SHORT COMMUNICATION

Genetic improvement of grain quality traits for CIMMYT semi-dwarf spring bread wheat varieties developed during 1965 to 2015: 50 years of breeding.

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For Field Crops Research

Abstract

The Global Wheat Program, now managed by the CGIAR consortium and led by CIMMYT, initiated wheat breeding about 70 years ago in Mexico. Currently, the key objectives are to develop wheat cultivars that have superior grain yield, durable disease resistance, drought and heat tolerance and meet the processing and end-use quality needs for diverse worldwide processing conditions and products. In this study, the genetic gains in grain quality of semi-dwarf spring wheat cultivars developed from 1965 to 2015 by CIMMYT and related breeding programs of national partners in the target areas were examined. Genetic gains for test weight, thousand kernel weight, grain hardness, flour yield, gluten extensibility and protein content were non-significant, and these traits remained stable despite grain yield increase over years. Positive genetic gains were found for dough strength related parameters mixograph mixing time (0.026 min. per year), torque (0.93 per year) and alveograph W (2.31 J*10-4 per year), and bread-making quality (loaf volume, 1.32 mL per year). We concluded that genetic gains for grain yield of CIMMYT spring wheat cultivars demonstrated by previous studies were not at the expense of processing and end-use quality traits. Both types of traits have been improved in the last 50 years through direct selection ensuring the acceptability of CIMMYT germplasm in the target countries by all wheat value chain stakeholders.

Keywords: bread wheat; wheat quality; genetic gains; bread-making.

1. Introduction

The International Maize and Wheat Improvement Center (CIMMYT) currently leads the Global Wheat Program of the CGIAR consortium. This breeding program was initiated 70 years ago in 1945 by the late Dr. Norman E. Borlaug to alleviate Mexico's dependence on wheat imports. After Mexico became self-sufficient in wheat production in 1956, Borlaug and his team developed semi-dwarf, high-yielding spring wheat cultivars that led to the Green Revolution in several countries, markedly increasing grain yield and undoubtedly contributing to alleviate global food shortages and famine that would have otherwise occurred at a much larger scale (Fan et al., 2008).

Currently, the priorities of CIMMYT's breeding program are high grain yield, disease resistance, and tolerance to abiotic stresses such as drought and heat. To meet the needs of millers, food processers (both household and industry) and consumers, it is critical to breed for grain quality (defined by the grains' physical characteristics, flour yield, dough handling characteristics, and bread-making properties). Consequently, the development of wheat cultivars with increased grain yield and meeting the processing and end-use quality needs for diverse worldwide processing conditions and products is a main objective for the CIMMYT breeding program.

For long term breeding programs, it is important to periodically evaluate the rate of success or gains for the genetic improvement to identify traits that may require increased efforts by breeders as well as the selection efficiency and associated traits that can be used as criteria for future selection (Cox et al., 1989). For this purpose, historical series of genotypes have been deployed and cultivated together to assess the genetic gains obtained through selection and breeding during a period of time for different traits (Gupta et al., 2016; Laidig et al., 2017; Morgounov et al., 2013). Even though wheat quality has been an integral part of CIMMYT's spring wheat breeding program for decades, only one study (Ortiz-Monasterio et al., 1997) so far was focused on the genetic gains for quality traits of CIMMYT germplasm. As with other agronomic traits, grain quality characteristics of a wheat cultivar will vary with the environment. Hence, estimates of genetic gain must be from diverse environments (Fufa et al., 2005).

The objective of our study was to evaluate the genetic gains in grain quality of spring wheat varieties developed from 1965 to 2015 by CIMMYT and related breeding programs.

