Multi-Environment Screening of Durum Wheat Genotypes for Drought Tolerance in Changing Climatic Events

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Abstract:
Durum wheat is the most widely grown cereal in Tunisia, but its production is threatened by drought, which is exacerbated by climate change. This study aimed to identify drought-tolerant durum wheat genotypes from five modern varieties and six landraces in a multi-environment trial at two sites (Kef and Siliana, Tunisia) during three growing seasons under rainfed and irrigated conditions. Six drought tolerance indices (mean productivity (MP), geometric mean productivity (GMP), stress susceptibility index (SSI), tolerance index (TOL), stress tolerance index (STI), and yield stability index (YSI)) were used to evaluate the 11 genotypes. The environment was the dominant source of variation for grain yield (GY; 94.27%), followed by the environment × genotype interaction (4.06%) and genotype (1.65%). Cluster analysis based on GY identified four environment-based groups with distinct water treatments, extreme minimum/maximum temperatures, and rainfall. Principal component analysis and a correlation matrix revealed that drought tolerance indices significantly correlated with GY in non-stressed and stressed conditions and could be separated into four groups. Based on STI, MP, and GMP, G6 and G8 (landraces) were the most drought-tolerant genotypes attaining high GY in both conditions. TOL was able to discriminate G1, G3, and G5 (modern varieties) as well as drought-susceptible genotypes, all of which were suitable for irrigation. Genotypes G7, G9, G10, and G11 (landraces), which had high SSI and lowest STI, MP, GMP, and YSI values, were susceptible to drought and were thus not suitable for cultivation in both conditions. Finally, G2 and G4 (modern varieties), which had an intermediate rank for different indices, were classified as semi-tolerant or sensitive genotypes. Drought tolerance indices and genotype ranks were helpful tools to screen drought-tolerant genotypes with a large adaptation to a range of environments, namely irrigated and rainfed conditions (landraces G6 and G8), or genotypes with the ability to adapt (modern varieties G1, G3, and G5) to irrigated conditions.

Keywords: durum wheat; multi-environment trials; tolerance indices; yield performance

1. Introduction
Among cereal crops, durum wheat (Triticum durum Desf.) is the 10th most commonly cultivated cereal worldwide and one of the most important food crops in the Mediterranean Rim with an important role in the human diet [1,2]. However, its production is threatened by climate change and extreme weather events [3–5]: North Africa, including Tunisia, is recognized as a climate change hotspot region [6–8] and is, therefore, particularly vulnerable to drought stress [9–13], which limits growth, development, and crop yield [14–17]. By 2030, Tunisia is expected to suffer from an annual average increase in temperature of 1.1 °C and thus an annual acute decrease in precipitation and water resources [6]. This will acutely influence rainfed durum wheat, which is the most important cultivated crop in
Tunisia representing 54% of the cereal growth area (~1.5 million ha) [18,19] and decreasing yield by almost 30% [8].

Faced with the influence of climate change and augmented demand for food supply (a 70% increase by 2050) caused by population growth, there is a need to increase durum wheat production [16,20,21]. Thus, screening durum wheat genotypes for drought tolerance and improving their water use efficiency were useful key tools employed by cereal breeders to increase production and productivity [16,21]. Grain yield (GY) and its components were extensively used in durum wheat breeding selection programs for drought tolerance [21]. Therefore, understanding the basis of the response of a crop to water stress is important, especially in areas with restricted water supply [22]. In wheat, water and drought stress generally generate changes in morphological, physiological, and biochemical traits [23–25]. A multi-environment trial to assess the response of wheat genotypes to diverse seasons and sites is a useful method to identify the most adaptive genotype for a specific environment [26,27]. In addition, several drought tolerance indices (DTIs) that are based on yield under drought and normal conditions have been used to increase selection efficiency and to screen genotypes grown under drought stress. Geometric mean productivity (GMP) was proposed by Fernandez [28] to select genotypes based on their performance in non-stressed and stressed environments. Rosielle and Hamblin [29] defined stress tolerance (TOL) as the difference in GY between the irrigated and stressed environments and mean productivity (MP) as the average GY of genotypes under both conditions. Fischer and Maurer [30] suggested a stress susceptibility index (SSI) to measure yield stability in variable environments. Gavuzzi et al. [31] and Sánchez-Reinoso et al. [32] defined the yield index (YI) as the stability of a genotype in both non-stressed and stressed conditions. In addition, Fernandez [28] proposed a stress tolerance index (STI) as a useful tool for identifying genotypes that produce high GY under contrasting conditions. Furthermore, correlation analysis between GY and DTIs could serve as a good criterion for screening the best genotypes and indices. Bennani et al. [33] and Pour-Aboughadareh et al. [34] reported that the most appropriate index for selecting drought-tolerant genotypes was an index that highly correlated with GY in non-stressed and stressed conditions. Grzesiak et al. [35] suggested that selection for drought tolerance in wheat could be conducted for high MP, GMP, and STI in both conditions. The selection of different genotypes grown under environmental stress was one of the main challenges for plant breeders who exploited genetic variation to improve drought-tolerant varieties [36].

