Research Article

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On-farm assessment of yield and quality traits in durum wheat

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Abstract

BACKGROUND: Durum wheat is key source of calories and nutrients for many regions of the world. Demand for it is predicted to increase. Further efforts are therefore needed to develop new cultivars adapted to different future scenarios. Developing a novel cultivar takes, on average, 10 years and advanced lines are tested during the process, in general, under standardized conditions. Although evaluating candidate genotypes for commercial release under different on-farm conditions is a strategy that is strongly recommended, its application for durum wheat and particularly for quality traits has been limited. This study evaluated the grain yield and quality performance of eight different genotypes across five contrasting farmers' fields over two seasons. Combining different analysis strategies, the most outstanding and stable genotypes were identified.

RESULTS: The analyses revealed that some traits were mainly explained by the genotype effect (thousand kernel weight, flour sodium dodecyl sulfate sedimentation volume, and flour yellowness), others by the management practices (yield and grain protein content), and others (test weight) by the year effect. In general, yield showed the highest range of variation across genotypes, management practices, and years and test weight the narrowest range. Flour yellowness was the most stable trait across management conditions, while yield-related traits were the most unstable. We also determined the most representative and discriminative field conditions, which is a beneficial strategy when breeders are constrained in their ability to develop multi-environment experiments.

CONCLUSIONS: We concluded that assessing genotypes in different farming systems is a valid and complementary strategy for on-station trials for determining the performance of future commercial cultivars in heterogeneous environments to improve the breeding process and resources.

Supporting information may be found in the online version of this article.

Keywords: wheat quality; on-farm; GGE analysis; flour yellowness

INTRODUCTION

Representing 6% of the total wheat production, durum wheat (*Triticum turgidum* subsp. *durum* (Desf.) Husnot), also known as pasta wheat, is cultivated on nearly 13 million ha worldwide, with an estimated global production of 33.8 Mmt in 2020–2021.[1,2] The milling of the durum grain yields semolina, which is used to make pasta, and other products such as couscous and unleavened and leavened breads.[3] Despite its importance as a staple crop, the production of durum wheat faces challenges due to diseases, pests, climate change, and environmental/management constraints such as drought and heat.[4] In addition to this, the grain produced should have enough quality to be accepted by the processing industries, which in the case of durum is linked to high gluten strength and bright yellow semolina color.

Developing a new wheat cultivar typically requires between 8 and 12 years[5] and its performance is assessed in on-station trials in which the majority of the field conditions are controlled (irrigation, fertilization, and diseases). As a consequence, the outcomes of standardized procedures tend to differ in comparison with management practices utilized by farmers, which might vary greatly depending on the technology and resources applied. Beres *et al.*[6] calculated durum yield gaps by comparing farm yields and attainable yields for certain durum producing regions and discovered yield gaps of 50% in Italy, Greece, and Cyprus; in

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Mexico, they observed a reduced yield gap of approximately 25–30% due to irrigation production. In this regard, Clarke *et al.*[7] examined the yield increase in Canadian durum wheat from 1960 to 2010, observing 0.6% genetic gains each year, but when synergy of genetic gain and different agronomic techniques were examined, 1.2% gains per year were recorded. Laidig *et al.*[8] also reported considerable differences between on-station and on-farm trials, which should be taken into account when developing new crops adapted to heterogeneous environments and farming systems.[9] These findings highlight the importance of evaluating new lines under real production conditions in addition to on-station trials in order to characterize their performance more accurately.

Despite the fact that yield remains the main objective in breeding programs, there is a growing demand for specialized quality improvement targets to meet the requirements for distinct and diverse quality features of various types of wheat-based products.[10] For this reason, further efforts are required to ensure improvements in most yield and quality traits, taking into account their high level of interaction with the environment, which makes the selection process more difficult.[11] Thus, developing new wheat durum varieties that satisfy future demands requires breeding programs that combine high yields and high quality with selection methods under different management practices to assess variability and performance in real field conditions used by farmers.

The objectives of this study were: (i) to evaluate the grain yield and quality performance of eight different genotypes across five different farmer's management practices over two seasons; (ii) to identify the most outstanding and stable genotypes through genotype and genotype-by-environment (GGE) analysis; (iii) to develop information to assist farmers for more efficient and sustainable use of resources for the management practices and environments under analysis.

