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Productivity of Wheat Landraces in Rainfed and Irrigated Conditions under Conventional and Organic Input in a Semiarid Mediterranean Environment

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Abstract: Wheat landraces are locally adapted populations that are suitable for low-input agromomic management and constraining pedo-climatic conditions. The productivity of landraces under high-input and optimal conditions is usually lower than modern wheat varieties. The present study compared the response of Sicilian wheat landraces and modern varieties to organic management, including organic fertilization, and conventional management, including mineral fertilization and chemical weed control, under rainfed condition and supplementary irrigation in a field trial conducted on a xerofluent soil in a semiarid Mediterranean climate. Modern varieties were on average more productive than landraces, although certain landraces achieved comparable yields, in particular under organic management. The increase in grain yield under conventional management in comparison with the organic management was higher for modern varieties than landraces. The loss of productivity in rainfed conditions was lower for landraces compared to modern varieties. The grain quality traits were similar between landraces and modern varieties and in both cases the conventional management led to an improvement of the traits. These findings highlight the resilience and adaptability of traditional wheat landraces to low-input agricultural systems and offer valuable insights into improving the sustainability and productivity of wheat production in Mediterranean environments.

Keywords: conventional; grain yield; irrigation; Mediterranean; organic; rainfed

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1. Introduction

Wheat landraces form a genetically variable population that evolved under the selective pressure of low-input farming systems and in response to breeding based on phenotypical traits [1,2]. This process led to populations that are locally adapted and suitable to marginal climate, soil and agronomic conditions [3,4]. Among the favorable traits that certain wheat landraces possess are adaptive traits to abiotic stresses like water scarcity, salinity and limited chemical inputs [5,6]. The constraining trait of wheat landraces is the lower grain productivity in comparison with modern wheat varieties under more favorable conditions, in particular under irrigated and high-chemical-input farming [7–9], despite having higher or comparable grain quality [10–13].

Climate change is expected to negatively influence the water availability for crops, due to drought and higher precipitation variability, and affect the phenological development of crops, in particular in climate change hot spots such as the Mediterranean Basin [14,15]. Estimations indicate that the main cereal crops such as wheat, maize and rice will be reduced by 5–50%, 20–45% and 20–30%, respectively, by 2100 [16]. Therefore, identifying wheat genotypes that are resilient to water availability variability and suitable for drier conditions becomes highly important to ensure food security.

Wheat varieties and landraces originating from drought-prone areas (e.g., southern Mediterranean and Middle East) are generally more suitable for dry conditions compared to those from wetter areas [8,17–19]. Drought tolerance has been linked to the ability to thoroughly utilize soil water deposits and, therefore, to the extension of the root system [20–22], which is particularly extended in landraces originating from semiarid areas [6,23–25].

Nitrogen mineral fertilization helps achieve high grain yields and improves grain quality; nevertheless, it contributes significantly to the carbon footprint of wheat farming [26,27], furthermore causing environmental impacts that are exacerbated by extreme precipitation events [28]. Additionally, there is a growing demand from both the public and end consumers for lower-environmental-footprint or organic products [29].

Most organic and low-input wheat production currently relies on conventionally bred varieties that are often unsuitable for low-input systems, having been bred for high-input farming and possessing many traits that can negatively impact organic farming, such as an increased harvest index and reduced plant height [30,31]. These traits often lead to reduced root size, reliance on high inorganic nitrogen inputs, lower nutrient use efficiency and increased disease susceptibility while providing some benefits like improved lodging resistance [30]. New breeding programs are developing wheat varieties specifically designed for organic conditions and low-input systems, enhancing traits such as nutrient efficiency, weed competition, disease resistance and processing quality [32]. A critical factor for wheat production in organic farming is the ability to absorb nitrogen and phosphorus in early spring when cold or waterlogged soils have low microbial activity, which limits the mineralization of soil organic matter. Under these conditions, conventionally bred varieties often achieve lower grain protein content compared to older cultivars [30]; however, the higher protein content is usually correlated with a lower grain yield [33]. The traits that can help plants cope with water and nutrient limitations are an efficient and deep root system, photosynthesis maintenance under nutrient stress, nutrient uptake capacity and translocation efficiency and the ability to establish beneficial interaction with soil microorganisms to enhance nutrient mineralization [30]. Old wheat varieties and landraces have proved to possess some of these traits, achieving higher nutrient absorption under limiting availability conditions [6,30]. Breeding under organic farming conditions is particularly important for traits that have low repeatability and a strong environment influence, such as grain yield, leaf inclination and vigorous growth during booting, while other traits that have high repeatability, such as heading date, sensitivity to leaf rust and powdery mildew, could be selected under conventional management [34].

Quality aspects of organic wheat production remain under-researched, but protein content is particularly important to organic farmers and consumers, as it affects bread-making quality and selling prices. Organic cereals often have lower protein content due to the challenges and costs associated with supplying nitrogen later in the growing season [30].

Further wheat breeding programs tailored for organic, low-input farming in drought-prone areas will need additional genetic resources, which could be obtained from landraces that evolved with low mineral fertilization inputs and no chemical weeding and under nonoptimal climatic conditions [35,36].

The aim of this study is to evaluate the response of Sicilian wheat landraces to organic and conventional agronomic management under rainfed conditions and with supplementary irrigation in order to identify genotypes that could be integrated into future breeding programs. The response of landraces is compared to the response of locally adapted modern wheat varieties.

2. Materials and Methods

2.1. Experimental Site Description

The field experiment was conducted over the periods 2021–2022 and 2022–2023 in southern Italy (Sicily) at the experimental farm of the University of Catania, Italy (37°24' N, 15°03' E, 10 m a.s.l.), located within an area of the Catania Plain characterized as having typical xerofluvent soil (Table 1).

Table 1. Soil characteristics of the field site in two layers (0–25 cm and 25–50 cm).

Soil Characteristics	Unit	0–25 cm	25–50 cm	Method
Sand	%	49.3	54.6	Gattorta [37]
Loam	%	22.4	11.8	Gattorta [37]
Clay	%	28.3	33.6	Gattorta [37]
pH		8.6	7.7	In water solution
Total calcareous	%	15.2	13.7	Gas volumetric [38]
Organic matter	%	1.4	1.6	Walkley and Black [38]
Total N	‰	1	0.09	Kjeldahl [38]
P ₂ O ₅ availability	mg kg ^{−1}	5	2.3	Ferrari [38]
K ₂ O availability	mg kg ^{−1}	245	200	Dirks and Scheffer [38]
Bulk density	g cm ^{−3}	1.1	1.35	
Field capacity at −0.03 MPa	%	27	28	
Wilting point at −1.5 MPa	%	11	18	

2.2. Climatic Conditions

Local climatic conditions are semiarid Mediterranean, characterized by mild rainy winters and hot dry summers.

Thermal trends, precipitation and reference evapotranspiration were typical of the Mediterranean climate during the duration of the experiment (Table 2, Figure 1).

Table 2. 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 according to [39]) for 2021–2022 and 2022–2023 growing seasons and long-term averages at the experimental site (Catania, 37°24' N, 15°03' E, 10 m a.s.l.).

Variable	2021–2022 Observed Values	2022–2023 Observed Values	Long-Term Average
Tmax	21 °C	20.8 °C	20.5 °C
Tmin	9.88 °C	10.03 °C	10 °C
Tavg	15.3 °C	15.5 °C	15.1 °C
ET0	588 mm	543.5 mm	586.8 mm
Precipitation October to July	835 mm	474 mm	544.1 mm
Precipitation Sowing to Harvesting	103.6 mm	303.4 mm	249 mm