Capitalizing upon these aspects, the present study aimed to (i) describe the tested environments and (ii) assess the effect of these environments on the agro-morphological attributes of 11 durum wheat genotypes via field experiments in three consecutive years in order to screen drought-tolerant genotypes.

2. Materials and Methods

2.1. Genetic Material

Eleven durum wheat genotypes, including five modern varieties and six landraces, were used for field experiments (Table 1). The selected modern varieties are the most cultivated genotypes in Tunisia. G3 is recognized as a drought-sensitive genotype, and G5 as a drought-tolerant genotype. The landraces, which are still conserved by smallholders, were selected based on their adaptability to marginal environments.
Table 1. Codes, names, type, origin, and release date of 11 durum wheat genotypes used in this study.

| Genotypes | Type             | Origin and Release Date                                      |
|-----------|------------------|--------------------------------------------------------------|
| G1        | Maali            | Modern variety Local cross released in 2007                 |
| G2        | Om Rabiaa        | Modern variety Cross L0589 made at ICARDA. Introduced in 1996|
| G3        | Karim *          | Modern variety Cross made at CIMMYT/Mexico and released in 1980|
| G4        | Nasr             | Modern variety ICD85–1340 cross made by ICARDA (1985) and released in 2004|
| G5        | Salim **         | Modern variety Released in 2009                             |
| G6        | Mahmoudi         | Landrace North of Tunisia and registered in 1953 CIMMYT introduced in 1968/1969|
| G7        | Maghrbi          | Landrace Selection and experimentation by INRAT Introduced by INRAT in 1972, officially registered in 1982|
| G8        | Ben Bechir       | Landrace Introduced from Armenia                            |
| G9        | Souri            | Landrace Center and south of Tunisia                        |
| G10       | Agili Glabre     | Landrace Center of Tunisia                                   |
| G11       | Azizi            | Landrace                                                    |

*Susceptible to drought; ** tolerant to drought.

2.2. Field Experiment and Crop Management

A field experiment was carried out in a split-plot design with three replicates per treatment (n = 3) during 2014–2015, 2015–2016, and 2016–2017 cropping seasons in two semi-arid regions of Tunisia, Kef and Siliana (Table S1). The treatment was defined by two water conditions: irrigated and non-irrigated surface. For each site, three blocs (190 m²) per treatment (i.e., irrigated and non-irrigated) were subdivided into 11 plots of 2 m² (in total, 66 plots) and consisted of five rows that were 2 m long with a 0.2 m inter-row spacing and a 0.5 m inter-plot spacing. The distance between control and treated blocs was 10 m. Seeds were hand sown at a rate of 350 grains m⁻².

The experimental field received 100 kg ha⁻¹ of di-ammonium phosphate at sowing. Nitrogen fertilizer (33.5% nitrogen (N), 16.80% nitrate (NO₃), and 16.70% ammonium (NH₄)) was split into three doses of 100 kg ha⁻¹ each and applied at the three-leaf stage (Z13), tillering (Z26), and again at the heading growth stage (Z32) [37]. To control weeds, a pre-emergence herbicide, Puma® evolution (fenoxaprop-p-ethyl + iodosulfuron-methyl sodium + mefenpyr-diethyl; Bayer CropScience, Beja, Tunisia), was used at a rate of 1 l ha⁻¹ at the 2–3-leaf stage.

2.3. Water Treatments

For the non-irrigated treatment (i.e., control, rainfed, or stressed conditions), plants only received water from natural rainfall. In the well-watered treatment (i.e., irrigated or non-stressed conditions), plants received a specific amount of water for irrigation, in addition to rainwater. Irrigation water in the latter was supplied by a sprinkler. The amount of water that was provided was determined in accordance to the needs of the crop using CROPWAT 8.0 software, which considered rainfall distribution over each growing season at each site (Table S2). Information about the tested environments is provided in Table 2.
Table 2. Description of tested environments during three cropping seasons (2014–2017) at Kef and Siliana sites.

| Environment Number | Sites   | Years             | Water Treatments |
|-------------------|---------|-------------------|------------------|
| E1                | Kef     | 2014–2015         | Irrigated        |
| E2                |         |                   | Rainfed          |
| E3                |         | 2015–2016         | Irrigated        |
| E4                |         |                   | Rainfed          |
| E5                |         | 2016–2017         | Irrigated        |
| E6                |         |                   | Rainfed          |
| E7                | Siliana | 2014–2015         | Irrigated        |
| E8                |         |                   | Rainfed          |
| E9                |         | 2015–2016         | Irrigated        |
| E10               |         |                   | Rainfed          |
| E11               |         | 2016–2017         | Irrigated        |
| E12               |         |                   | Rainfed          |

2.4. Measured Traits

At maturity, seven agronomic traits were recorded from the three plots (2 m$^2$ each) per genotype under irrigated and rainfed conditions, including plant height (PH, cm), spike length (SL, cm), grain number/spike (GN/S), spike number/m$^2$ (SN), 1000-kernel weight (TKW, g), biological yield (BY, kg m$^{-2}$), and grain yield/m$^2$ (GY, kg m$^{-2}$). In addition, six DTIs were measured (Table 3).