MATERIAL AND METHODS

Field trials and experimental design

The trials were conducted in five different farmers' fields during the 2015–2016 and 2016–2017 seasons, at the Yaqui Valley, Sonora, Mexico. The lines analyzed included eight genotypes consisting of three commercial varieties and five candidate lines (full data, names of the genotypes, and pedigree are provided in Table S1). The experimental design, the same for all farmers' fields, was a randomized complete block with three replicates and each experimental unit had an area of 32 m^2 (10 m length × 3.2 m width). Trials were sown between the end of November and the first week of December and harvest dates ranged from the last week of April to the first week of May. No preceding crops were cultivated for any of the seasons. Different combinations of irrigation and nitrogen fertilization were applied depending on each farmer´s field (considered as different management practices, hereafter) as shown in Table 1, where the name of each management practice is represented as a combination of the irrigation and total fertilization levels. The first and second irrigations were applied 60 and 90 days after sowing, respectively. Third and fourth irrigation were applied during grain filling. The first fertilization was applied prior to the pre-plant irrigation, which took place approximately 18 days before sowing and at the end of tillering (second fertilization), then 50 additional kg ha^{-1} of N were applied in some trials close to heading (third fertilization). Pesticides and herbicides were applied depending on the practices used by each farmer, and weeds, diseases, and insects were controlled. Meteorological conditions during the two crop seasons were obtained from the NASA Prediction of Worldwide Energy Resource (https://power.larc.nasa.gov/). Monthly precipitation for the period between November and May was 4.8, 0.3, 8.8, 1.9, 10.4, 0.7, and 0 mm in 2015–2016, and 0.1, 8.5, 5.4, 45.6, 0.1, 0, and 0.7 mm in 2016–2017. Monthly maximum and minimum temperatures for the same period were 19.5–27, 16–23.7, 14.6–23, 16.7–26.1, 17.7–26, 19.2–27.6, and 21.8–29 °C in 2015–2016 and 21–28.2, 16.6–23.5, 14.7–22.1, 15.7–23.9, 17.9–26.6, 19.6–28.7, and 21.4–29.2 °C in 2016–2017.

Parameters quantified

Grain yield values (kg ha^{-1}) were adjusted to 12% of moisture after harvesting. Test weight (TESTWT, kg hL^{-1}) and thousand kernel weight (TKW, g) values were registered through the digital image system SeedCount SC5000 (Next Instruments, Canterbury-Bankstown, Australia). Grain protein content (GPC, %) was determined by near-infrared spectroscopy (NIRS), using NIR Systems 6500 (Foss, Hilleroed, Denmark) calibrated based on official American Association of Cereal Chemist (AACC) methods 39–10, 55–30, and 46-11A[12] and reported at a 12.5% moisture basis. For milling, grain samples were processed according to the official AACC method 26–95[12] and milled into flour using a Brabender Quadrumat Senior mill (CW Brabender, Duisburg, Germany). Sodium dodecyl sulfate sedimentation volume from flour samples (FLRSDS, mL) was measured as described by Peña *et al.*[13] Flour yellowness (FYELLOW) was obtained as the b value of a Minolta color meter (Konica Minolta, Tokyo, Japan).

Statistical analyses

Analyses of variance were performed with R software version 4.0.1.[14] The statistical model applied is detailed in the File S1. To complement the analysis and facilitate the identification of the best genotypes across the different field conditions, genotype and genotype-by-environment analysis[15] was carried out to analyze detail genotypic and management practices interactions in more detail using the 'GGEBiplots' package[16] for R. For this

Table 1. Full description of the trials environments conditioned by management practices during the 2015–2016 and 2016–2017 seasons at the Yaqui Valley of Mexico

			Irrigation (mm)					Fertilization (kg ha^{-1})			
Environment	Sowing date	Regime	1st	2nd	3rd	4th	1st	2nd	3rd	Total
F291	1st week December	Full	120	80–100	80–100	80–100	241	50	0	291
F295	4th week November	Full	120	80–100	80–100	80–100	149	96	50	295
F341	1st week December	Full	120	80–100	80–100	80–100	241	50	50	341
R291	1st week December	Reduced	120	80–100			241	50	0	291
R341	1st week December	Reduced	120	80–100			241	50	50	341

analysis, data from both growing seasons were averaged. Four different GGE biplot analyses were performed:[17] (i) The 'mean against stability' analysis, which facilitates the visualization of the mean performance and stability of genotypes; (ii) the 'ranking genotypes' tool, which defines an ideal genotype that has the highest performance in all environments and is absolutely stable – those genotypes closer to the ideal genotype show the best performance and stability; (iii) the 'ranking environment' tool, which allows the identification of an ideal environment (management practice in this case and defined as the most discriminating and representative) and compares all environments to it, and (iv) the 'which-won-where' analysis, which groups environments (management practices) into mega-environments (M-E) indicating similarity among them.