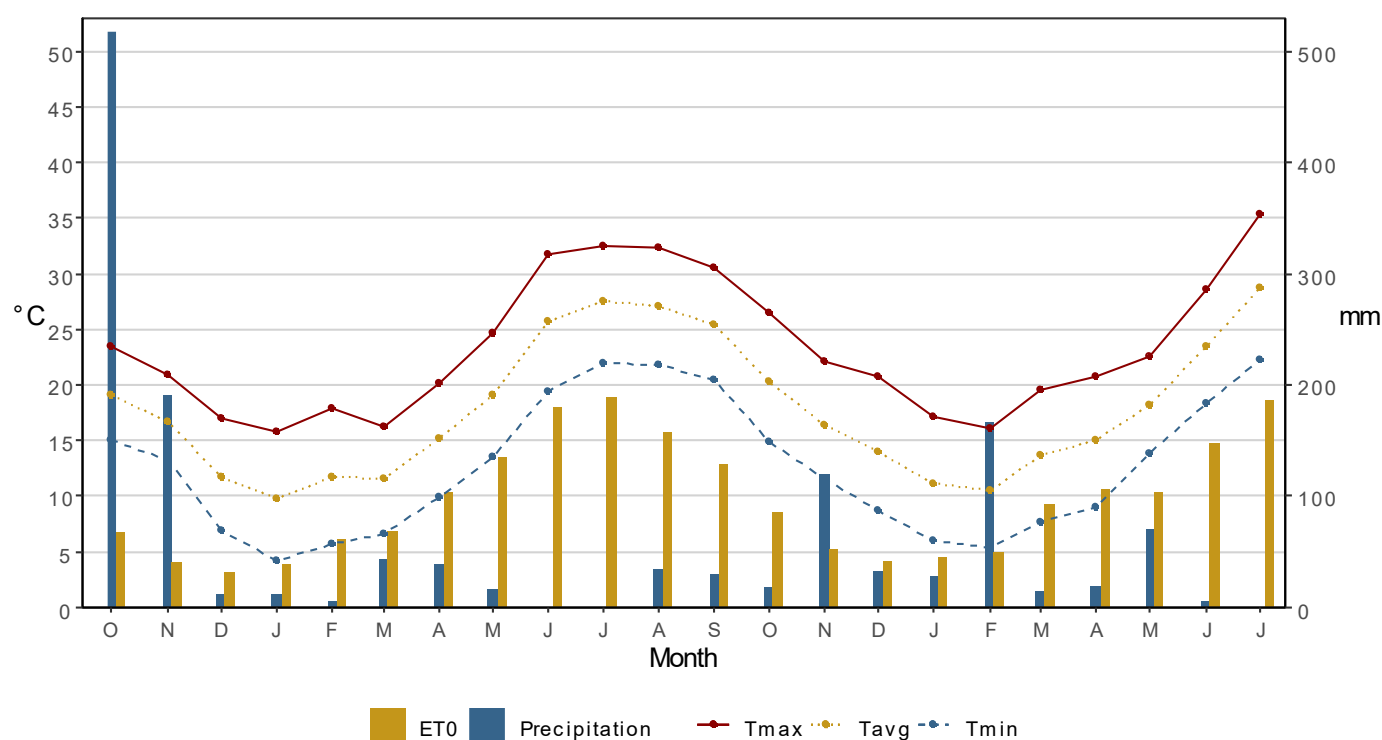


Figure 1. Meteorological variables (Tmax = month average of daily maximum temperature, Tavg = month average of daily mean temperature, Tmin = month average of daily minimum temperature, ET0 = month sum of daily reference evapotranspiration according to [39], Precipitation = monthly precipitation) from October 2021 to July 2023 at the experimental site (Catania, 37°24' N, 15°03' E, 10 m a.s.l.).

Mean air temperatures throughout the growing seasons (January–June) were slightly higher in 2022 than 2023: the month averages of daily mean temperature were 15.5 °C and 15.3 °C in 2022 and 2023, respectively. The month averages of daily minimum temperature throughout the growing seasons were 9.88 °C and 10.03 °C in 2022 and 2023, respectively, in line with the long-term average of 10 °C. The month averages of daily maximum temperature were 21 °C and 20.8 °C in 2022 and 2023, respectively, both higher than the long-term average of 20.5 °C. The reference evapotranspiration was higher during the 2022 growing season (588 mm) than the 2023 growing season (543.5 mm), which was lower than the long-term average (586.8 mm). Precipitation was higher during the period from October 2021 to July 2022 (835 mm) than the period from October 2022 to July 2023 (474 mm), while the long-term average was 544.1 mm (Figure 1).

Considering only the precipitation from sowing to harvesting, the 2022 growing season was drier than 2023, reaching 103.6 mm and 303.4 mm in 2022 and 2023, respectively.

2.3. Experimental Design

The experiment design included three factors (irrigation, management and genotype) and used a split-split plot with three replicates. Irrigation was the factor assigned to the main plots, management was the factor assigned to the subplot and the genotype was the factor assigned to the secondary subplot. Each secondary subplot measured 10 m².

2.4. Irrigation Factor

The irrigation factor had two levels: 100% of maximum evapotranspiration (ETm) restitution after the flowering phase and rainfed.

Irrigation was provided by a drip irrigation system and was scheduled when the sum of daily ETm exceeded 60% of the available soil water content at field capacity (105.6 mm)

Daily ET_m was calculated according to

$$ET_m = ET_o \times K_c \quad (1)$$

where ET_o is reference evapotranspiration (mm) according to [39] and K_c is the crop coefficient for wheat according to [39].

Irrigation was applied after the flowering phase on 4 May 2022 in the first year and on 1 June 2023 in the second year, providing 95 mm in 2022 and 63 mm in 2023. No irrigation was provided to the rainfed plots.

2.5. Management Factor

The management factor had two levels: conventional management (C) and organic management (OR).

The conventional management included mineral fertilization and chemical weed control. Mineral fertilization consisted of the application of 54 kg N ha⁻¹ and 138 kg P₂O₅ ha⁻¹ provided as diammonium phosphate (18N 46P) before sowing and 18 kg N ha⁻¹ provided as ammonium nitrate (34%) as a top dressing.

The weed control was performed by spraying iodosulfuron-methyl-sodium + mesosulfuron-methyl + thien carbazon-methyl (0.34 mL ha⁻¹) and clopyralid + florasulam + fluroxypyr-meptyl (0.28 mL ha⁻¹) at stem elongation.

The organic management included organic fertilization and no chemical weeding. The fertilization consisted of the application of 72 kg N ha⁻¹ and 148 kg P₂O₅ ha⁻¹ provided as organic fertilizer (7N 13P, Regenor, Haifa, Israel) before sowing.

Potassium was not provided with the fertilization in both treatments since the soil availability was already high (Table 1).

2.6. Genotype Factor

The genotype factor had eighteen categories (Table 3): eleven local Sicilian landraces of durum wheat (*Triticum turgidum* subsp. *durum* (Desf.)) (“Bidi”, “Castiglione Glabro”, “Giustalisa”, “Margherito”, “Realforte”, “Ruscia”, “Russello Priziusa”, “Russello Ibleo”, “Timilia”, “Tripolino” and “Urria”), one local Sicilian landrace of *T. turgidum* L. subsp. *turanicum* (Jakubz.) Á. Löve & D. Löve (“Perciasacchi”), one local Sicilian landrace of soft wheat (*T. aestivum* L.) (“Maiorca”), one ancient variety of durum wheat (“Senatore Cappelli”), three modern varieties of durum wheat (“Core”, “Mongibello” and “Amedeo”) and one modern variety of soft wheat (“Bologna”).

Table 3. Pedigree of the wheat genotypes studied in the trial.

Genotypes Name	Origin	Pedigree
Amedeo	Italy	Maristella × Capeiti [40]
Bidi	Italy	Selection from Tunisian landrace [41]
Bologna	Italy	(H89092 × H89136) × Soissons [42]
Castiglione Glabro	Italy	Indigenous landrace from Sicily [43]
Core	Italy	Platani × Gianni [43]
Giustalisa	Italy	Indigenous landrace from Sicily [43]
Maiorca	Italy	Indigenous landrace from Sicily [44]
Margherito	Italy	Selection from Tunisian landrace Mahmoudi [41]
Mongibello	Italy	Trinakria × Valforte [45]
Perciasacchi	Italy	Indigenous landrace from Sicily [44]
Realforte	Italy	Indigenous landrace from Sicily [43]
Ruscia	Italy	Indigenous landrace from Sicily [43]
Russello Ibleo	Italy	Indigenous landrace from Sicily [44]
Russello Priziusa	Italy	Indigenous landrace from Sicily [46]
Senatore Cappelli	North African	Strampelli’s selection. North African cultivar derived from Jennah Khetifa [47]

Timilia	Italy	Indigenous landrace from Sicily [44]
Tripolino	Italy	Indigenous landrace from Sicily [43]
Urria	Italy	Indigenous landrace from Sicily [43]

2.7. Agronomic Management

The seedbed was prepared after the first autumn rains using a skim plow at 0.40 m soil depth followed by a disk harrowing.

Sowing was carried out on 9th February 2022 and 2nd January 2023 in the first and second growing season by using a self-propelled plot seeder (Vignoli Tartaro, Forlì, Italy). The sowing rate was 200 kg ha⁻¹, and the seeds were planted in 6 rows (21 cm apart) that were 8 m long each.

The harvest was carried out at full ripening on 12th July 2022 and 13th July 2023 using a plot combine harvester (Winterstaiger, Ried, Austria).

2.8. Measurements

The main meteorological data (maximum and minimum air temperatures and rainfall) were measured by an automatic weather station (Delta-T, WS-GP1 Compact) located near the experimental field. The occurrence of the phenological phases of the crop was assessed according to the Zadoks scale [48].

The amount of grain harvest from each secondary subplot was weighed using an electronic scale and reported per unit area to calculate grain yield (Gy) at 13% moisture. The plant height (cm) was measured on a representative subsample of 100 plants collected from the secondary subplots.

A subsample of 1 kg of wheat was collected from each secondary subplot to measure 1000-seed weight (TSW) (g), starchy kernel (%), shrunken kernel (%) and total nitrogen content according to the Kjeldahl method [49]. The grain protein content (Gp) was calculated by multiplying Kjeldahl N by 5.75.

