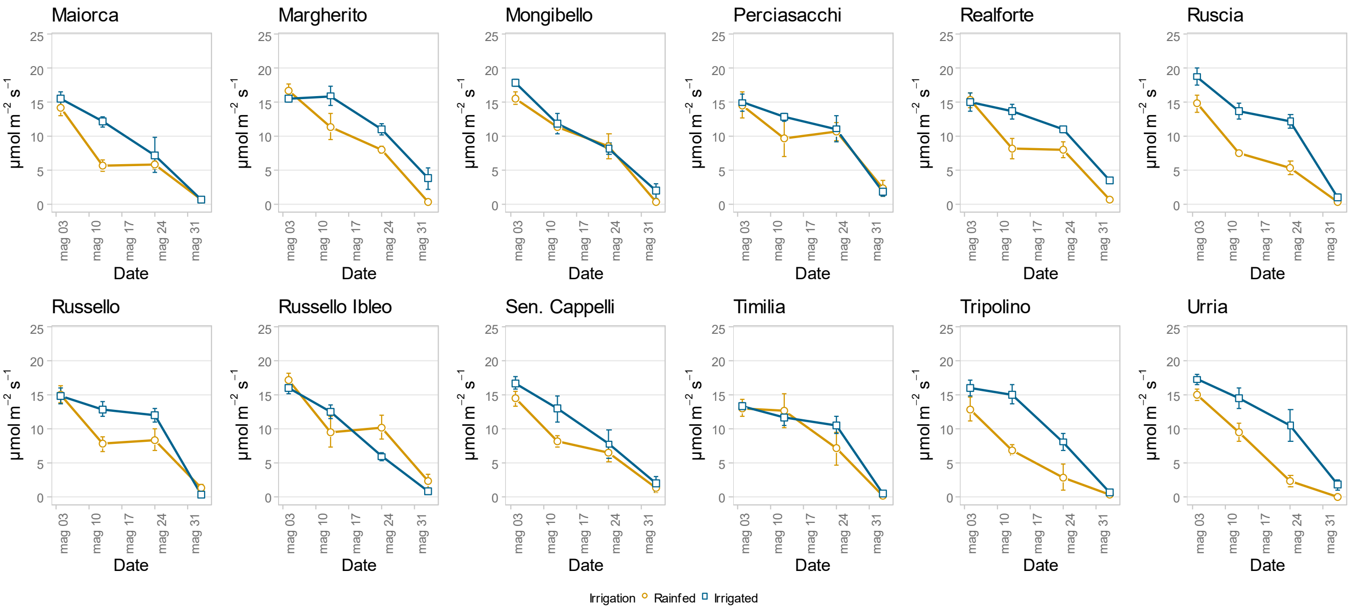

Figure 12. Net assimilation rate (µmol m^{-2} s^{-1}) during 2021 cropping seasons under two irrigation levels (rainfed and irrigated) for 17 wheat genotypes.