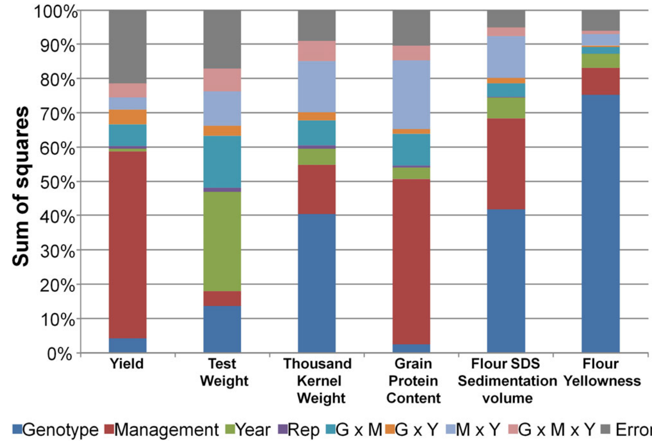

Figure 1. Percentage of the total sum of squares from ANOVA analysis of eight durum wheat genotypes across five different field conditions cultured in both 2015–2016 and 2016–2017.

RESULTS

Genotype, management practices, year, and their interaction effects on grain yield and quality traits

Six traits related to grain yield and quality were studied in eight different genotypes across five different management practices during the 2015–2016 and 2016–2017 seasons. Analysis of variance values for all the traits including the significance of genotype (G), management practice (M), year (Y), and interactions effects are shown in Table 2. All the triple interactions (G × M × Y) were significant except for grain yield and FYELLOW. For the double interactions (G × M, G × Y, and, M × Y) significant P-values were observed except for the FY G × Y interaction. The three main effects (G, M, and Y) showed significant P-values for all the traits. The influences of each effect on traits were also calculated (Fig. 1). The genotypic effect explained most of the variation in TKW (40.3%), FLRSDS (41.8%), and FYELLOW (75.2%). The management practice effect, represented by the farmer's fields, showed the highest influence on variability for grain yield (56.4%) and GPC (48.3%) and influenced TKW and FLRSDS considerably. Finally, the year effect explained the highest variation only in TESTWT (29.1%) with much less influence on the other traits (3.8% on average).

We then performed Tukey tests for all the double interactions and main effects. Similar trends were found among all analyses, for each trait, for cultivars, management practices, and years. For this reason, and to simplify the report of the results, Fig. 2 shows differences among genotypes, farmer's field conditions, and years based on the principal effects (results were then compared and confirmed through GGE biplot analysis).

When genotypes were analyzed, different ranges of variation were observed. While grain yield showed the highest ranges (at least a 2.1-fold difference between the minimum and maximum values), TESTWT had a narrow range (1.05 on average). Differences in the mean values for all the traits were also identified and significance among genotypes depended on the trait. For instance, the Tukey test found two subgroups for grain yield but five subgroups were identified for FYELLOW. When genotypes were assessed individually, some patterns were observed: genotypes 2 and 7 (both check lines) had the highest grain yield values but low performance for quality traits, with the lowest values for GPC, FLRSDS, and FYELLOW. Genotype 1 (also control line), performed well in terms of yield and related traits, acceptable values for GPC, the lowest values for FLRSDS but the highest values for FYELLOW. Among the candidate lines, genotypes 5 and 8 showed similar performance with high grain yield and TKW, intermediate values for GPC but one of the lowest values for TW and especially for FLRSDS and FYELLOW. Genotype 6 showed lower grain yield in comparison with control lines (however it was not significantly different from the other lines) with high values for TW and TKW; this genotype had the highest values for GPC and FLRSDS and one of the highest for FYELLOW. Genotype 4 showed a similar grain yield to genotype 6 but lower values for TW and TKW; at quality level, it ranked second for GPC and FLRSDS but showed intermediate values for FYELLOW. Finally, genotype 3 had one of the lowest overall performances for grain yield and quality traits with the exception of FYELLOW showing the second highest value.