2. Materials and methods

2.1 Plant materials/Agronomic trials

A trial consisting of 54 bread wheat cultivars (Electronic Supplementary Table 1) was sown in the 2012–2013 and the 2013–2014 crop seasons in Ciudad Obregon, Sonora, Mexico. The cultivars (most of them bred either at CIMMYT or with a CIMMYT parent) were selected because they represented unique genetic improvements (e.g., *Sonalika*, *Siete Cerros T66*), were grown on a large area and/or over a long period of time (e.g., *PBW343*, *Inqalab 91*), are of current vital importance for the breeding program (e.g, *Kachu*, *Borlaug100 F2014*), or are promising breeding lines that could be released as varieties by national partners in the near future. For the genotypes released as varieties in several countries the year in which a genotype was first released was used for this study. In certain years only one genotype was released while in other years several genotypes were released; therefore, in order to achieve certain degree of balance, the years of release of the genotypes were grouped in lustrums according to the year they were included in CIMMYT international nurseries or released as varieties. The trial was planted with three replicates in a Randomized Complete Block Design (RCBD) under six different environmental conditions: full drip (optimum conditions) and basin irrigation, medium and severe drought stress, and medium and severe heat stress. All the trials were planted in November, except medium heat stress (January) and severe heat stress (February). All the trials had full irrigation (>500 mm), except the medium drought stress (300 mm) and the severe drought stress (180 mm). The plot size was 6.5 m^2 and the sowing rate was 120 Kg/ha. Weeds, diseases, and insects were all optimally controlled. In all the trials, N was applied (pre-planting) at a rate of 50 kg of N/ha, and at tillering, 150 additional units of N were applied in all the trials except in severe drought stress (50 N units). Two field replicates of each of the wheat lines were used for analyzing the quality traits.

2.2 Grain quality evaluation

Grain morphological characteristics, such as thousand kernel weight (g) and test weight (kg/hL), were measured with the digital imaging system SeedCount SC5000 (Next Instruments, Australia). Grain moisture and protein content (12.5 % moisture basis) were obtained by near-infrared spectroscopy (DA 7200 NIR, Perten Instruments, Sweden), verifying its calibration with the chemical Kjeldahl method according to the AACC method 46-12 (AACC, 2010). Prior to milling, the grain samples were conditioned at 16 % moisture content for 48 hours. Tempered wheat was milled in a Brabender Quadrumat Jr. (C.W. Brabender OHG, Germany).

To evaluate the mixing properties such as the optimum dough mixing time (MixT) and torque at that peak (TQ), a mixograph (National Mfg. Co.) equipped with a 35 g bowl according to the AACC method 54-40 (AACC, 2010) was employed. In addition, to measure the visco-elastic properties of the dough, an alveograph (Chopin, France) was used with 60 g flour samples. The energy required to deform the dough-bubble until the point of rupture (AlvW, 10^{-4} J), as well as the dough tenacity and extensibility ratio AlvP/L, were recorded. A basic straight-dough bread-making method was utilized based on the AACC method 10- 09 (AACC, 2010) and loaf volume was recorded. The water absorption criteria used for mixograph, alveograph and bread-making tests is described in Guzman et al. (2015).

2.4 Statistical Analysis

. As previously mentioned in order to achieve certain degree of balance between genotypes released at different years the genotypes were group in lustrums. Therefore, the objective was to estimate the best linear unbiased estimates (BLUE) of the lustrums (comprising an imbalanced set of lines within each lustrum) across years and environments. The linear mixed model employed to analyze the data includes the random effect of replicate nested within year and environments, and the fixed effect of year, environment, year × environment, lustrum, lustrum × year, lustrum × environment, lustrum × year × environment. Furthermore, we also fitted a linear mixed model like the previous one but considering lustrum, lustrum × year, lustrum × environment, lustrum × year × environment as random effects. The results of the genetic gains per lustrum were very similar in both cases thus results from the fixed effects model are shown.

These BLUE of the lustrums for the different trait response were regressed on the lustrum. The regression coefficient represents the average increase in each trait per unit increase in lustrums (from one lustrum to another). Least significant difference (LSD) test was used for means comparison of the traits of the varieties grouped in lustrums using SAS.