2.9. Statistical Analysis

The data were subjected to an analysis of variance (four-way ANOVA) to assess the effect of irrigation, management and genotype as fixed factors and year as a random factor on grain yield, grain protein content, plant height, white starchy index (WS), shrunken kernel (SK) fraction, seed weight, the interval between sowing and earing (S–E) and the interval between earing and physiological maturity.

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 has been performed for pairwise comparison of the genotype × management × irrigation interaction means. The correlation between variables has been studied with the Pearson's product-moment correlation test. All analyses were performed using the R CRAN version 4.4.0 software [50].

3. Results

3.1. Crop Phenology

Irrigation had no significant effect on the interval between sowing and earing, while management and genotype had a significant effect (Table 4).

Table 4. Four-way ANOVA for main effects (irrigation, management, genotype, year) and interactions (irrigation × management, irrigation × genotype, management × genotype, irrigation × management × genotype) on grain yield, grain protein content, plant height, white starchy index (WS), shrunk kernel (SK) fraction, seed weight, interval between sowing and earing (S–E) and interval between earing and physiological maturity (E–PM). The *p* values are reported.

Source of Variation	Grain Yield	Protein Content	Plant Height	WS	SK	Seed Weight	S-E	E-PM
Irrigation	1.43×10^{-5}	0.73	0.01	0.82	0.34	0.92	0.25	0.12
Management	1.01×10^{-5}	0.003	0.34	5.28×10^{-7}	9.05×10^{-2}	0.004	0.01	0.02
Genotype	1.22×10^{-5}	0.09	2.2×10^{-16}	2.20×10^{-16}	2.2×10^{-16}	1.32×10^{-5}	2.00×10^{-16}	2.00×10^{-16}
Year	2.20×10^{-16}	2.20×10^{-16}	0.22	0.001	0.24	0.08	2.00×10^{-16}	2.00×10^{-16}
Irrigation × Management	0.03	0.43	0	0.68	4.90×10^{-6}	0.36	0.83	0.05
Irrigation × Genotype	0.96	0.94	0.43	2.82×10^{-7}	0.0002473	0.41	1	0.99
Management × Genotype	0.05	0.44	0.14	8.78×10^{-10}	2.2×10^{-16}	0.24	0.54	0.43
Irrigation × Management × Genotype	1	0.86	0.98	2.08×10^{-9}	3.23×10^{-4}	0.89	1	0.65

Intervals between sowing and earing were longer in 2023 than in 2022, averaging 110.9 and 105.6 days, respectively. Organic treatment resulted in longer intervals compared to conventional treatment, with averages of 108.7 and 107.8 days, respectively (Table 5). Additionally, no difference was observed between rainfed and irrigated plots, with intervals averaging 108.4 and 108.1 days, respectively. Among the landraces, the soft wheat genotype Bologna had the longest interval (112.2 days), followed by Maiorca (110.6 days), while Timilia had the longest interval among the durum wheat genotypes (110.4 days) (Figure 2). The genotypes with the shortest intervals were the modern varieties Amedeo and Core (105.3 and 102 days, respectively). Irrigation had no significant effect on the interval between earing and physiological maturity, while management and genotype had a significant effect (Table 2). The intervals between earing and physiological maturity were longer in 2023 than 2022 (42.4 and 24.5 days on average, respectively). Conventional treatment led to longer intervals than organic treatments, with intervals of 33.9 and 33.01 days on average, respectively (Table 3). The difference between irrigated treatment and rainfed treatment was not significant (33.7 and 33.2 days on average, respectively).

The modern durum wheat varieties (Core, Mongibello and Amedeo) had the longest interval (37.6, 37.5 and 36.8 days, respectively), followed by the durum wheat landrace Perciasacchi (35.2 days). Among the genotypes with the shortest intervals, Castiglione Glabro and Timilia had the shortest intervals (30.8 and 29.7 days, respectively) (Figure 3).

Table 5. Mean values of grain yield, grain protein content, plant height, white starchy index (WS), shrunk kernel (SK) fraction, seed weight, interval between sowing and earing (S–E) and interval between earing and physiological maturity (E–PM) for the experimental factors irrigation and management.

Trait	Irrigation		Management	
	Rainfed	Irrigated	Organic	Conventional
Grain yield	1.48 ± 0.37	1.67 ± 0.42	1.48 ± 0.35	1.68 ± 0.43
Protein content	11.13 ± 1.44	11.09 ± 1.52	10.85 ± 1.50	11.36 ± 1.41
Plant height	103.52 ± 23.15	111.08 ± 21.30	108.10 ± 23.09	106.49 ± 22.01
WS	33.86 ± 12.50	34.72 ± 12.10	32.50 ± 13.13	36.08 ± 11.15
SK	16.21 ± 12.17	16.05 ± 10.04	18.36 ± 11.55	13.91 ± 10.27
1000-seed weight	40.28 ± 5.13	40.33 ± 5.27	41.10 ± 5.33	39.51 ± 4.94
S-E	108.44 ± 4.43	108.06 ± 4.18	108.67 ± 4.44	107.83 ± 4.14
E-PM	33.17 ± 9.48	33.70 ± 9.88	33.01 ± 9.57	33.85 ± 9.78

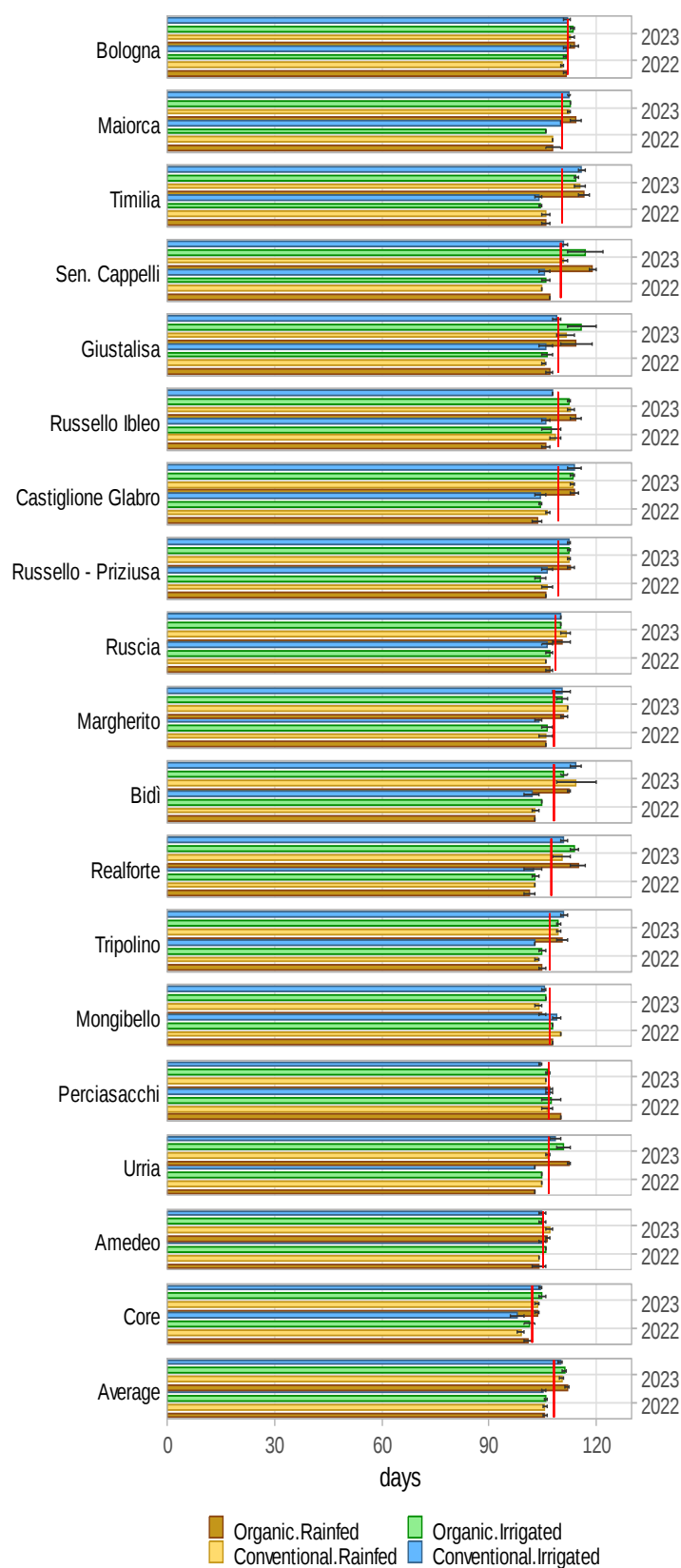


Figure 2. Interval between sowing and earing (gg) during 2022 and 2023 cropping seasons under two irrigation levels and two management levels for eighteen wheat genotypes. The red lines represent the average grain yield for each genotype. LSD of interval between sowing and earing = 5.48 days.