When management practices were compared (Fig. 2), grain yield had the greatest variability (at least a 1.93-fold difference between the minimum and maximum values) while TESTWT had

Table 2. Sum of squares from ANOVA analysis in eight durum wheat genotypes across five different field conditions cultured in both 2015–2016 and 2016–2017 for six different traits: Yield, test weight (TESTWT), thousand kernel weight (TKW), grain protein content (GPC), flour SDS-sedimentation volume (FLRSDS), and flour yellowness (FYELLOW). *** $P < 0.001$, ** $P < 0.01$, * $P < 0.05$

Source	d.f.	Yield	TESTWT	TKW	GPC	FLRSDS	FYELLOW
Genotype (G)	7	1.8E+07***	44.9***	1959.2***	6.8***	374.1***	582.8***
Management (M)	4	2.4E+08***	14.4***	699.0***	140.2***	236.5***	61.4***
Year (Y)	1	3.8E+06*	96.7***	226.5***	10.0***	55.1***	32.4***
G × M	28	2.7E+07*	50.3***	362.2***	26.7***	34.9***	15.2*
G × Y	7	1.9E+07***	10.0***	112.5***	3.9**	13.7***	2.0
M × Y	4	1.5E+07***	33.3***	724.6***	58.7***	109.9***	26.1***
G × M × Y	28	1.8E+07	22.4**	291.2***	12.5***	21.6***	8.4

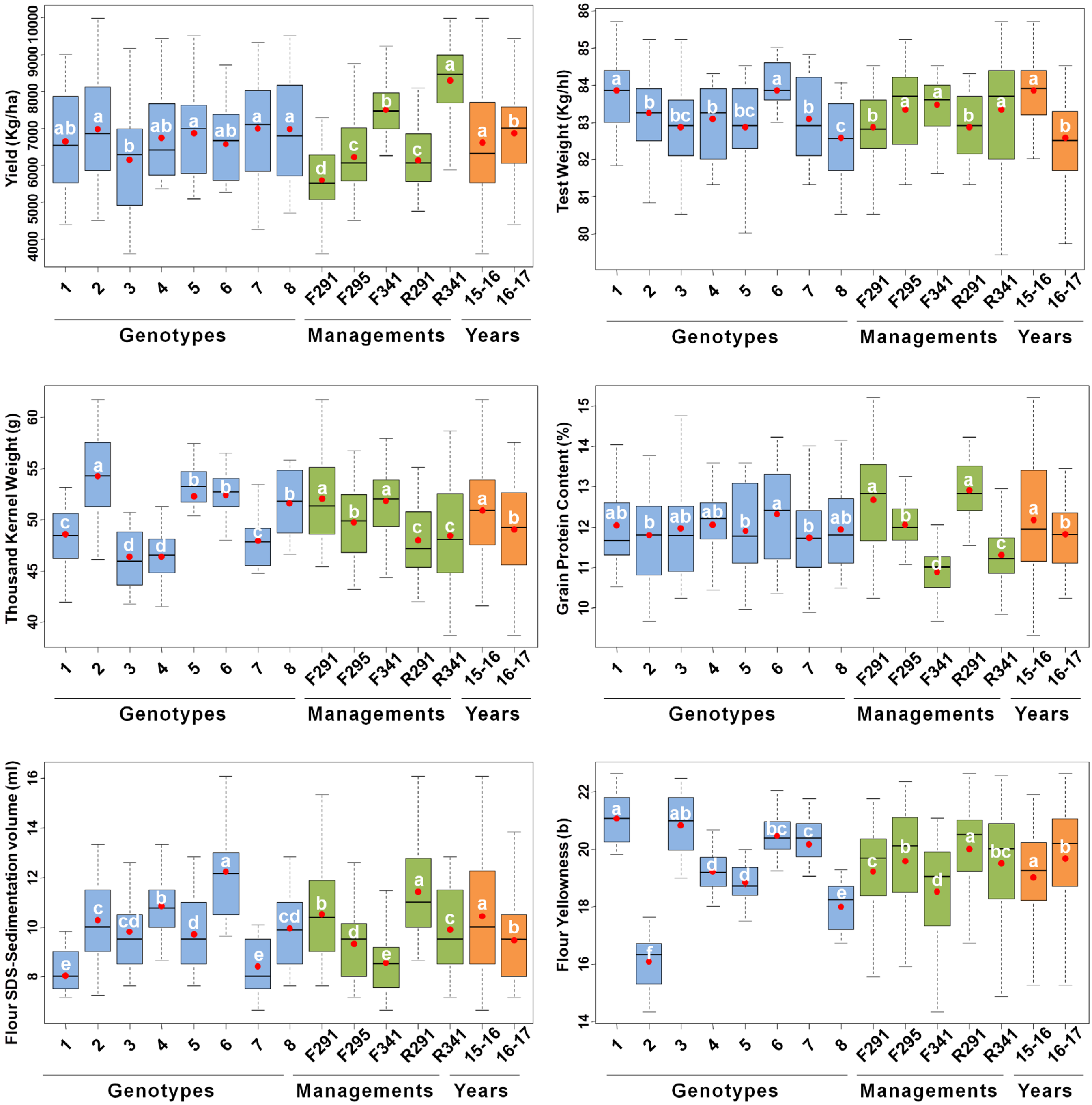

Figure 2. Box plots for genotypes (blue bars), management (green bars) and years (orange bars). Red points referred to the mean values. Values with the same letter are not significantly different at $P = 0.05$ according to the Tukey test.