Table 3. Drought tolerant indices measured on the basis of grain yield under irrigated and rainfed conditions.

| Indices                      | Formula                                      | Unit   | References                  |
|------------------------------|----------------------------------------------|--------|-----------------------------|
| Mean productivity (MP)       | $\frac{Y_s + Y_p}{2}$                        | kg m$^{-2}$ | Rosielle and Hamblin [29] |
| Geometric mean productivity  | $GMP = \sqrt{(Y_s) \times (Y_p)}$            | kg m$^{-2}$ | Fernandez [28]             |
| (GMP)                        |                                              |        |                             |
| Stress susceptibility index  | $SSI = \frac{1 - (Y_s)}{1 - (Y_p)}$         | -      | Fischer and Maurer [30]    |
| (SSI)                        |                                              |        |                             |
| Stress tolerance index       | $STI = \frac{Y_p}{Y_s}$                      | -      | Fernandez [28]             |
| (STI)                        |                                              |        |                             |
| Stress tolerance (TOL)       | $TOL = Y_p - Y_s$                            | kg m$^{-2}$ | Rosielle and Hamblin [29] |
| Yield stability index (YSI)  | $YSI = \frac{Y_s}{Y_p}$                      | -      | Gavuzzi et al. [31]        |

$Y_p$ and $Y_s$ are the mean yield of genotypes under irrigated and rainfed conditions, respectively. $\overline{Y_p}$ and $\overline{Y_s}$ are the mean yield of all genotypes under irrigated and rainfed conditions, respectively.

2.5. Data Analysis

An analysis of variance (ANOVA) of the data for each trait was computed using R statistical software version 4.0 (The R Foundation for Statistical Computing). Significant differences between means were determined by Duncan’s multiple range test ($p \leq 0.05$, $p \leq 0.01$, and $p \leq 0.001$). Pearson’s correlation coefficient and principal component analysis (PCA) were also calculated.

3. Results

3.1. Environment Assessment

The amount (mm) and distribution of precipitation, as well as mean temperature (°C) during the three durum wheat-growing seasons at both sites, were recorded from the national weather stations in Kef and Siliana (Figure 1). Precipitation (mm) and extreme temperature events (low and high, °C) during the most sensitive period of durum wheat growth (i.e., the reproductive stage, which occurs in March, April, and May) from 2007 to 2017 at Kef and Siliana sites are presented in Figures 2 and 3.
weight (TKW, g), biological yield (BY, kg m\(^{-2}\)), and grain yield/m\(^2\) (GY, kg m\(^{-2}\)). In addition, six DTIs were measured (Table 3).

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|--------------------------|----------------------------------------------|----------|------------------|
| Mean productivity (MP)   | \(\text{MP} = \frac{Y_s + Y_p}{2}\)          | kg m\(^{-2}\)| Rosielle and Hamblin [29] |
| Geometric mean productivity (GMP) | \(\text{GMP} = \sqrt[6]{(Y_s)^6 + (Y_p)^6}\) | kg m\(^{-2}\)| Fernandez [28] |
| Stress susceptibility index (SSI) | \(\text{SSI} = 1 - \frac{\overline{x}_{Y_s}}{\overline{x}_{Y_p}}\) |  | Fischer and Maurer [30] |
| Stress tolerance index (STI) | \(\text{STI} = \frac{(Y_s)^6}{(Y_p)^6}\) |  | Fernandez [28] |
| Stress tolerance (TOL)   | \(\text{TOL} = Y_p - Y_s\)                    | kg m\(^{-2}\)| Rosielle and Hamblin [29] |
| Yield stability index (YSI) | \(\text{YSI} = \frac{Y_s}{Y_p}\)           |          | Gavuzzi et al. [31] |

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**Figure 1.** Precipitation (a, mm) and temperature (b, °C) during the three-year (2014–2017) field experiment at Kef and Siliana sites.

**Figure 2.** Extreme minimum and maximum temperatures (°C) from 2007 to 2017 during spring months (March, April, and May) at Kef (a,b) and Siliana (c,d) sites.
Figure 2. Extreme minimum and maximum temperatures (°C) from 2007 to 2017 during spring months (March, April, and May) at Kef (a) and Siliana (b) sites.