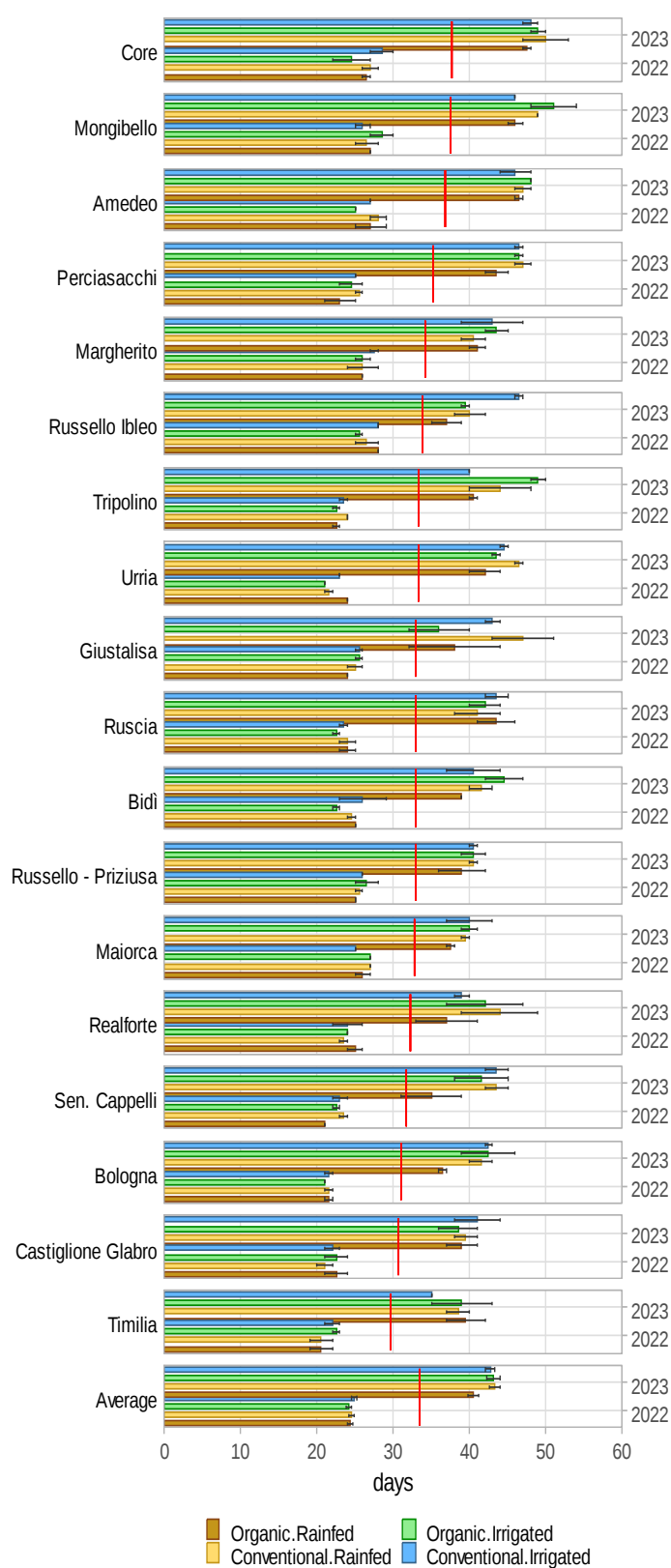


Figure 3. Interval between earing and physiological maturity (gg) during 2022 and 2023 cropping seasons under two irrigation levels and two management levels for eighteen wheat genotypes. The red lines represent the average grain yield for each genotype. LSD of interval between earing and physiological maturity = 5.79 days.

3.2. Morphological and Productive Traits

3.2.1. Grain Yield

Grain yield was significantly affected by genotype, management, irrigation and the irrigation $\times$ management interaction (Table 2).

Irrigation contributed to a 11.6% increase in grain yield compared to the rainfed treatment in 2022 and a 14.6% increase in 2023 (Table 3).

The agronomic inputs provided as experimental factors in this trial (irrigation and conventional management) led to a lesser increase in grain yield of landraces in comparison with modern varieties: landraces achieved an increase in grain yield of 15.4% on average under conventional irrigated management in comparison with the rainfed organic management, while the increment observed in modern varieties was on average 27.5% (Figure 4).

Irrigation increased grain yield by 4.60% and 15.9% for landraces and modern varieties, respectively, under conventional management, while the increase was 10.3% and 4.10% for landraces and modern varieties, respectively, under organic management. Conventional management led to a 6.20% and 22.5% increase in grain yield for landraces and modern varieties, respectively, under irrigated conditions, while the increase was 8.60% and 10% under rainfed conditions. Grain yields were higher in 2023 than in 2022, averaging 1.80 and 1.35 Mg ha⁻¹, respectively. Conventional treatment resulted in higher yields compared to organic treatment, with averages of 1.68 and 1.47 Mg ha⁻¹, respectively. Grain yields were also higher in irrigated plots compared to rainfed plots, averaging 1.67 and 1.47 Mg ha⁻¹, respectively. Two modern varieties, Mongibello and Amedeo, achieved the highest grain yields (1.80 Mg ha⁻¹ and 1.78 Mg ha⁻¹ on average across treatments, respectively), while the modern variety Core was outperformed by the landrace Bidi (1.71 Mg ha⁻¹ and 1.75 Mg ha⁻¹ on average across treatments, respectively) (Figure 4). The durum wheat landrace Realforte had the lowest yield in both 2022 and 2023, with an average yield of 1.29 Mg ha⁻¹ across treatments.

3.2.2. Seed Weight (TSW)

The management and the genotype had a significant effect on the thousand-seed weight (TSW), while the irrigation had a nonsignificant influence (Table 2).

TSW values were higher in 2023 than in 2022 (40.8 and 39.8 g, respectively) (Figure 5). The organic treatment led to an increase in TSW values compared to conventional treatment, with an average weight of 41.1 g and 39.5 g, respectively (Table 3). The TSW was not significantly different in the irrigated plots compared to the rainfed plots (40.3 and 40.3 g, respectively). The durum wheat landraces Perciasacchi and Margherito showed the highest TSW values (44.4 g and 44.3 g, respectively). The soft wheat landrace Maiorca had the lowest TSW (35.4 g) in both 2022 and 2023.

3.2.3. Plant Height

The effect of irrigation and the genotype on plant height was significant, while the management had a nonsignificant effect (Table 2).

Plant heights were higher in 2023 than in 2022 (108.3 and 106.3 cm, respectively (Figure 6)). Organic treatments led to taller plants compared to conventional treatments, with an average plant height of 108.1 cm and 106.5 cm, respectively (Table 3). Irrigated plants were taller than rainfed plants (111.1 and 103.5 cm on average for the treatments, respectively). Landraces were higher than the modern varieties: Castiglione Glabro, Perciasacchi, Russello Priziusa and Margherito were taller than 120 cm on average for the treatments, while the modern varieties were below 90 cm. Among the modern varieties, Mongibello was the shortest, with an average height of 59.2 cm.