a narrow range (1.05 on average). FLSRSDS showed the highest number of subgroups identified by the Tukey test (five in total) while TESTWT had the lowest one (two in total). The different management practices had a clear influence on grain yield and quality traits. While R341 and F341 had the highest grain yield and TESTWT values and the lowest performance for quality traits, management practices R291, and F291, on the contrary, had the lowest performance for grain yield and TESTWT but the highest values for GPC and FLRSDS. FYELLOW had a mixed response with R291 in the top followed by F295 and R341.

The 2015–2016 season had the widest ranges for most of the traits with the highest values for TESTWT, TKW, GPC, and FLRSDS when the year effect was analyzed (Fig. 2). The 2016–2017 season had the highest mean values for grain yield and FYELLOW and the lowest for quality traits, which was most likely due to a wetter season than the previous one.

Specific Tukey test analyses for genotypes for each management practice were also performed (Table S2). With a few exceptions, similar trends to those mentioned above were discovered. For grain yield, genotypes 2 and 7 performed well in most of the management practices; genotypes 4, 1, and 8 also had remarkable values for management practices F291, F295, and F341/R341, respectively. The tendencies for genotypes 4 and 6 with a slight reduction in yield and high values for quality traits remained for most of the management practices (except for F291 where quality performance was lower for both). Under certain management conditions, some genotypes showed exceptional performance for quality traits. Genotypes 1 and 3, for instance, had the greatest GPC values at F341 and F295, respectively. For FYELLOW, genotypes 1 and 3 ranked first in all management conditions followed primarily by genotype 6. Finally, because phenology has a strong impact on adaptation, days to anthesis and days to maturity were analyzed for each genotype and management practice for the 2016–2017 season. The Tukey test showed that no significant differences were found between genotypes for any of the management practices (Table S2).

Genotype and genotype-by-environment biplot analysis

Genotype and genotype-by-environment biplot approaches were used to complement and confirm the previous analyses and facilitate the identification of the best genotypes across the different field conditions. The plots obtained for each analysis and trait were overlapped to facilitate the description of the results (Fig. 3).

With the GGE biplot analysis we identified the best and most stable genotypes based on their proximity to the ideal genotype. As expected and consistent with the Tukey test analyses mentioned above, genotypes performed differently depending on the trait. Genotype 2 showed the highest mean and stability values for grain yield; however, it had some of the lowest values for the GPC and FYELLOW traits. Genotype 7 followed genotype 2, with high grain yield values but low mean value for GPC. For GPC, and FLRSDS, genotypes 4 and 6 showed their superiority and stability by being the closest to the ideal genotype. For FYELLOW, genotypes 1 and 3 showed the best performances, combining high mean values and high stability. For grain yield, management practice, F341 was the closest to the ideal environment, as expected, whereas for TESTWT and TKW management condition F295 performed better. For GPC, and FLRSDS, environment R291 was the closest to the ideal environment followed by those practices with high doses of nitrogen (F341 or R341). For FYELLOW, in contrast to the other traits, the management conditions did not show much dispersion, being F291 and R341 the closest to the ideal environment. Finally, the GGE biplot analysis identified 5 M-E for all the traits (indicated by different background colors in each plot). For some traits, the management conditions were grouped in only 1 M-E (TKW, FLRSDS and, FYELLOW), in two (TESTWT), or in three (Yield and GPC), showing how management conditions could influence in the variability of each trait.