3. Results

Grain samples from the 54 bread wheat genotypes cultivated in six different environmental conditions over two years were completely characterized for quality traits. Table 1 shows the mean values for each quality trait obtained from the wheat genotypes grouped in different lustrums depending on the year they were released. Visual impressions of the different patterns of change for the different quality traits are provided in the regression plots (Fig. 1), in which the genetic gains for each trait obtained in the last 50 years are given.

Regressions of the parameters related to grain morphology and, therefore, to potential milling quality, test weight and thousand kernel weight did not show a significant trend, although it seems that, in general, grains are larger in genotypes from more recent lustrums. The results obtained for experimental flour yield showed no genetic gain for this trait, with most of the lustrums showing very similar average values. Protein content

Table 1. Mean values for each quality trait across the whole trial (averaged environment and years) for the cultivars grouped in lustrums. Note that letters apply only to comparisons within the same column.

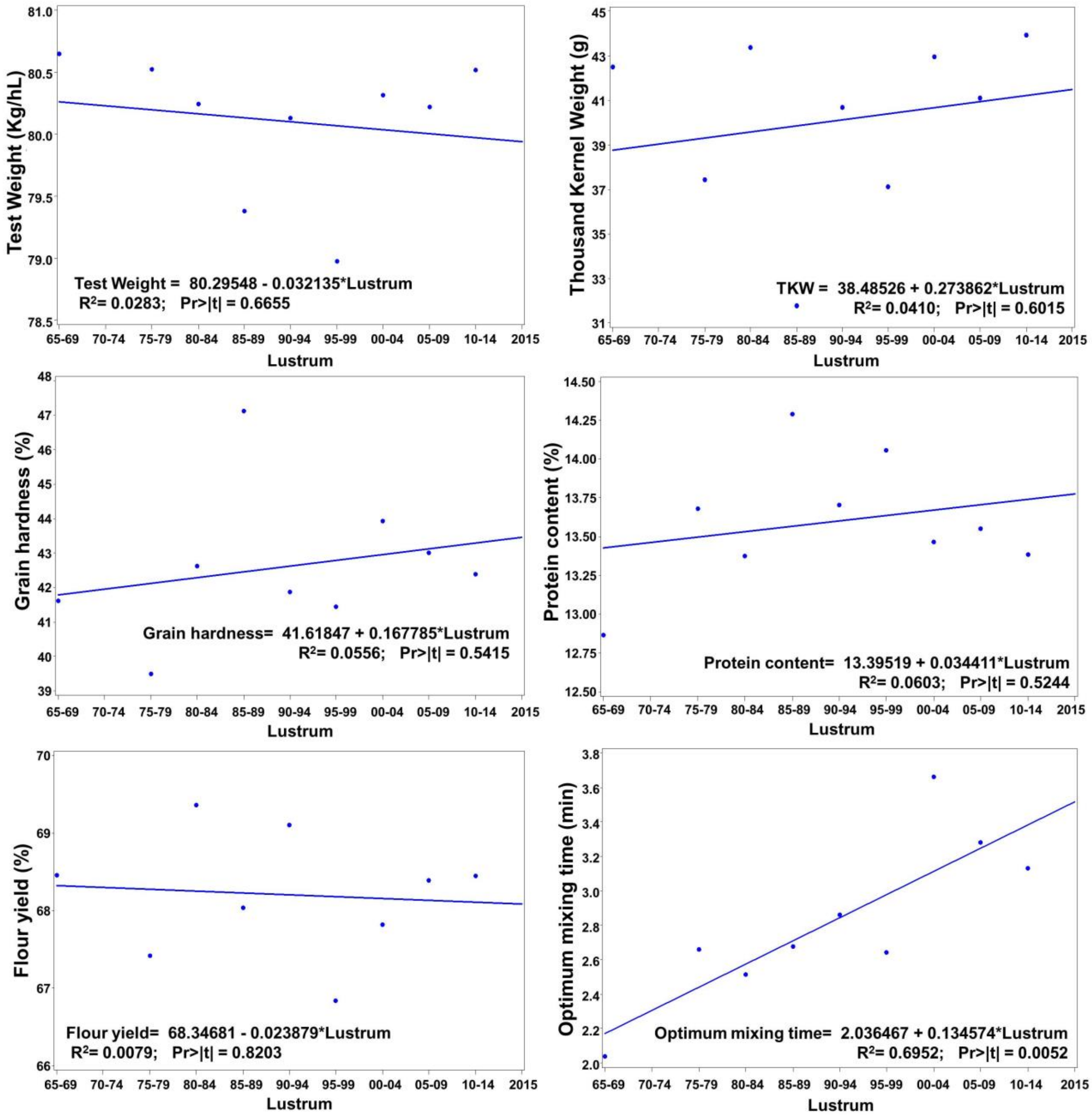
Lustrum	Nº of cvs.	TW (kg/hL)	TKW (g)	Hardness (%)	GPRO (%)	Flour yield (%)	MixT (min)	TQ	ALV W ($J*10^{-4}$)	ALV P/L	Loaf volume (mL)
1965-69	2	80.6a*	42.5b	41.6ef	12.9e	68.4bc	2.0f	86.7f	237f	1.91e	780e
1975-79	2	80.5ab	37.4d	39.5g	13.7bc	67.4de	2.7de	111.0cde	326bc	1.12b	826d
1980-84	4	80.3ab	43.4ab	42.61cd	13.4d	69.4a	2.5e	102.8e	275e	0.81ef	836cd
1985-89	1	79.4c	31.8e	47.1a	14.3a	68.0cd	2.7de	110.3cde	297cde	0.65f	864ab
1990-94	3	80.1b	40.7c	41.9def	13.7b	69.1ab	2.9d	116.0cd	314cd	0.9cde	859b
1994-99	4	78.9c	37.1d	41.4f	14.1a	66.8e	2.6de	106.3be	287de	0.95cd	851bc
2000-04	5	80.3ba	42.9b	43.9b	13.5cd	67.8cd	3.7a	147.5a	412a	0.97c	854b
2005-09	21	80.2b	41.1c	43.0c	13.5bc	68.4c	3.3b	131.5b	354b	0.87de	874a
2010-14	12	80.5ab	43.9a	42.4de	13.4d	68.4c	3.1c	123.3c	330bc	0.87de	837cd