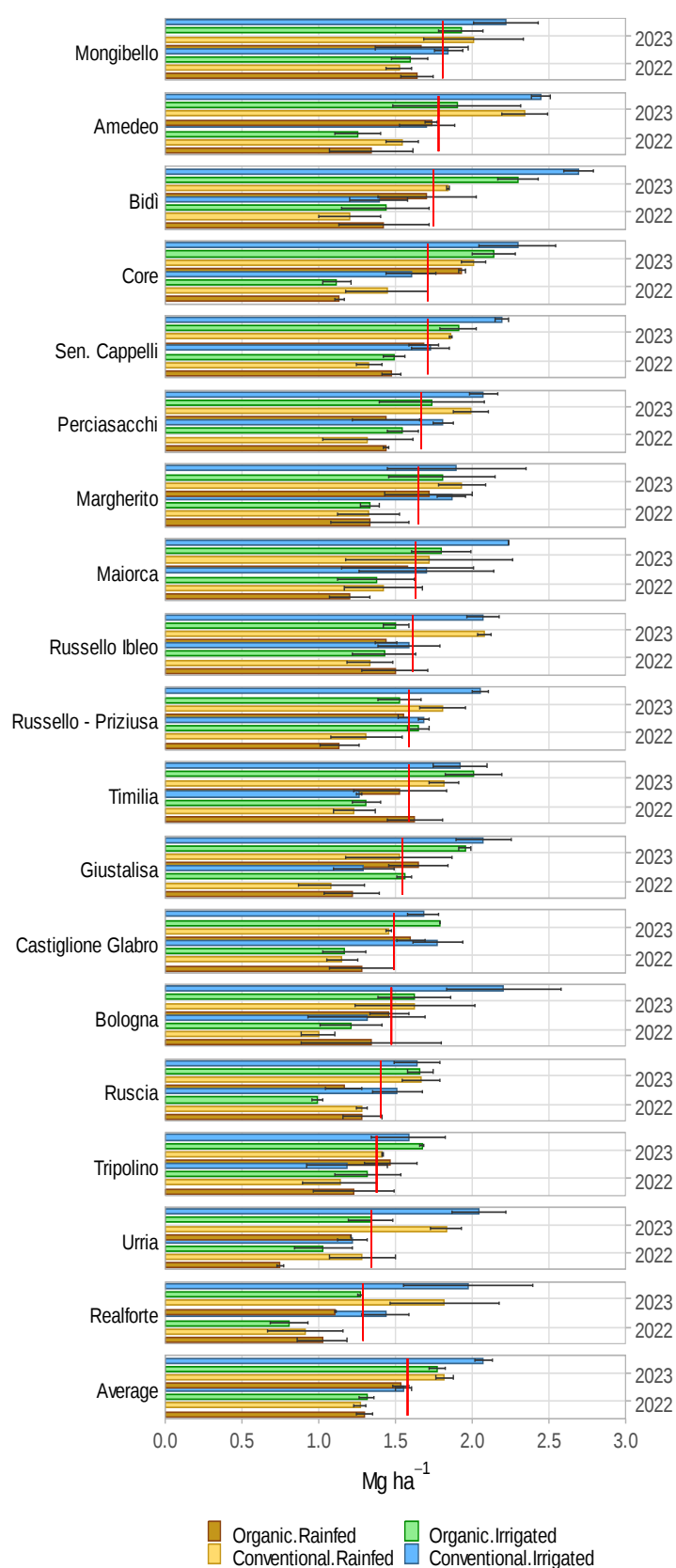


Figure 4. Grain yield (Mg ha⁻¹) during 2022 and 2023 cropping seasons under two irrigation levels and two management levels for eighteen wheat genotypes. The red lines represent the average grain yield for each genotype. Grain yield LSD = 0.56 Mg ha⁻¹.

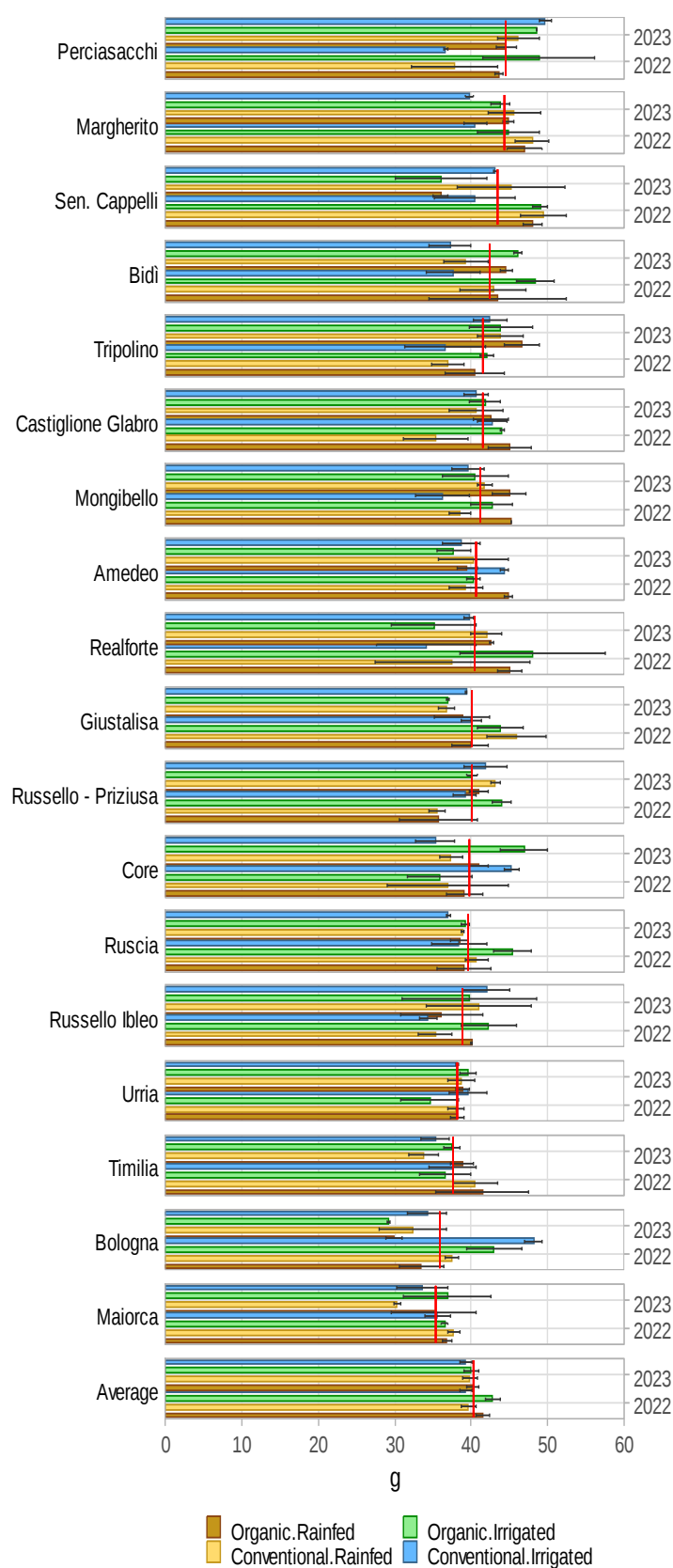


Figure 5. Thousand-seed weight (TSW) during 2022 and 2023 cropping seasons under two irrigation levels and two management levels for eighteen wheat genotypes. The red lines represent the average grain yield for each genotype. Thousand-seed weight LSD = 9.16 g.

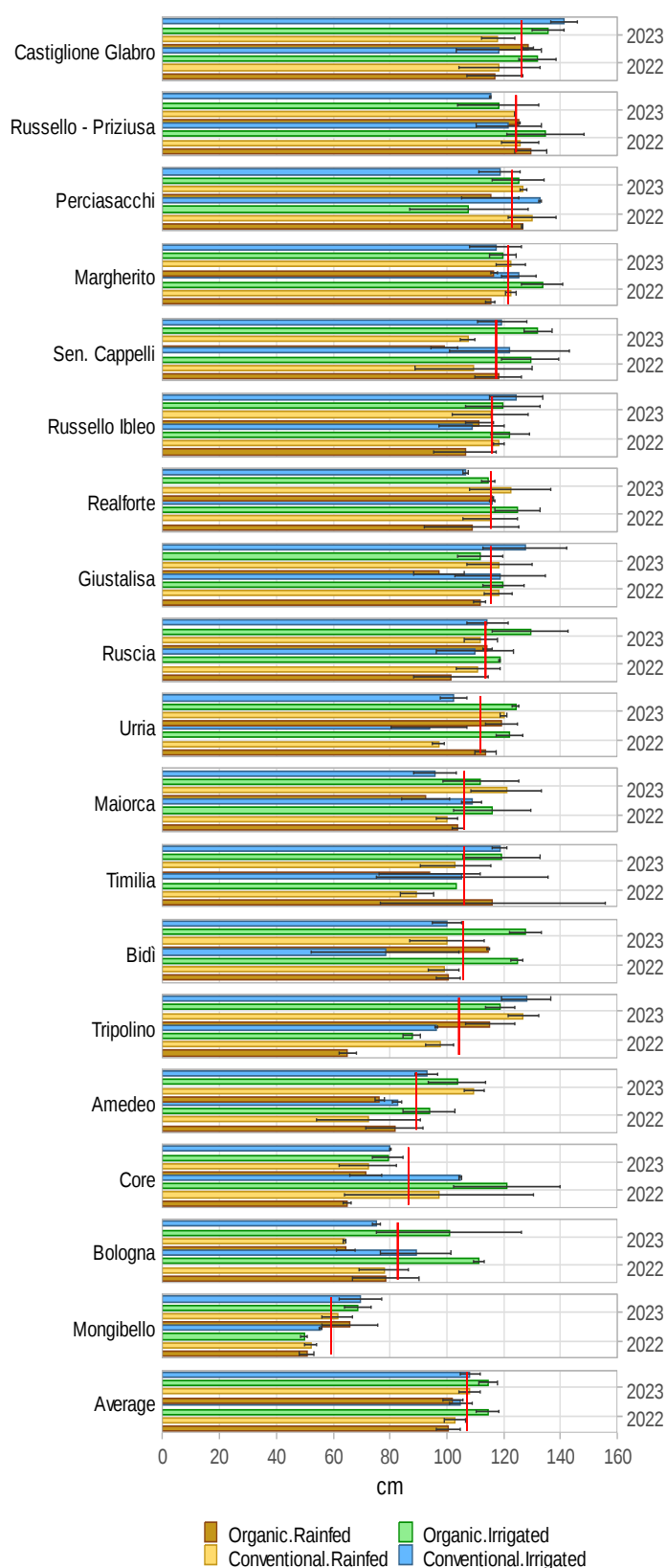


Figure 6. Plant height during 2022 and 2023 cropping seasons under two irrigation levels and two management levels for eighteen wheat genotypes. The red lines represent the average grain yield for each genotype. Plant height LSD = 28.21 cm.