Some patterns could be derived from the GGE biplot analysis combined with the ANOVA and Tukey test analysis. Genotypes 2, 7, and 8 performed best for grain yield with acceptable stability across management practices; however, these genotypes had different performances for quality traits: for GPC, genotypes 2 and 7 had the lowest values while genotype 8 intermediate performance, for FLRSDS genotypes 2 and 8 showed values similar to the general media while genotype 7 had one of the lowest performances; on the other hand, genotype 7 had good performance for FYELLOW while genotypes 1 and 8 showed the lowest values. Genotypes 4 and 6 had the highest values for GPC, and FLRSDS, being highly stable across field conditions; nevertheless, their grain yield performance was lower when compared with the top cultivars showing the Tukey test significant differences only in two management practices. Genotype 3, one of the furthest cultivars from the ideal genotype has one of the lowest and most unstable performances for grain yield, TESTWT, and TKW in any of the management practices and intermediate/low performance for quality traits, making it a candidate to be discarded from the breeding program. The ideal environment, on the other hand, indicates the most discriminating and representative environment. R291 was the closest to the ideal environment for most of the traits, but F291 was the furthest away – a candidate to be discarded if resources are limited in the breeding programs.

Irrigation and nitrogen levels

The different regimes of irrigation and nitrogen fertilization were evaluated to develop information for more efficient and sustainable use of resources. Data from management practices F291, F341, R291, and F341, which allowed a full comparison of treatments across these conditions, was used for this analysis. Table S3 summarizes the results for the six traits including mean values, *P*-values and Tukey's test comparison for the main effects and their interactions. The irrigation by nitrogen interaction was significant only for FLRSDS (where reduced irrigation and low doses of nitrogen showed the highest mean values). For the rest of the traits, the main effects were significant ($P < 0.0001$) except for the irrigation effect for TESTWT and nitrogen level for TKW. From the analyses, we observed that full irrigation was not necessary to maximize grain yield but high doses of nitrogen are suggested. According to our results, reduced irrigation with 291 kg ha^{-1} of nitrogen was enough to maximize GPC and FYELLOW values.

DISCUSSION

To develop high-yielding, high-quality cultivars it is necessary to assess the phenotypic variation caused by the genotype, the environment, and their interaction in order to determine the stability of each genotype across environments (Lin and Binns 1994). Although yield gaps between on-farm production and attainable yield have been reported,[6] and evaluating candidate genotypes for commercial release under different on-farm conditions is a strongly recommended strategy for assessing the performance and stability of new cultivars in different farming systems, its application in durum wheat and particularly for quality traits is limited. In this study, eight durum genotypes represented by five candidate lines and three commercial varieties, exposed to different on-farm management practices during two growing seasons at the Yaqui Valley, Sonora, Mexico, were evaluated for grain yield and quality traits. Our studies revealed that the genotype and/or management practices effects explained the majority of the observed variability. The small size of the influence of the year effect might be explained by similar conditions between seasons and the fact that a considerable portion of the variation was absorbed by the contrasting management practices. The influence of the genotype was the highest for FYELLOW, FLRSDS, and TKW while the management practice effect was remarkable for grain yield and GPC. The impact of management practices and/or the environment on grain yield and GPC was expected, as reported in other studies,[18-20] although, differences in the influence of principal effects were observed. Environmental factors or management practices, as in our study, were shown as the main sources of variation for grain yield.[18,19,21] However, contrasting tendencies have been reported for GPC, where in some cases the genotype was the main source of variation[18,21] but in others