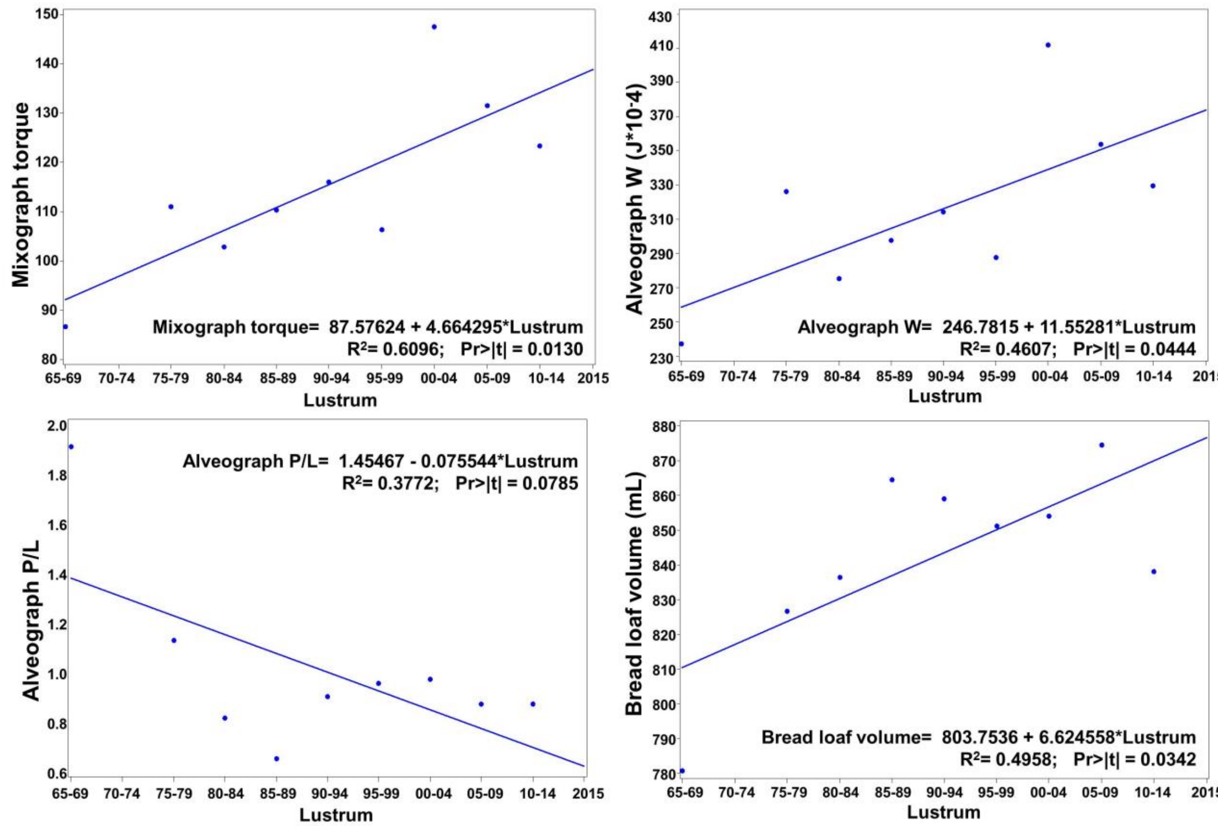
TW, test weight; TKW, thousand kernel weight; GPRO, grain protein content; MixtT, mixograph optimum mixing time; TQ, mixograph torque; ALV W, alveograph W; ALV P/L, alveograph P/L.
*Means with different letters are significantly different ($p<0.05$) (LSD test).