3.3. Quality Traits

3.3.1. Protein Content

The protein content was significantly affected by the management, while the effect of irrigation and genotype was not significant (Table 2).

The protein content increased by 2.29% in 2023 compared to 2022 (12.3% and 9.96%, respectively) (Figure 7). The protein content was increased by the conventional treatment compared to the organic treatment (11.36% and 10.85% on average for the treatments, respectively) (Table 3). However, there was no increase in protein content due to the irrigation input. The durum wheat populations reached the highest values of protein content, with Realforte, Mongibello and Perciasacchi having 11.6%, 11.4% and 11.4% protein content, respectively. Conversely, the lowest values were observed in the Urria and Bologna genotypes, with 10.6% and 10.5% protein content, respectively.

3.3.2. White Starchy Index (WS)

The white starchy index (WS) was significantly affected by management and genotype, while the effect of irrigation was nonsignificant (Table 2).

WS decreased by 1.05% in 2023 compared to 2022 (33.8% and 34.8% on average for the treatments, respectively), although the difference was not statistically significant. The conventional treatment led to an increase in WS in comparison to the organic treatment (36.1% and 32.5% on average for the treatments, respectively) (Table 3). Irrigation input caused a nonsignificant increase in the WS.

Among landraces, Senatore Cappelli achieved the highest WS (46.2%), while the durum wheat landraces Margherito and Timilia and the durum wheat modern variety Core scored the lowest value for WS (27%, 26.9% and 26.1%, respectively) (Figure 8).

3.3.3. Shrunken Kernel (SK) Fraction

The fraction of shrunken kernels (SKs) was significantly affected by management and genotype, while the effect of irrigation was nonsignificant (Table 2).

SK fraction decreased by 2.38% in 2023 compared to 2022 (15% and 17.3% on average for the treatments, respectively) (Figure 9). The conventional treatment led to a decrease in SK fraction in comparison to the organic treatment (13.9% and 18.4 on average for the treatments, respectively) (Table 3). Irrigation input caused a nonsignificant increase in SK fraction.

The durum wheat modern variety Core had the highest SK fraction (40.4% on average for the treatments), followed by the durum wheat landrace Realforte (24.3% on average for the treatments). Meanwhile, the durum wheat modern variety Mongibello and the landrace Bidi achieved the lowest SK fractions (7.81% and 8.67% on average for the treatments, respectively).

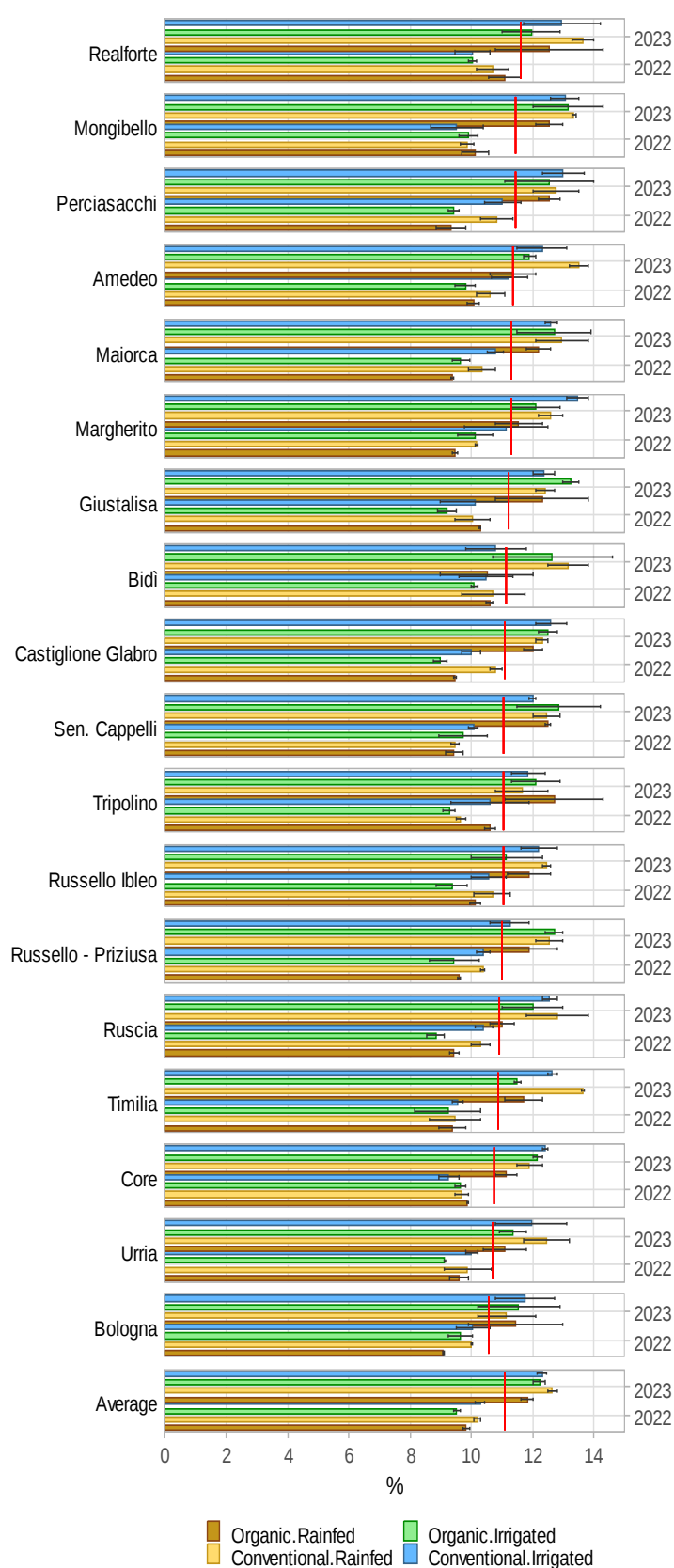


Figure 7. Protein content (%) during 2022 and 2023 cropping seasons under two irrigation levels and two management levels for eighteen wheat genotypes. The red lines represent the average grain yield for each genotype. Protein content LSD = 1.78%.

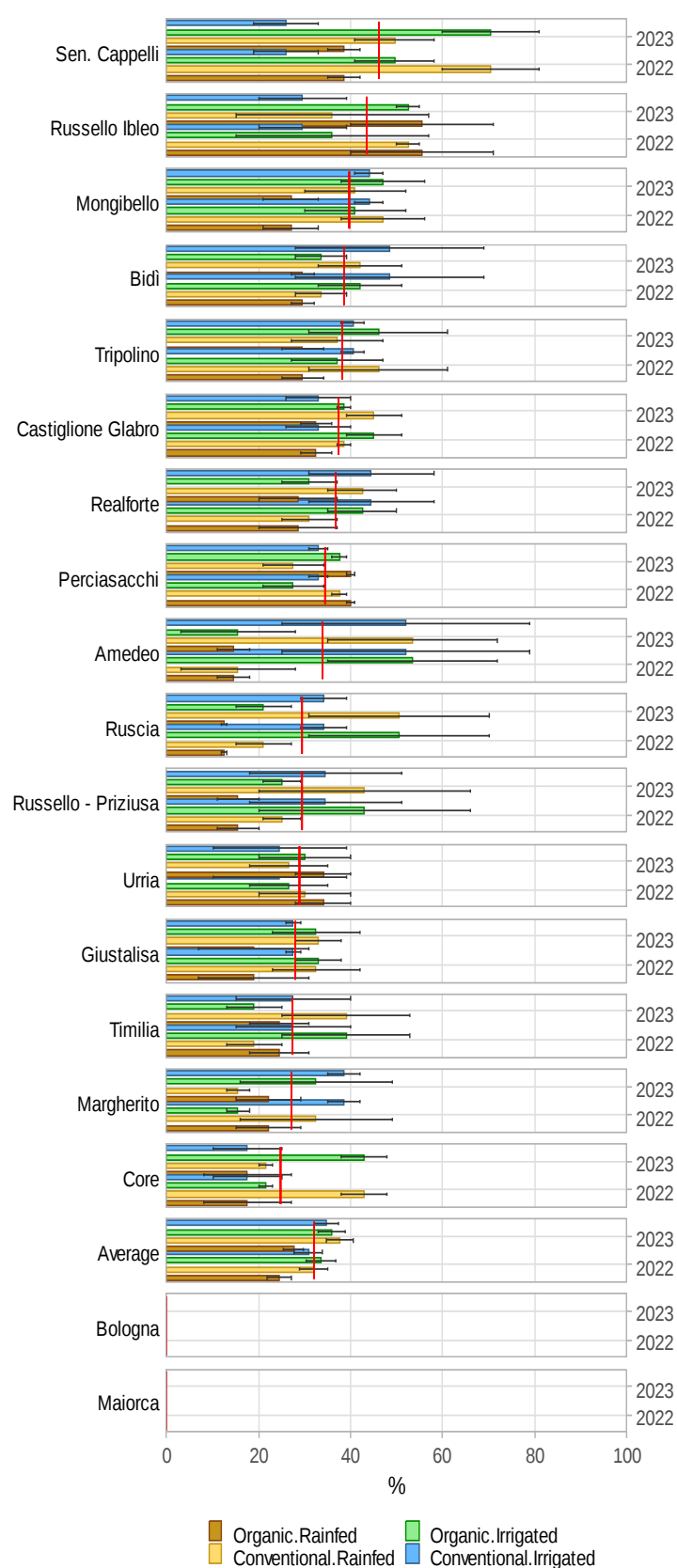


Figure 8. White starchy index, WS (%), during 2022 and 2023 cropping seasons under two irrigation levels and two management levels for eighteen wheat genotypes. The red lines represent the average grain yield for each genotype. White starchy index LSD = 14.11%.