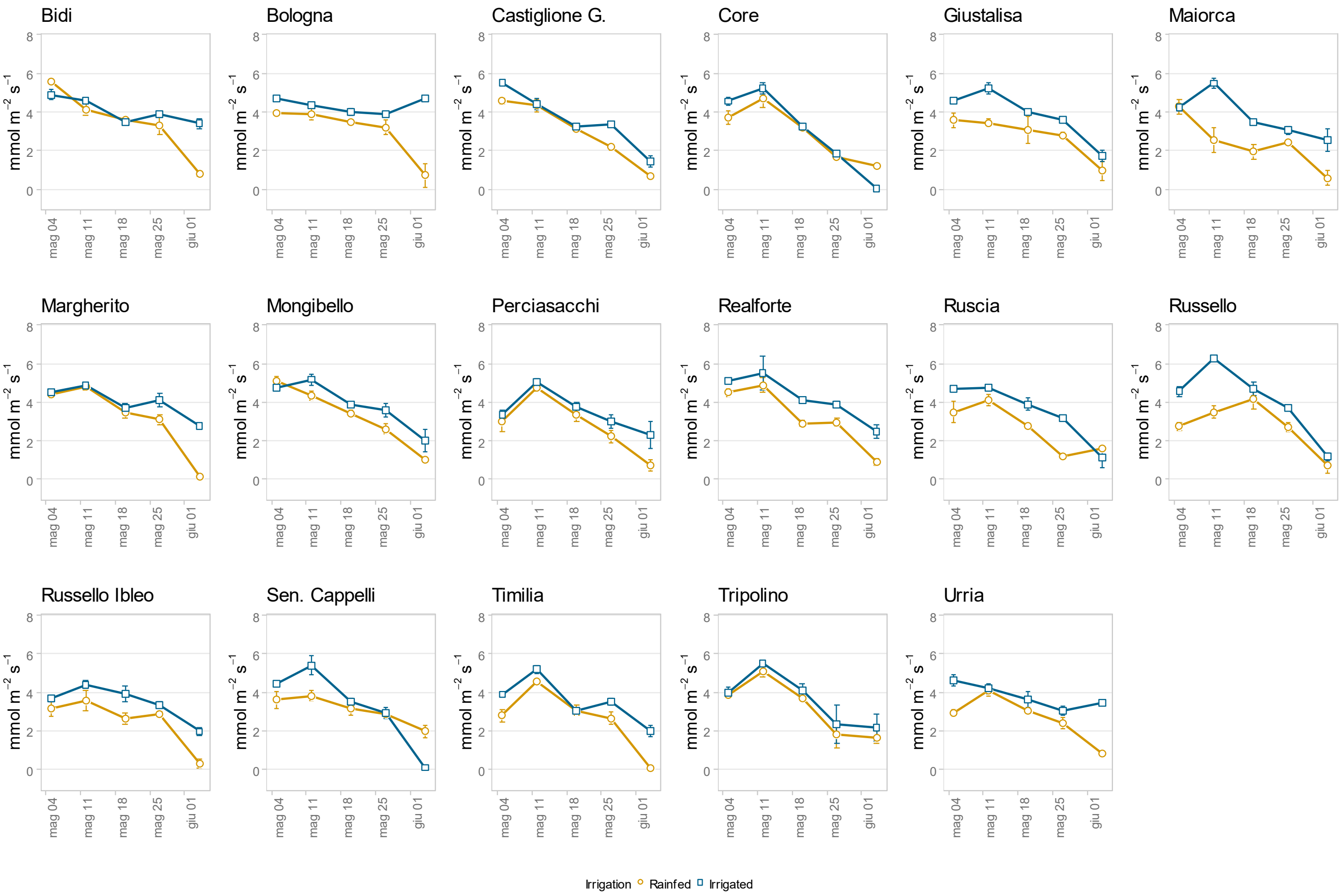

Figure 13. Transpiration rate (mmol m^{-2} s^{-1}) during 2020 cropping seasons under two irrigation levels (rainfed and irrigated) for 17 wheat genotypes. The red lines represent the average value for each genotype.