and hardness showed slight but non-significant positive trends, which in the latter case indicated slightly softer endosperm in more current lustrums.

Gluten quality and dough handling characteristics were analyzed by the mixograph and alveograph. The three parameters registered related to gluten strength mixograph optimum mixing time (0.026 min. per year), torque (0.93 per year) and alveograph W (2.31 J*10-4 per year) had significant and positive coefficients, which means genetic improvement in the last 50 years. The genotypes developed in 2000-04 (*Tacupeto F2001* and *Norteña F2007*, among others) showed particularly strong gluten, while genotypes from the two last lustrums (2005-09 and 2010-14) also maintained high levels of gluten strength. The gluten tenacity/extensibility ratio (alveograph P/L) did not show significant negative trends across the years, with average values since 1980 lower than 1, meaning that gluten had acceptable extensibility for the elaboration of diverse products. Finally, significant genetic gains were found for bread loaf volume (1.32 mL per year). The genotypes developed during 2005-09 were the best for this trait.

Figure 1. Genetic gains for test weight, thousand kernel weight, grain hardness, protein content, mixograph optimum mixing time and torque, alveograph W and P/L, and bread loaf volume, in the set of cultivars developed from 1965 to 2015.


Test Weight (Kg/hL)
Test Weight = 80.29548 - 0.032135*Lustrum
R2= 0.0283; Pr>|t| = 0.6655
Thousand Kernel Weight (g)
TKW = 38.48526 + 0.273862*Lustrum
R2= 0.0410; Pr>|t| = 0.6015
Grain hardness (%)
Grain hardness= 41.61847 + 0.167785*Lustrum
R2= 0.0556; Pr>|t| = 0.5415
Protein content (%)
Protein content= 13.39519 + 0.034411*Lustrum
R2= 0.0603; Pr>|t| = 0.5244
Flour yield (%)
Flour yield= 68.34681 - 0.023879*Lustrum
R2= 0.0079; Pr>|t| = 0.8203
Optimum mixing time (min)
Optimum mixing time= 2.036467 + 0.134574*Lustrum
R2= 0.6952; Pr>|t| = 0.0052
65-69
70-74
75-79
80-84
85-89
90-94
95-99
00-04
05-09
10-14
2015
Lustrum



4. Discussion

From the beginning of the breeding program at CIMMYT, grain yield was considered as the primary objective because of the urgent need to substantially increase wheat production in many developing countries. This emphasis on breeding for grain yield has translated into continuous genetic gains for this trait in CIMMYT materials (Aisawi et al., 2015; Crespo-Herrera et al., 2017; Lopes et al., 2012; Ortiz-Monasterio et al., 1997), which was also found with the set of genotypes used in the current study (Mondal et al., 2015). Supplying germplasm with desirable quality to elaborate diverse products (leavened and flat breads, noodles, etc.) at different conditions (mechanized, semi-mechanized, and handmade) has been another objective of the breeding program.

Grain characteristics used as indicators of milling quality include grain volume weight, kernel weight, and experimental flour yield, and did not show a significant trend, indicating the maintenance of these traits over time. The fact that milling quality has not been improved in the last 50 years in CIMMYT spring bread wheat germplasm is due to the fact that it was not a high priority trait since in most important geographical target for the CIMMYT breeding program (South Asia), grain is mainly milled in rural areas by small local mills to produce whole-meal flour (*atta* in India), which is used for the elaboration of different types of flat breads. However, the increase of the urban population in the developing world will possibly increase demands of refined flour for the mechanized food industry. As such, flour extraction should receive more attention in the coming years in the breeding program. This trait has not been improved by other breeding programs where it was supposed to have more importance (Cox et al. 1989; Fufa et al., 2005; Hucl et al. 2015; Souza et al. 1993; Underdahl et al. 2008). This illustrates the difficulty in obtaining genetic gains for the trait. It is also possible that this trait is already optimized to its near maximum genetic potential, making further progress unrealistic. Other traits related to the milling process (grain hardness) did not show a significant trend over the years. In most CIMMYT target areas, hard or semi-hard grains are preferred for the elaboration of diverse products, hence a strong visual selection is made for desired grain hardness, which has resulted in similar characteristics over 5 decades.

Interestingly, despite increases in grain yields observed over years for these materials (0.79% per year; Mondal et al., 2015) the trend for protein content was non-significant. This important trait, which is used for market class classification in several countries, is believed to be inversely correlated with grain yield. In this vein, several studies have shown a negative trend for protein content over years of breeding and have attributed this to increased grain yield (Cox et al., 1989; Fufa et al., 2005; Laidig et al., 2017; Sanchez-Garcia et al. 2015; Souza et al., 1993); an undesirable situation for the development of cultivars eligible for market class grades. However, some other studies (De Pauw et al., 2007; Underdahl et al., 2008) have reported results similar to ours, or, even an increase in protein content over time (Hucl et al., 2015). Keeping protein content constant while increasing grain yield is an excellent achievement considering that grain yield improved by 40% since 1965 and it is important for the breeding program to maintain not only industrial quality but nutritional quality of the grain, a paramount objective for CIMMYT.