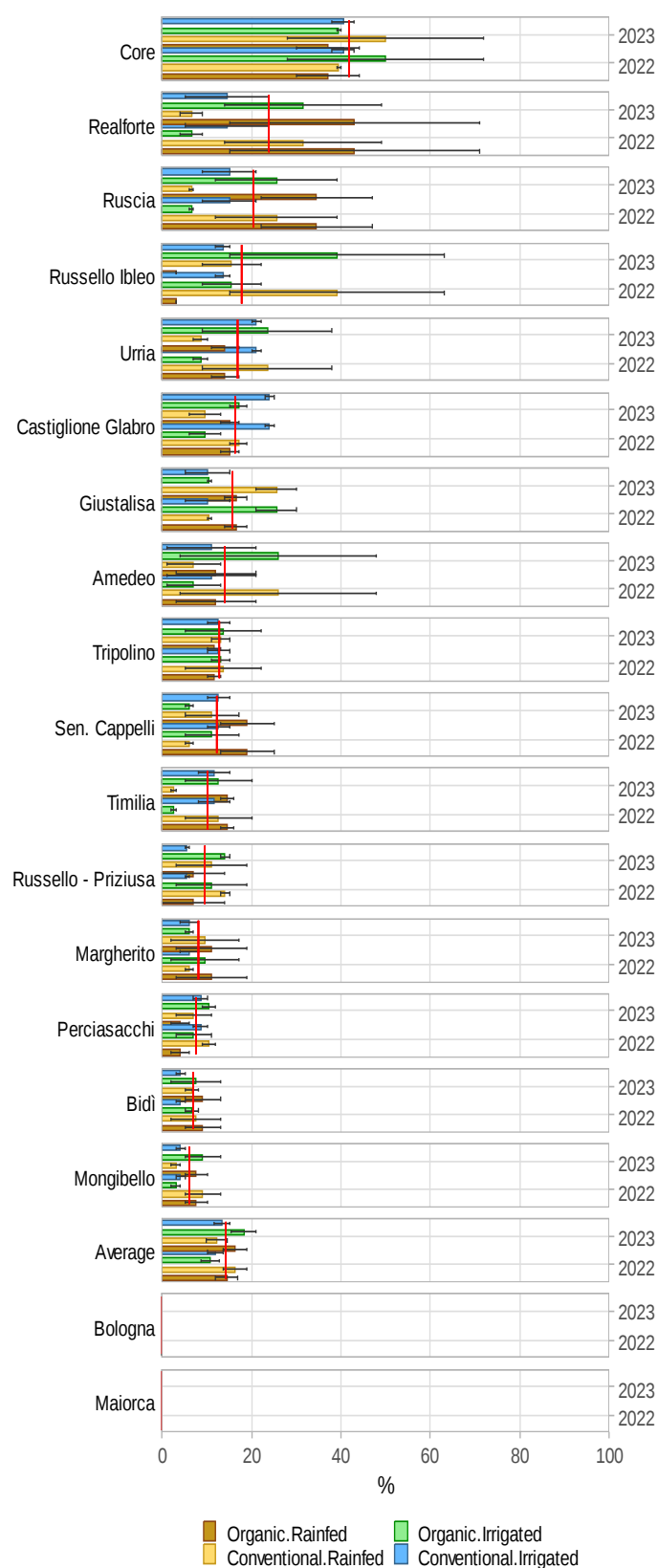


Figure 9. Shrunken kernel fraction (%) during 2022 and 2023 cropping seasons under two irrigation levels and two management levels for eighteen wheat genotypes. The red lines represent the average grain yield for each genotype. Shrunken kernel fraction LSD = 10.73%.

3.4. Correlation between Variables

A strong positive correlation has been observed between grain yield and the length of the interval between anthesis and seed ripening (Pearson correlation coefficient $r = 0.67$, p value $< 2.2 \times 10^{-16}$), while the correlation between grain yield and the length of the interval between sowing and anthesis was lower but still significant ($r = 0.33$, p value $= 1.65 \times 10^{-4}$) (Figure 10).

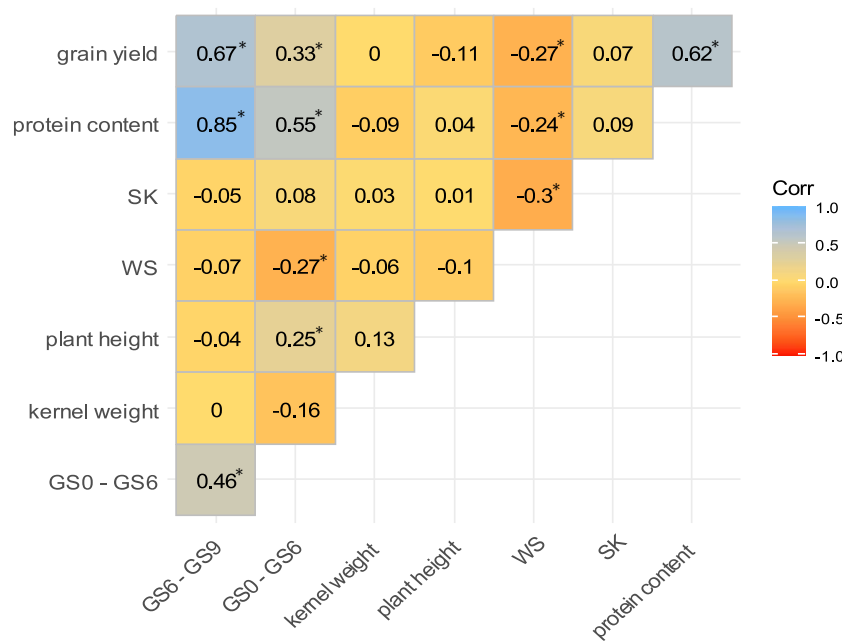


Figure 10. Heatmap plot according to Pearson of the measured variables (grain yield, protein content, SK = shrunken kernel fraction, WS = white starchy index, plant height, kernel weight, GS0–GS6 = length of the interval between sowing and anthesis, GS6–GS9 = length of the interval between anthesis and seed ripening). * indicates correlation values ≥ 0.174 or ≤ -0.174 , which are significant at a 95% confidence level in a two-tailed test.

Grain yield was also correlated positively to the protein content of the grain ($r = 0.62$, p value $= 1.06 \times 10^{-14}$) and negatively correlated with the white starchy index ($r = -0.27$, p value $= 2.30 \times 10^{-3}$).

The protein content of the grain was positively correlated to the interval between anthesis and seed ripening ($r = 0.85$, p value $< 2.2 \times 10^{-16}$) and to the interval between sowing and anthesis ($r = 0.55$, p value $= 1.41 \times 10^{-11}$). The correlation between grain protein content and the white starchy index was significant and negative ($r = -0.24$, p value $= 7.41 \times 10^{-3}$). The fraction of shrunken kernels was negatively correlated with the white starchy index ($r = -0.3$, p value $= 4.83 \times 10^{-4}$).

The length of the interval between sowing and anthesis was positively correlated with the plant height ($r = 0.25$, p value $= 3.71 \times 10^{-3}$) and negatively correlated with the white starchy index ($r = -0.27$, p value $= 1.79 \times 10^{-3}$).

The length of the interval between sowing and anthesis and the interval between anthesis and seed ripening were positively correlated ($r = 0.46$, p value $= 5.35 \times 10^{-8}$).

4. Discussion

This study assessed the influence of irrigation input and conventional farming methods in comparison with organic farming methods on the productivity traits and grain quality traits of a selection of wheat landraces compared with modern varieties.

Wheat grain yield is mainly determined by the amount of photosynthetic products synthesized during the phases between emergence and the earing and by the grain filling, which is fueled by the translocation of previously synthesized photosynthetic products

and by the availability of photosynthetic products that are synthesized during the grain filling stage [51].