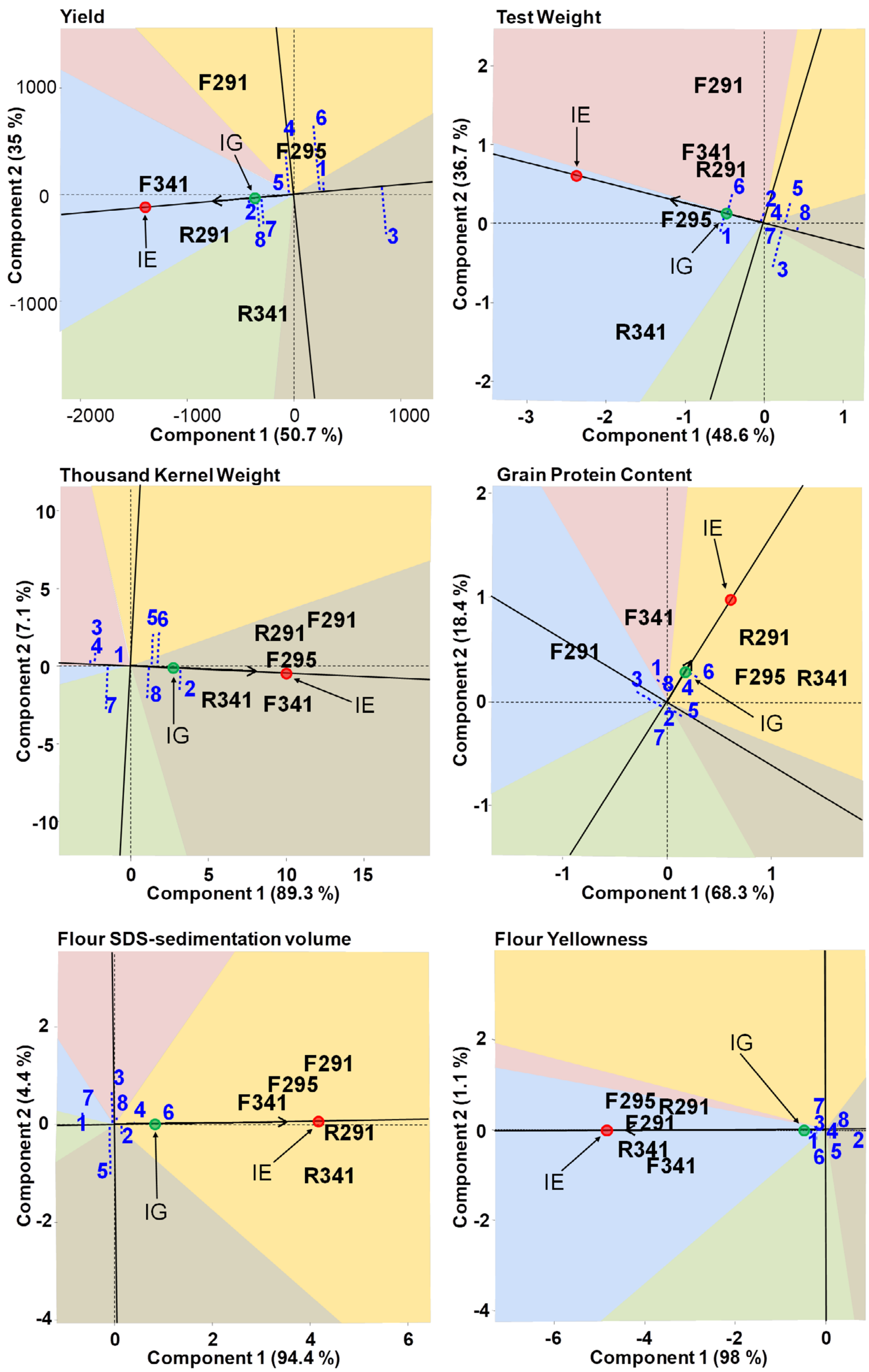

Figure 3. 'Mean against stability', 'ranking genotypes', 'ranking environments', and 'which-won-where' GGEBiplots analysis analyzed genotypes across five different field conditions cultured in 2015–2016 and 2016–2017. Green point = ideal genotype (IG). Red point = ideal environment (IE). Background colors discriminate mega-environments. Axes indicate variation explained by components 1 and 2.

it was the environment.[19,22,23] In addition to the main effects, we observed that the majority of the double and triple interactions were significant, as in previous studies.[18,20,22] The significant impact of the environment or management practices as well as the interactions on grain yield and GPC highlight the importance of testing under real field conditions in order to characterize the potential of new genotypes with greater accuracy. It has been suggested that TESTWT and TKW are usually explained by climatic conditions.[23] According to Li *et al.*[19] the genotype effect was predominant for TESTWT while the environment effect was higher for TKW. For Magallanes-López *et al.*[18] TW and TKW were mostly explained by the genotype rather than the water regime while for El Hassouni *et al.*[24] the effect of multiple-environments under different water regimes explained main variation in TKW. In bread wheat, Bilgin *et al.*[25] observed that TESTWT and TKW variations were mainly explained by the genotype effect while for Guzmán *et al.*[26] the environment explained most of the variation for these traits. In our study, the year effect explained the highest variation in TESTWT whereas TKW was mainly influenced by the genotype. Interaction effects have also influenced the two traits differently: for TESTWT the G × M interaction was the most representative, but M × Y was the most important for TKW. The discrepancies in the references cited, combined with our findings, suggests that there is no clear trend of dominant effects for these traits, and thus the development of new varieties will be dependent, in each case, not only on the germplasm used but also on the management conditions applied by farmers and their interaction. The FLRSDS is an important quality trait because it reflects protein quality (gluten strength). In our case, FLRSDS was primarily explained by the genotype effect followed by the management practices; several studies noticed this tendency in both durum and bread wheat.[18,19,23,26] FLRSDS can be influenced by GPC which is strongly influenced by the environment;[19] however, there was no direct relationship between the two traits, as genotypes with similar GPC had significant differences in FLRSDS. This could be explained by differences in the proportions of gluten proteins accumulated due to genotype and management effects as well as their interaction.[27] FYELLOW is another determinant quality attribute for durum wheat where high yellow color is desired. In this work, we showed the high influence of the genotype effect which is associated with high heritability in other studies.[18,19,22,23,28] Based on this and the small environmental influence, the selection of new varieties with the desired phenotypes for this trait, under different field conditions, should not be an impediment in the breeding programs.