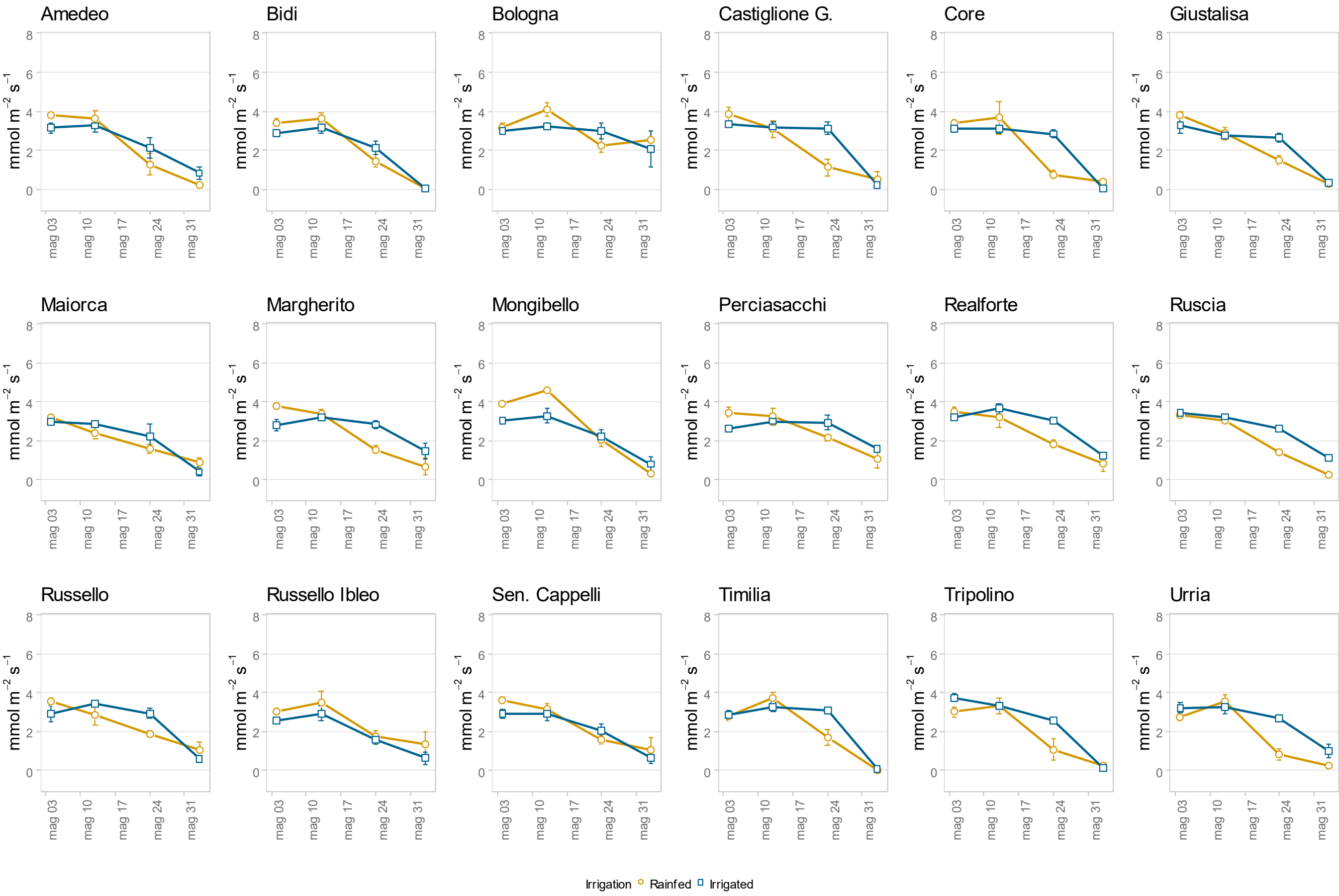

Figure 14. Transpiration rate (mmol m^{-2} s^{-1}) during 2021 cropping seasons under two irrigation levels (rainfed and irrigated) for 17 wheat genotypes. The red lines represent the average value for each genotype.