Figure 3. Precipitation (mm) from 2007 to 2017 during spring months (March, April, and May) at Kef (a) and Siliana (b) sites.

At both sites, rainfall and temperature (spring heat and frost shock) in each cropping season differed, affecting the performance of genotypes under rainfed and irrigated conditions. On observing the 10-year (2007–2017) climatic data, the 2014–2015 cropping season was characterized by, on the one hand, a precipitation record (i.e., April had the lowest rainfall amount (0 mm) at both sites), and, on the other hand, extreme minimum temperatures (−1.3 °C in April was observed in Kef and −1.4 °C in May in Siliana; Figures 2 and 3). During the same cropping season (2014–2015), extreme maximum temperatures (40.6 and 40.7 °C for Kef and Siliana, respectively) were experienced in May. However, from 2007 to 2017, the 2015–2016 cropping season showed an extreme maximum temperature record (42.4 and 43.3 °C for Kef and Siliana, respectively) in May. Otherwise, there was no noticeable variation in rainfall. In the 2016–2017 cropping season, there was a shortage of rainfall, with the record lowest amount in March (2 and 21 mm) and May (2 and 1 mm) in Kef and Siliana, respectively, while an early heatwave was registered in May (36.1 °C). In these years, a notable frost shock, compared to the 10 years (2007–2017), occurred in April (−1.3 °C) in Kef.

ANOVA revealed significant ($p < 0.01$) effects of environments and genotypes on all agronomic traits. Except for SN and GY, the environment × genotype interactions were significant ($p < 0.05$, $p < 0.01$, and $p < 0.001$) for almost all traits (Table 4). In addition, combined ANOVA results showed that 94.27% of the variation in GY was explained by the effect of environments followed by the environment × genotype interaction (4.08%) and by the genotype variation (1.65%; Table S3).

A cluster analysis dendrogram for environments based on GY showed that they could be clustered into four groups (Figure 4). First, environments under irrigated treatments were separated (E1, E3, E5, E7, E9, and E11) from those under rainfed treatments (E2, E4, E6, E8, E10, and E12). Then, irrigated environment group 1 (EG1: E1, E5, and E7), which experienced extreme minimum temperatures, was separated from irrigated environment group 2 (EG2: E3, E9, and E11). In the rainfed treatments, environment group 3 (EG3: E6, E8, and E12) with the lowest rainfall was separated from EG4 with the highest precipitation (E2, E4, and E10). The weakest performance for most traits was observed in EG3, while the best performance was observed in EG2 (Table 4).
3.2. Genotypic Grain Yield Performance and Drought Tolerance Selection

The GY of each durum wheat genotype under the different tested environments is shown in Table 5. In the 2014–2015 cropping season, when frost shock and early heatwaves were experienced, the highest mean GY was obtained by G6 in Kef and by G1 and G4 in Siliana in the irrigated treatment. In the 2015–2016 season, the three top-yielding genotypes in the irrigated treatment were the modern varieties G2, G5, and G1 at Kef, and G5, G1, and G3 in Siliana, but these did not differ significantly from other genotypes. Under stressed conditions, the highest GY was obtained for modern variety G5 at Siliana. Despite this, genotypes showed the same trends in Kef. In the last cropping season (2016–2017), modern varieties G1 and G3 had the highest GY, while landrace G11 displayed the lowest GY (0.34 kg m$^{-2}$) under favorable conditions in Siliana. Under water stress, landrace G6 and modern variety G1 showed the greatest GY in Kef and Siliana, respectively. Over the 12 environments, the highest GY was observed for G1, G3, and G6 (0.29 kg m$^{-2}$) and the lowest GY for G11 (0.23 kg m$^{-2}$).

Table 5. Grain yield of 11 durum wheat genotypes under different tested environments across the three cropping seasons (2014–2017).

| Source of Variation | PH 1 (cm) | SL 2 (cm) | GN/S 3 | SN 4 | TKW 5 (g) | BY 6 (kg m$^{-2}$) | GY 7 (kg m$^{-2}$) |
|---------------------|-----------|-----------|---------|------|-----------|-------------------|-------------------|
| Environment (E) 8   | 11        | 114.44*** | 122.43*** | 245.75*** | 430.74*** | 330.59*** | 144.44*** | 235.48*** |
| Genotypes (G)       | 11        | 47.45***  | 6.61***  | 3.50*** | 2.37**    | 6.20***  | 5.50***  | 4.54***  |
| E × G               | 110       | 2.62***   | 2.45**   | 3.68*** | 1.28ns    | 2.18***  | 1.40*    | 1.01ns   |
| EG1 9               | 98.70a    | 7.65a     | 38.61b   | 618.94a | 44.74b    | 1.17b    | 1.07b    | 0.34b    |
| EG2                 | 99.8a     | 7.48a     | 59.08a   | 617.77a | 48.22a    | 1.38a    | 0.92a    | 0.45a    |
| EG3                 | 54.58c    | 5.19c     | 29.58d   | 281.29c | 25.73d    | 0.84d    | 0.09d    | 0.09d    |
| EG4                 | 65.30b    | 5.79b     | 34.63c   | 410.23b | 31.05c    | 0.54c    | 0.16c    | 0.09d    |