The Tukey test and GGE biplot analysis were used to determine the best and most stable genotypes across management practices. This strategy was used in different studies to determine the optimal genotypes in M-E trials.[25,29] The incorporation of control lines to the field tests proved to be an effective approach as it allowed us to identify which of the candidate lines were superior depending on the desired phenotype. Currently, grain yield continues as the main objective of most wheat breeding programs.[10] Check lines, specifically genotypes 2 and 7 showed the highest grain yield values with high stability but lower quality values compared with potential candidates lines. In this sense according to GGE biplot analysis, genotype 8 with similar grain yield but higher GPC values than control lines, is the indicated to be selected. Due to increasing market demand for high-quality durum wheat, quality improvement has become one of the goals of breeding programs.[22] Although genotype 6 had a lower but acceptable grain yield, it showed the highest values for GPC and FLRSDS being a candidate for farmers if end-use quality is the priority. It also showed one of the best values for TESTWT, a highly desirable commercial trait in the cereal market.[30] Clearly, genotype 3 had the lowest values for most of the traits and management practices, being a candidate to be discarded unless it is used as a source of variation for FYELLOW in future breeding programs.

Phenology is an important factor in crop adaptation because it influences grain yield and quality. All the genotypes tested in this study were bred for the same growing area, so anthesis and maturity occurred at similar times for all of them. We found no significant differences among management conditions (despite the fact that in F295 sowing occurred 1 week earlier than the rest of the conditions) indicating that the contrasting management practices applied in this study had no effect on adaptation. Other studies had similar results: Li *et al.*[19] found no differences in phenology when they examined several genotypes under different heat and drought conditions.

The GGE biplot studies were effective in characterizing each management condition and identifying the closest practice to the ideal environment (the most representative and discriminative one). When breeders have limited resources to design multi-environment trials, this is a valuable technique for deciding the locations in which trials should be conducted. The management practice with the highest resources (F341) was, as expected, the closest one to the ideal environment for grain yield whereas R291 was the closest one to the ideal environment for quality traits. Different studies showed higher grain yield values under non-restricted conditions and higher values for some quality traits because of limited resources.[18,31-33] Management practice F291, on the other hand, was less discriminative and a candidate to be discarded as a location for future characterizations.

Finally, to identify the most efficient use of resources in the different farmers' fields under study, the individual irrigation and nitrogen effects and their interaction were analyzed. Based on our results, it seems that full irrigation is not necessary to maximize grain yield and TESTWT, so farmers could reduce the use of water. Similar results were observed by Yang *et al.*[34] and Walsh *et al.*[35] in trials under varied irrigation levels. On the other hand, Dai *et al.*[36] showed that GPC decreased when irrigation increased but it increased due to N fertilization.[31] Reduced irrigation combined with low doses of nitrogen (291 kg ha^{-1}) showed the highest values for GPC under our management conditions.

CONCLUSION

Understanding the genetic basis, the environmental effects under different management conditions, and their interactions on grain yield and quality traits is key for durum wheat-breeding programs. This study revealed the results of on-farm multi-location trials conducted for eight distinct genotypes over two seasons with different management practices commonly used by Mexican farmers. We observed that the genotype, the management practices, seasons, and their interactions exerted different influences depending on the evaluated trait. The statistical and GGE biplot analysis allowed the identification of the best genotypes in terms of grain yield/quality performance and stability. Genotypes 6 and 8 are potential candidates for commercial release depending on whether grain yield or quality is prioritized. Assessing genotypes in heterogeneous farming systems is a valid strategy that, in addition to controlled trials, allows for a more accurate characterization of the performance of novel cultivars to improve the breeding process and resources applied by farmers. This could contribute to increasing and stabilizing future durum wheat production, as well as the durum industry's future growth.

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DATA AVAILABILITY STATEMENT

The data that supports the findings of this study are available in the supplementary material of this article.

SUPPORTING INFORMATION

Supporting information may be found in the online version of this article.

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