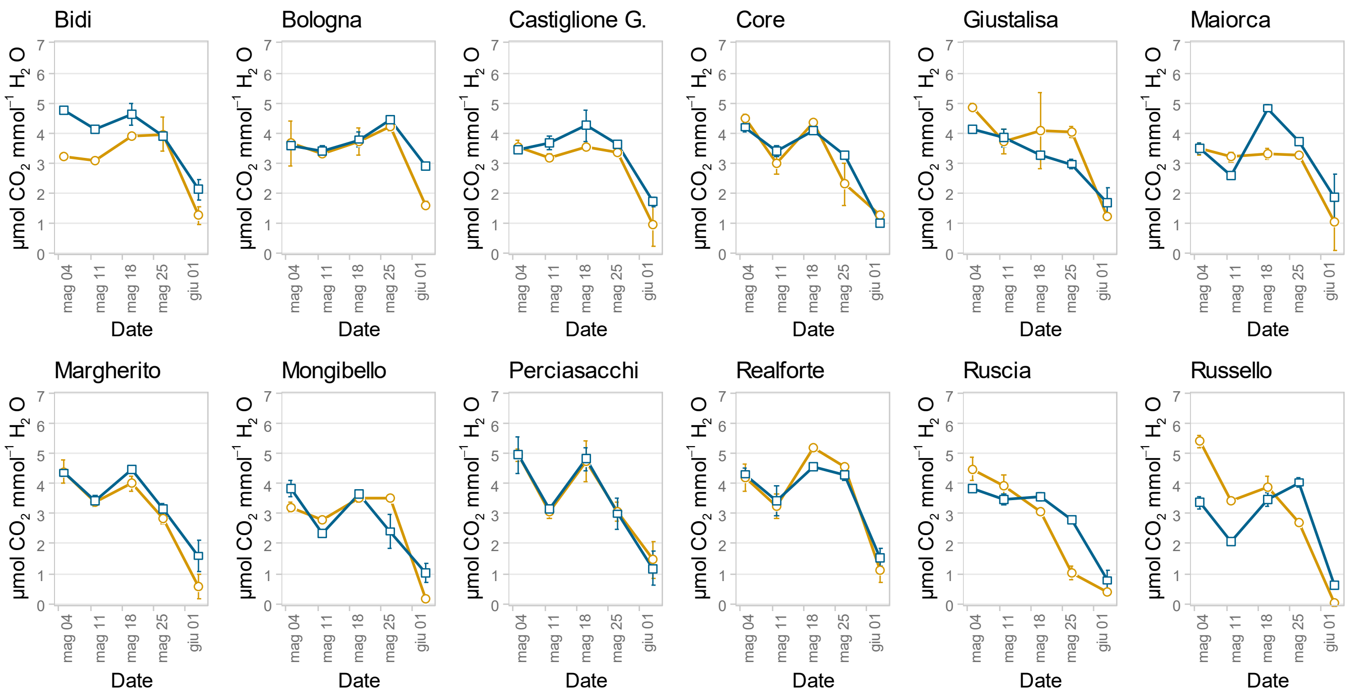

Figure 15. *Cont.*

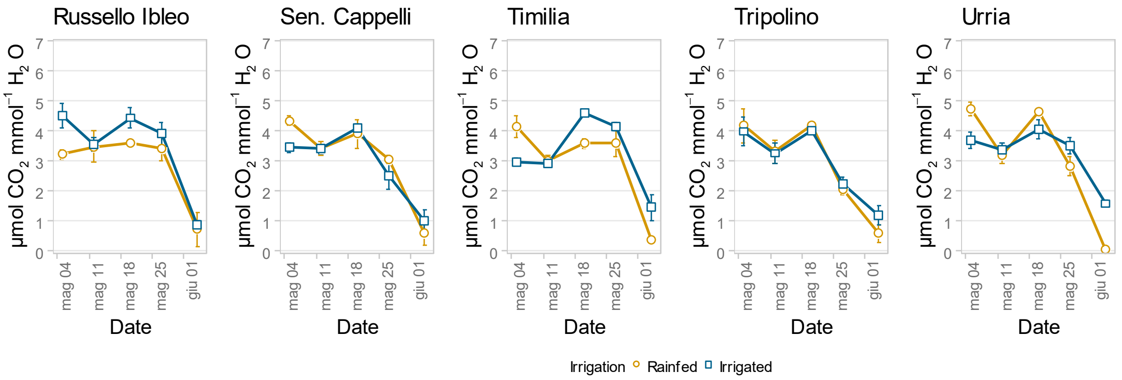

Figure 15. Instantaneous water use efficiency (µmol mmol m^{-2} s^{-1}) during 2020 cropping seasons under two irrigation levels (rainfed and irrigated) for 17 wheat genotypes.