1 PH: plant height; 2 SL: spike length; 3 GN/S: grain number/spike; 4 SN: spike number/m$^{-2}$; 5 TKW: 1000-kernel weight; 6 BY: biological yield; 7 GY: grain yield; 8 E: environment which is a combination of site, years, and water treatment (see Table 2); 9 EG: environment group identified based on cluster analysis (see Figure 4); 10 Level of significance: ns, not significant; * $p \leq 0.05$; ** $p \leq 0.01$; *** $p \leq 0.001$; 11 Means with similar letter(s) in each trait are not significantly different at $p \leq 0.05$ (Duncan’s multiple range test).

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G3 in Siliana, but these did not differ significantly from other genotypes. Under stressed conditions, the highest GY was obtained for modern variety G5 at Siliana. Despite this, genotypes showed the same trends in Kef. In the last cropping season (2016–2017), modern varieties G1 and G3 had the highest GY, while landrace G11 displayed the lowest GY (0.29 kg m\(^{-2}\)) and the lowest GY for G11 (0.23 kg m\(^{-2}\)).

**Table 5.** Grain yield of 11 durum wheat genotypes under different tested environments across the three cropping seasons (2014–2017).

| No. | E1 \(^2\) | E2 | E3 | E4 | E5 | E6 | E7 | E8 | E9 | E10 | E11 | E12 | Means |
|-----|----------|----|----|----|----|----|----|----|----|-----|-----|-----|-------|
| G1  | 0.38ab   | 0.18 | 0.51a| 0.14a| 0.32a| 0.08abcd| 0.40a| 0.12a| 0.49a| 0.17bc| 0.50a| 0.15a| 0.29  |
| G2  | 0.34b    | 0.19a| 0.53a| 0.14a| 0.32a| 0.07bcd| 0.34ab| 0.13a| 0.44a| 0.14c | 0.41cd| 0.12abc| 0.26 |
| G3  | 0.39ab   | 0.18a| 0.49a| 0.18a| 0.32a| 0.08abcd| 0.39ab| 0.14a| 0.49a| 0.14c | 0.49a | 0.13abc| 0.29 |
| G4  | 0.36b    | 0.18a| 0.45a| 0.16a| 0.32a| 0.07de  | 0.40a | 0.15a| 0.45a| 0.14c | 0.45abc| 0.06bc| 0.28 |
| G5  | 0.39ab   | 0.17a| 0.53a| 0.17a| 0.32a| 0.08abc | 0.33ab| 0.14a| 0.52a| 0.24a | 0.48 ab| 0.05c | 0.28 |
| G6  | 0.54a    | 0.19a| 0.43a| 0.20a| 0.31a| 0.09a  | 0.34ab| 0.14a| 0.47a| 0.17bc| 0.42 cd| 0.14ab| 0.29 |
| G7  | 0.35b    | 0.12a| 0.47a| 0.12a| 0.32a| 0.08ab  | 0.31ab| 0.12a| 0.44a| 0.13c | 0.43bcd| 0.13abc| 0.25 |
| G8  | 0.38ab   | 0.23a| 0.47a| 0.19a| 0.32a| 0.08abcd| 0.32ab| 0.14a| 0.47a| 0.22ab| 0.46abc| 0.11abc| 0.28 |
| G9  | 0.33b    | 0.18a| 0.44a| 0.20a| 0.31a| 0.07bcd | 0.31ab| 0.10a| 0.40a| 0.11c | 0.48abc| 0.07abc| 0.25 |
| G10 | 0.31b    | 0.16a| 0.45a| 0.15a| 0.32a| 0.06e  | 0.36ab| 0.08a| 0.40a| 0.15c | 0.38de | 0.09abc| 0.24 |
| G11 | 0.26b    | 0.13a| 0.46a| 0.18a| 0.31a| 0.07cde | 0.27b | 0.07a| 0.48a| 0.12c | 0.34e  | 0.09abc| 0.23 |
| CV% | 18.90    | 17.11| 7   | 15.37| 1.66 | 9.86  | 11.79| 21.67| 8.22 | 25.65 | 11.11 | 31.54 |

\(^1\) GY: grain yield; \(^2\) G: genotypes (see Table 1); \(^3\) E: environment, which is a combination of site, years, and water treatment (see Table 2); \(^4\) means with similar letter(s) in each trait are not significantly different at \(p \leq 0.05\) (Duncan’s multiple range test).