Consequently, under nonlimiting water availability, grain yield is influenced by the length of the interval between emergence and earing and between earing and physiological maturity [52]. Water stress during late spring can hinder grain filling; therefore, early-ripening genotypes can achieve higher yield than late-ripening genotypes by avoiding severe water limitation in drought-prone areas [53].

The present study found a positive correlation between grain yield and the length of the interval between anthesis and seed ripening, which, under non severe water limitation, allows for complete grain filling and, therefore, higher productivity. However, the study by Frankin et al. [3] found that early-ripening wheat landraces are advantaged under limiting water conditions.

Numerous studies have projected a decline in agricultural yields due to global warming, attributing this reduction to the shortening of phenological phases, without considering agronomic management practices [54]. According to Chowdhury et al. [55], water stress accelerates the growth phase and causes a reduction in the number of days to heading. However, the present study found that irrigated and rainfed management had no significant differences on the sowing–earring interval (108 days on average), while the shortening of the interval could be caused by higher temperatures during the growing season and the late sowing.

Significant variations in heading time were observed among the genotypes, likely due to differences in plant characteristics and the drought conditions experienced during the winter months. The interval from earing to physiological maturity showed no significant differences between irrigated and rainfed management, with an average duration of 33 days.

Water and nitrogen availability are the main limiting factors for attainable wheat yield [56] and can affect grain quality, in particular the fraction of shrunken kernels, due to water limitation during grain filling, grain protein content and the white starchy index, caused mainly by nitrogen limitation [35].

Both landraces and modern varieties responded to the irrigation input coherently with the results reported by Corinzia et al. [19], who reported 9.50% and 12.20% increases in grain yield under irrigated conditions in comparison with rainfed conditions for landraces and modern varieties, respectively. Similar results were reported by Eser et al. [8], who observed a higher tolerance of landraces evolved in drought-prone areas (Turkey, Iran and Afghanistan) and lower grain yield loss due to water limitation than modern varieties.

Conventional management led to higher grain yield and the increase was greater for modern varieties than local landraces, which were often developed under low-input farming systems without the aid of chemical weed control and mineral fertilizers.

The results agree with those of Anastasi et al. [57] and Cséplő et al. [9], who observed, respectively, 45.9% and 21.6% reductions in grain yield for modern durum wheat varieties under organic management in comparison with conventional management.

Similarly, Korpetis et al. [58] observed a 31.3% grain yield increase under conventional management in comparison with organic management for soft wheat in the Mediterranean area, with landraces showing a higher suitability to low-input farming systems than modern varieties.

Studies by Eser et al. and Korpetis et al. [8,58] reported overall higher grain yields for modern wheat varieties in comparison with local landraces, while Corinzia et al. [19] and Korpetis et al. [58] assessed the potential of some local landraces to achieve higher productivity than modern varieties in low-input or organic management. High-yielding wheat landraces were characterized by higher net photosynthesis and high instant water use efficiency in the study by Corinzia et al. [19].

Among the tested landraces, Bidì, Castiglione Glabro, Giustalisa, Sen. Cappelli, Timilia and Tripolino achieved equal or higher grain yield in organic farming than

conventional farming under rainfed conditions. These landraces, despite having slightly lower yield than the most productive modern variety (i.e., Mongibello), confirmed their suitability to suboptimal conditions and, therefore, could be integrated into breeding programs for organic farming in drought-prone Mediterranean areas.

The thousand-seed weight (TSW) is a crucial productivity and quality trait, as it determines the suitability of the wheat for improved milling due to its starch and protein content. Abd El-Rady et al. [59] and Abdelghany et al. [60] identified water availability as the main contributor to the TSW. Contrary to these findings, this study showed no clear effect of the water availability and identified the genotype as the main determinant of TSW. The studies by Mitura et al. [61], Sobolewska and Stankowski [62] and Rolnicza [63] reported lower TSW values in the conventional management cultivation system compared to the organic cultivation system, observations also confirmed by this work.

Plant height is a trait that has a complex influence on grain yield, since taller genotypes tend to allocate more resources to vegetative growth, therefore attaining lower harvest index and lower grain yield; the same trait can be favorable under no-chemical weed-farming, where taller plants are more competitive against wild flora [64].

According to Eser et al. [8], plant height is significantly affected by drought stress, which reduces the photosynthetic rates and the availability of metabolites, resulting in shorter plant stature. The present study found similar results; specifically, plant height was greater under the irrigated regime compared to the rainfed conditions. However, the analysis of the two types of fertilization, conventional and organic, showed no significant differences over the two years of the study. Landraces were taller than modern varieties, confirming their advantage against wild flora in organic farming. Contrarily, Harfe et al. [65] found that the application of nitrogen (N) can increase plant height in wheat.

The protein concentration of wheat is an important quality parameter for durum wheat, as it is widely used as a criterion to determine premium prices. Reid et al. [66] found that wheat lines cultivated under conventional management had lower protein content compared to those cultivated under organic management. Due to the typically lower yields of organic crops compared to conventional ones, the effect of protein dilution from higher yields is likely more pronounced in conventionally managed systems. In the present study, the protein content in conventional management was higher compared to the organic management (11.4% and 10.4% on average, respectively). Mazzoncini et al. and Sobolewska and Stankowski [62,67] confirmed our study by finding higher protein content in conventional management compared to organic management, due to the higher nitrogen availability than in organic management. Similar results were reported by Caseviciene et al. [68], who observed a significant decrease in protein content and sedimentation volume across four different cultivars of organic wheat. This inconsistency may be explained by the varying ability of cultivars to adapt to organic growing conditions and the timing of N application, since the amount of nitrogen remobilized from vegetative organs to grains depends on environmental factors and genotype characteristics [69]. Palta et al. [70] demonstrated that nitrogen remobilization efficiency was high in sites where wheat plants typically experience water stress during grain filling. Xu et al. [71] found that both normal irrigation and water-saving irrigation led to an increase in the amount of remobilized nitrogen and the nitrogen contribution fraction in wheat compared to rainfed treatment. In our study, the irrigation treatment failed to influence the grain protein content, likely due to the increase in grain yield being balanced by the increased nitrogen uptake during grain filling. Previous studies reported contrasting responses of grain protein content to irrigation treatment: Guler [72] found higher protein content under irrigated treatment, while Whitfield et al. [73] reported that water stress leads to an increase in protein content.

According to Dexter et al. [74], white starch index significantly affects the quality of durum wheat, particularly impacting protein content and the structure of the endosperm. Kernels showing high levels of white starch tend to exhibit lower protein content and a disrupted reserve protein matrix, resulting in softer kernels compared to those with a

vitreous appearance. Moreover, an increase in white starch has been observed to be correlated with a slight decrease in kernel weight and an increase in ash content.

The present study found a higher prevalence of white starchy kernels in the conventional management in comparison with the organic management despite the overall higher protein content.

Shrunken kernels are the result of the abnormal wheat filling and maturation processes, often induced by heat stress, drought or biotic stress [35]; the presence of these defects leads to a deterioration in quality characteristics even with optimal protein content [75]. The present study found that the genotype factor described most of the variability in the fraction of shrunken kernels, while the nitrogen and water limitation led to higher prevalence of shrunken kernels only in certain genotypes.

5. Conclusions

The lack of modern wheat varieties that are specifically bred for low-input or organic farming methods has emphasized the significance of preserving landraces to increase the pool of traits and genetic resources that can be used for breeding programs. Moreover, climate instability can affect the productivity and quality of modern varieties that were selected under high-input management and optimal growing conditions, while landraces are typically more adaptable to low-input agricultural practices and show a lower variability under suboptimal growing conditions.

This study evaluated the performance of local wheat varieties under high- and low-input agricultural management in a semiarid Mediterranean environment. The loss of productivity due to water limitation was lower for landraces than for modern varieties, despite modern varieties achieving, on average, a higher grain yield.

The adoption of organic management led to a decrease in productivity for both landraces and modern varieties, but the latter showed a higher loss. Several landraces achieved higher or equal grain yield under organic farming in comparison with conventional farming, in particular under rainfed conditions.

Protein content was significantly affected by management practices, while irrigation or genotype had a nonsignificant effect. Protein content was higher under conventional treatment than under organic treatment.

The intervals from sowing to earing and from earing to physiological maturity were longer in 2023 than in 2022 and were affected by the genotype and management method but not by irrigation.

The white starchy index (WS) and the fraction of shrunken kernels (SKs) were strongly affected by the genotypes, while there was no evident difference between landraces and modern varieties. Both traits were affected by agronomic management: the organic treatment led to lower WS and the conventional treatment led to a smaller SK fraction.

These results highlight the resilience and adaptability of several local wheat varieties to low-input agricultural systems, suggesting they are viable alternatives to high-input modern varieties and could provide genetic traits to help breeding programs using low-chemical-input systems with nonoptimal soil water availability, enhancing the sustainability and resilience of the production of wheat in Mediterranean environments.

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