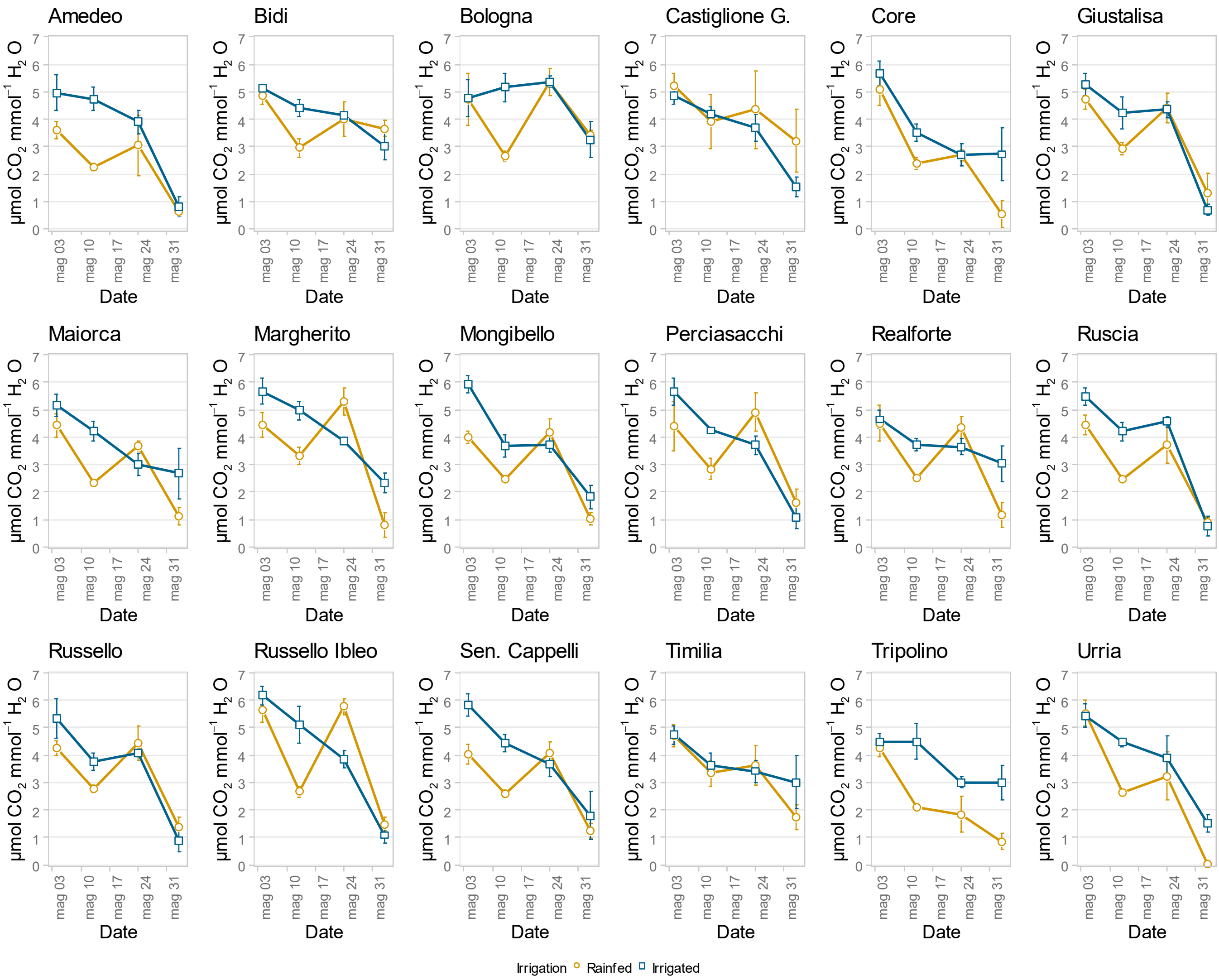

Figure 16. Instantaneous water use efficiency (µmol mmol m^{-2} s^{-1}) during 2021 cropping seasons under two irrigation levels (rainfed and irrigated) for 17 wheat genotypes.

4. Discussion

Wheat landraces responded to the different levels of water availability in the soil similarly to modern wheat varieties, showing a lower stomatal conductance during the period from anthesis to seed ripening in rainfed condition, as a consequence of the reduced water availability. The reduction in the stomatal conductance limited the transpiration and therefore the water consumption of the crop, but also led to a reduction in the net photosynthesis rate. During the period from anthesis to seed ripening, stomatal conduction, transpiration, and net assimilation rate decreased in response to leaf senescence under both irrigated and rainfed conditions. The same decreasing trend has been observed by [33] in analogous conditions.

Few studies have compared the gas exchanges of wheat landraces and modern wheat varieties. Among these studies, [33] found the landrace "Russello" having lower net photosynthesis rate during the grain filling stage than the modern variety "Mongibello", while the transpiration rate was higher, leading to a lower iWUE in open field conditions; under heat stress generated by a greenhouse, "Russello" achieved higher net photosynthesis rate and similar iWUE to "Mongibello", confirming the adaptability of landraces to under-optimal environmental conditions.