DTIs and genotype ranks are provided in Table 6. A significant effect of years on GY was observed, hence the variation in genotype ranks from year to year. Thus, durum wheat genotypes were screened for drought tolerance each year. The highest STI, MP, and GMP were observed for G6, followed by G3 and G8 in the first cropping season (2014–2015), and for G5 and G8 in the second season (2015–2016). In contrast, G1 and G3 performed best under stressed and non-stressed conditions in the third cropping season (2016–2017). Lowest TOL was observed for G11 and G8, G6 and G8, and G11 and G6 during the first, second, and third cropping seasons, respectively. According to this index, these genotypes experienced the least reduction in GY under rainfed conditions and were more resistant to drought stress. SSI displayed a similar ranking pattern as YSI. Lowest SSI and highest YSI were observed in G8 and G2 in the first cropping season, G8 and G6 in the second cropping season, and G6 and G7 in the third cropping season.

To identify a suitable index for the drought tolerance selection, the correlation coefficient between different DTIs and GY in both conditions was determined (Table 7). Results indicate a positive and significant correlation between Yp and STI (\(r = 0.35; p < 0.01\)), MP (\(r = 0.89; p < 0.01\)), and GMP (\(r = 0.68; p < 0.01\)), and between Ys and STI (\(r = 0.88; p < 0.01\)), GMP (\(r = 0.93; p < 0.01\)), and MP (\(r = 0.76; p < 0.01\)). In addition, these indices had a positive and significant (\(p < 0.05\)) correlation between each other. Thus, STI, MP, and GMP seem to be the most effective parameters to select drought-tolerant genotypes in both conditions. TOL, which was significantly and positively correlated with Yp (\(r = 0.75; p < 0.01\)) and significantly and negatively correlated with Ys (\(r = -0.32; p < 0.01\)), might be useful to select genotypes with large GY, but only in the stressed environment.
Table 6. Drought tolerance indices and genotype ranks based on grain yield under irrigated and rainfed conditions across three cropping seasons (2014–2017).

| No. | 2014–2015 | 2015–2016 | 2016–2017 |
|-----|-----------|-----------|-----------|
| STI | GMP 1     | GMP 2     | GMP 3     |
| -   | (kg m⁻²) | -         | (kg m⁻²) | -         | (kg m⁻²) | -         |
| G1  | 0.46      | 0.27      | 0.24      | 0.24      | 1.06      | 0.38      | 0.36      |
| G2  | 0.50      | 0.28      | 0.25      | 0.23      | 1.01      | 0.41      | 0.36      |
| G3  | 0.49      | 0.27      | 0.25      | 0.21      | 0.96      | 0.44      | 0.31      |
| G4  | 0.44      | 0.26      | 0.23      | 0.20      | 0.97      | 0.43      | 0.48      |
| G5  | 0.58      | 0.30      | 0.27      | 0.28      | 1.07      | 0.37      | 0.38      |
| G6  | 0.31      | 0.22      | 0.20      | 0.21      | 0.99      | 0.41      | 0.29      |
| G7  | 0.52      | 0.27      | 0.25      | 0.17      | 0.83      | 0.52      | 0.44      |
| G9  | 0.36      | 0.23      | 0.21      | 0.18      | 0.95      | 0.44      | 0.30      |
| G10 | 0.32      | 0.23      | 0.20      | 0.22      | 1.10      | 0.35      | 0.29      |
| G11 | 0.21      | 0.19      | 0.05      | 0.17      | 1.06      | 0.38      | 0.32      |

Ranking pattern: 1 G1 7 ; 2 G1 7 ; 3 G1 7 ; 4 STI: stress index; 5 GY: grain yield; 6 G: genotypes (see Table 1); 7 E: environment, which is a combination of site, years, and water treatment. Three cropping seasons (2014–2017).

Table 7. Correlation coefficient between drought tolerance indices and grain yield under irrigated and rainfed conditions.

| Yp  | Ys  | STI  | MP  | GMP  | TOL  | SSI  | YSI  |
|-----|-----|------|-----|------|------|------|------|
| Yp  | 1   | 0.378**  | 0.347**  | 0.890**  | 0.685**  | 0.750**  | 0.154ns  | −0.146ns  |
| Ys  | 1   | 0.879**  | 0.759**  | 0.929**  | −0.328**  | −0.655**  | 0.845**  |
| STI | 1   | 0.677**  | 0.815**  | −0.273**  | −0.512**  | 0.722**  |
| MP  | 1   | 0.940**  | 0.366**  | −0.214*  | 0.314**  |
| GMP | 1   | 0.036ns  | −0.430**  | 0.599**  |
| TOL | 1   | 0.625**  | −0.753**  |
| SSI | 1   | −0.797**  |
| YSI | 1   | 1        |

1 Yp: yield under irrigated conditions; 2 Ys: yield under rainfed conditions; 3 STI: stress tolerance index; 4 MP: mean productivity; 5 GMP: geometric mean productivity; 6 TOL: stress tolerance; 7 SSI: stress susceptibility index; 8 YSI: yield stability index; 9 Level of significance: ns, not significant; * p < 0.05; ** p ≤ 0.01.

To better separate and classify the different genotypes, PCA was employed (Figure 5). The first two PCAs explained 99.2% of the total variation in GY. The observed positive and significant correlation between STI, MP, and GMP, and between YSI and Ys indicated that these indices were able to discriminate G6 and G8 (Group I) as the stress-tolerant group with high GY in both conditions and good stability in the control conditions. Based on the positive and significant correlation between TOL and Yp, G1, G3, and G5 in Group II appeared to be susceptible to drought stress, although they performed well under irrigated conditions. Ys had a highly positive and significant correlation with STI, MP, GMP, and YSI and a significantly negative correlation with SSI. These last correlations indicated that G7, G9, G10, and G11 (Group III), which had the highest SSI, could be separated and were considered to be susceptible to drought and thus unsuitable in both conditions, especially unstable GY in the stressed conditions. G2 and G4 (Group IV) had an intermediate rank for the different indices, so they could be classified as semi-tolerant or sensitive genotypes.
4. Discussion

Variation in wheat GY is strongly dependent on environmental conditions [38,39]. In this study, water treatment had a dominant effect on GY, in addition to the effect of the cropping season, which was significant due to climatic changes. Variation in annual weather conditions can affect the degree of stress experienced by a crop [40]. In our study, rainfall (amount and distribution) and temperature varied considerably from year to year, especially during critical periods of crop development (anthesis and grain filling), as was recorded in the first and the third cropping seasons, where a record lowest amount of rainfall and extreme minimum temperatures were registered (Figures 2 and 3). Therefore, four environmental groups were identified based on drought and temperature stresses (Figure 4). Under well-watered conditions, GY was significantly correlated to GN/S ($r = 0.63; p < 0.01$), BY ($r = 0.4; p < 0.01$), and TKW ($r = 0.20; p < 0.01$; Table S4). Nonetheless, GY significantly correlated with all agro-morphological traits (i.e., PH, SL, GN/S, SN/m², TKW, and BY) under water stress. In the same conditions, the lowest PH, SL, GN/S, SN, TKW, BY, and GY were observed for all durum wheat genotypes in the third environment group (EG3) due to a deficit in rainfall. Similar findings were obtained by Maqbool et al. [41] and Liu et al. [42], who reported that drought stress significantly reduced GY, PH, GN/S, and TKW in bread wheat. According to Dehgahi et al. [43], wheat GY positively correlated with annual rainfall, and its effect varies from year to year. In Tunisia, in semi-arid regions, the amount of precipitation was unable to cover water requirements for durum wheat, especially during March, April, and May when crop water needs are high, and the amount of rainfall played a crucial role in determining crop production [44]. That was the main reason why irrigation was necessary for Tunisian conditions.

GY was also influenced by extreme temperature events. A review by Akter and Islam [45] revealed that heat stress reduces wheat grain number and size by reducing the grain-filling period and assimilate translocation. In addition, Shirdelmoghanloo et al. [46] reported that from 600 wheat field trials, 15% of the reduction in GY was due to temperatures exceeding 30 °C during or around flowering [47]. In our research, the lowest GY, its related traits (i.e., GN/S, SN, and TKW), and BY were obtained in the third growing season, which could be due to the combined effect of drought and heat stress. However, the joint impact of drought and heat stress on wheat growth and GY could be more pronounced than individually [48]. Together, these stressors reduced the number of plants/m², PH, and BY/m² of rainfed wheat and barley [49] and GY in wheat by as much as 50% [50]. In general, this reduction could be explained by the greatest damage caused by frost and heat

![Figure 5. Biplot derived from the principal component analysis of 11 durum wheat genotypes and drought tolerance indices.](image-url)
occurring during ear emergence and near anthesis. In all durum species, anthesis was the most sensitive stage when heat and frost shock caused sterility and the abortion of formed grains, and thus a significant loss of yield [51,52]. Heat and frost shock, which are serious limiting factors for GY, may increase during future climate change scenarios [51].