A positive linear relation between net assimilation rate and grain yield has been found among the genotypes, considering both years under irrigated and rainfed conditions. As a consequence, the limited photosynthesis rate during the period from anthesis to seed ripening led to a lower grain yield in rainfed conditions than in irrigated conditions. Similar results have been reported by [19], who found wheat grain yield was consistently and positively associated with net photosynthetic rates during all phenological stages and in particular post-anthesis, and by [17], who found a positive linear relation between post-anthesis net assimilation rate and grain yield among modern cultivar and landraces. The same study reported lower net photosynthesis rate in wheat landraces compared to modern cultivars under favorable climatic conditions and high nitrogen input [17]. Another study by [18] found a weak correlation between pre-anthesis net assimilation rate and grain yield on wheat modern commercial cultivars.

A previous study by [33] reported lower productivity of bread wheat Sicilian landraces when compared to modern commercial varieties. In the present study, the grain yields of modern durum wheat varieties were slightly above the average among the examined genotypes; in spite of that, several landraces achieved higher grain yield. These landraces were characterized by higher than average net photosynthesis rate (Margherito, Castiglione Glabro, Bidi) and therefore higher productivity per unit of leaf area, or higher than average iWUE (Margherito, Russello Ibleo, Bidi), which allows higher productivity per unit of water transpired.

Considering the landraces and the modern commercial varieties in both rainfed and irrigated conditions, grain yield was highly correlated with stomatal conductance and transpiration rate and non-significantly correlated with iWUE, suggesting that high yield is linked to crop water use rather than merely the efficiency of crop water use. The ability to thoroughly utilize soil water depends on the extension of the root system [37–39], which is particularly deep in landraces selected in semi-arid areas [7–10].

Leaf area index and leaf area duration are further responsible for biomass and grain yield in wheat [40,41]. Whether wheat landraces are able to develop and maintain a greater leaf area than modern commercial varieties in water-limiting conditions has yet to be assessed.

Soil water availability effect on grain yield is more pronounced during the second part of the trial, due to the lower rainfall during the vegetative phases. Among the high-yielding landraces, Russello Ibleo and Pierciasacchi were least affected by the rainfed condition with a 3.8% and 6.6% reduction, respectively, while Castiglione Glabro was the most affected by the rainfed condition during the second year, reaching a reduction of 35%.

The reduction in grain yield due to the limiting soil water availability was higher in modern varieties than the average of the examined genotypes.

Grain yield losses due to the effect of soil water availability were in line with the results reported by [6], who found losses of 8% when wheat was irrigated based on long-term precipitation, between 41% and 51%, or between 37% and 48% when wheat was affected by, respectively, pre-heading and post-heading water limitation compared to the high water input yield. The same study reported that landraces from Turkey, Iran, and Afghanistan, where the precipitation distribution is similar to that of the Mediterranean climate, had a lower yield loss compared to modern varieties under limiting soil water, although modern varieties achieved higher grain yield [6]. In the present study, the difference between dry and irrigated grain yields was low due to the high soil water availability until the beginning of the seed ripening stage, leading to an optimal seed set in both rainfed and irrigated conditions. As a consequence, the difference in grain yield was only attributable to differences in grain filling.

Some Sicilian landraces, namely Margherito, Castiglione Glabro, Bidi, and Russello Ibleo, showed better performances in terms of grain yield and physiological responses than the most suited modern commercial varieties for the local environmental conditions. The genetic base of these phenotypic traits should be better investigated in order to provide additional tools for the wheat breeding programs in water-limited Mediterranean regions.

5. Conclusions

Wheat landraces responded to the different levels of water availability in the soil, showing a 26.8% reduction in stomatal conductance in rainfed condition, as a consequence of the reduced water availability. The reduction in the stomatal conductance limited the transpiration by 11.5% and therefore the water consumption of the crop, but also led to a reduction in the photosynthetic rate by 18.1%. Among local wheat landraces, Margherito, Castiglione Glabro, Bidi, and Russello exhibit equivalent or higher flag leaf net photosynthesis rates and reduced transpiration levels, resulting in higher grain yields under both rainfed and irrigated conditions. This reaffirms their value as a genetic resource for wheat breeding programs in drought-vulnerable Mediterranean areas.

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