Based on the obtained results for GY, which was the main criterion for the selection of drought tolerance, important genetic variability was observed between genotypes. Genotypic variation in GY was greater (higher CV, %) in the rainfed environment than in the irrigated environment (lower CV, %; Table 5). Under stress conditions, large genotypic differences and responses were expected [53]. Thus, germplasm might be a useful genetic source in wheat breeding programs for developing drought tolerance. Similar results were obtained by Mwadzingeni et al. [21] in 88 bread wheat lines that were evaluated under greenhouse and field conditions during two growth seasons (four tested environments) in South Africa in order to determine the level of drought tolerance. In the present study, most modern varieties had the best response to supplemental irrigation. However, under rainfed conditions, landraces displayed the highest GY. Several studies showed that landraces were better adapted and tolerant to environmental stress, especially drought, compared to breeding lines, modern, and old varieties [40,54–56]. Landraces were characterized by superior stem length, biomass production, and late flowering which cumulatively played a crucial role in the determination of GY. A longer stem, which resulted in a greater amount of transferred assimilates in the form of soluble carbohydrates [57], significantly contributed to grain filling [48]. Under water stress, in 18 durum wheat genotypes, the plant biomass had a positive effect on GY ($r = 0.80$) between tillering and maturity stages [58]. Late flowering and early heading by vigorous and rapid growth were important traits to avoid spring frost shock in durum wheat genotypes [51]. In addition, under a Mediterranean environment, where terminal drought frequently occurs, early heading was a defining characteristic to obtain high GY [59].

Based on the correlation matrix, cluster, and PCA analyses, three DTIs (STI, MP, and GMP) were highly correlated to each other and to GY in non-stressed and stressed conditions (Table 7), prompting us to use them to screen drought-tolerant genotypes with high GY in both conditions. Our findings were in agreement with findings by Mohammadi [40] in 24 durum wheat genotypes assessed over four years under rainfed and irrigated conditions. They found that the correlation between these indices was significant ($p \leq 0.01$) at all stress levels (mild, moderate, and severe), which indicated that they were useful for ranking genotypes. In addition, Nouri et al. [60] and Subhani et al. [61] reported that these drought indices were preferred and useful to differentiate durum wheat and barley genotypes. In the present work, STI, MP, and GMP identified G6 and G8 (landraces) as the most drought-tolerant genotypes with high GY under irrigated and rainfed conditions. These genotypes have a good tolerance compared to G3, a drought-tolerant genotype. Thus, this group of genotypes had a good adaptation in a specific environment under drought conditions with irregular rainfall distribution, insufficient rainfall, as well as extreme temperature events. Otherwise, TOL was significantly and positively correlated with GY under optimal conditions but negatively correlated under rainfed conditions. TOL discriminated G1, G3, and G5 (modern varieties) as susceptible genotypes to drought but as suitable genotypes in irrigated conditions. The selection based on this index resulted in enhanced GY under favorable conditions [62]. Anwaar et al. [63] used SSI to identify drought-tolerant genotypes in 50 bread wheat landraces evaluated under rainfed and irrigated conditions and showed that tolerant genotypes could be selected by low SSI and TOL values. In this study, genotypes G7, G9, G10, and G11 (landraces), which had high SSI and lowest STI, MP, GMP, and YSI, were susceptible to drought and unsuitable genotypes for cultivation in both conditions.

5. Conclusions

The present study showed, on the one hand, a significant environmental effect on genotypic GY performance: the amount and distribution of rainfall, as well as extreme
temperature events, were the main factors reducing durum wheat growth and GY in semi-arid environments. On the other hand, DTIs and genotype ranks served as helpful tools to screen drought-tolerant genotypes under a range of environments. Our results revealed that DTIs were significantly correlated with GY under non-stressed and stressed conditions. Landraces G6 and G8 were the most drought-tolerant genotypes, attaining high GY in both conditions. However, modern varieties (G1, G3, and G5), which were drought-susceptible genotypes, were only suitable for irrigation. Wide genotypic variation offered a tremendous opportunity for further crop improvement to drought as well as extreme minimum and extreme maximum temperature stresses.

Supplementary Materials: The following are available online at https://www.mdpi.com/article/10.3390/agronomy11050875/s1: Table S1—Geographic and soil information of studied sites. Table S2—Precipitation (mm) and supplemental irrigation amount (mm) during three cropping seasons (2014–2017) at Kef and Siliana sites. Table S3—Combined analysis of a variation for grain yield of 11 durum wheat genotypes under two water treatments during three cropping seasons (2014–2017) at Kef and Siliana sites. Table S4—Pearson correlation between grain yield and different agro-morphological traits under irrigated and rainfed conditions.

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Abbreviations

| Abbreviation | Description                  |
|--------------|------------------------------|
| BY           | biological yield             |
| CMP          | geometric mean productivity  |
| GN/S         | grain number/spike           |
| GY           | grain yield                  |
| MP           | mean productivity            |
| PCA          | principle component analysis |
| PH           | plant height                 |
| SL           | spike length                 |
| SN           | spike number/m²              |
| SSI          | stress susceptibility index   |
| STI          | stress tolerance index       |
| TKW          | 1000-kernel weight           |
| TOL          | tolerance index              |
| YI           | yield index                  |
| Yp           | yield under irrigated conditions |
| Ys           | yield under rainfed conditions |
| YSI          | yield stability index        |
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