Despite the absence of an increase in grain protein content, we found improvements for physical properties of dough and loaf volumes in this historical set of cultivars. Optimum mixing time (0.026 min per year) and gluten strength (2.31 $J*10^{-4}$ per year for alveograph W) increased constantly until the 00`s. Other breeding programs have also been successful to genetically improve these traits at similar rates (Morgounov et al. 2013; Sanchez-Garcia et al. 2015; Souza et al. 1993). Part of this progress could probably be explained by changes in protein quality or composition of glutenins (Morgounov et al. 2013), for which profiles are determined routinely for all the lines included in the crossing block (Guzman et al. 2016). For gluten extensibility, while the trend found was not statistically significant, there was a trend to decrease tenacity and increase extensibility (alveograph P/L ratio) that can be clearly observed. Balanced doughs are required for the elaboration of any bread wheat products, which explains the better values in alveograph P/L found in more recent genotypes compared to the oldest ones. Therefore, although breeding efforts could not produce an increase of protein concentration when raising yield level, breeding was successful in increasing protein quality, which ensures better dough handling properties in CIMMYT materials. Finally, and probably more important, bread-making quality expressed as loaf volume showed significant genetic gains (1.32 mL per year). This is in agreement with data from other breeding programs (Cox et al., 1989; Souza et al., 1993), but in others a non-significant (Underdahl et al., 2008) or negative trend for loaf volume (bread-making quality) was found, probably because the increase in protein quality was not enough to mitigate the effect of the reduction on protein content due to higher grain yield (Laidig et al., 2017).

5. Conclusions

Genetic gains in the grain yield performance of CIMMYT spring wheat cultivars (Mondal et al., 2015) were not at the expense of processing nor end-use quality traits. Both types of traits have been improved in the last 50 years through direct selection ensuring the acceptability of CIMMYT germplasm in the target countries by all wheat value chain stakeholders.

Acknowledgements

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To evaluate the mixing properties such as the optimum dough mixing time (MixT) and torque at that peak (TQ), a mixograph (National Mfg. Co.) equipped with a 35 g bowl according to the AACC method 54-40 (AACC, 2010) was employed. In addition, to measure the visco-elastic properties of the dough, an alveograph (Chopin, France) was used with 60 g flour samples. The energy required to deform the dough-bubble until the point of rupture (AlvW, 10^{-4} J), as well as the dough tenacity and extensibility ratio AlvP/L, were recorded. A basic straight-dough bread-making method was utilized based on the AACC method 10- 09 (AACC, 2010) and loaf volume was recorded. The water absorption criteria used for mixograph, alveograph and bread-making tests is described in Guzman et al. (2015).

2.4 Statistical Analysis

As previously mentioned, in order to achieve certain degree of balance between genotypes released at different years the genotypes were group in lustrums. Therefore, the objective was to estimate the best linear unbiased estimates (BLUE) of the lustrums (comprising an imbalanced set of lines within each lustrum) across years and environments. The linear mixed model employed to analyze the data includes the random effect of replicate nested within year and environments, and the fixed effect of year, environment, year × environment, lustrum, lustrum × year, lustrum × environment, lustrum × year × environment. Furthermore, we also fitted a linear mixed model like the previous one but considering lustrum, lustrum × year, lustrum × environment, lustrum × year × environment as random effects. The results of the genetic gains per lustrum were very similar in both cases thus results from the fixed effects model are shown.

These BLUE of the lustrums for the different trait response were regressed on the lustrum. The regression coefficient represents the average increase in each trait per unit increase in lustrums (from one lustrum to another). Least significant difference (LSD) test was used for means comparison of the traits of the varieties grouped in lustrums using SAS.

3. Results

Grain samples from the 54 bread wheat genotypes cultivated in six different environmental conditions over two years were completely characterized for quality traits. Table 1 shows the mean values for each quality trait obtained from the wheat genotypes grouped in different lustrums depending on the year they were released. Visual impressions of the different patterns of change for the different quality traits are provided in the regression plots (Fig. 1), in which the genetic gains for each trait obtained in the last 50 years are given.

Regressions of the parameters related to grain morphology and, therefore, to potential milling quality, test weight and thousand kernel weight did not show a significant trend, although it seems that, in general, grains are larger in genotypes from more recent lustrums. The results obtained for experimental flour yield showed no genetic gain for this trait, with most of the lustrums showing very similar average values. Protein content and hardness showed slight but non-significant positive trends, which in the latter case indicated slightly softer endosperm in more current lustrums.

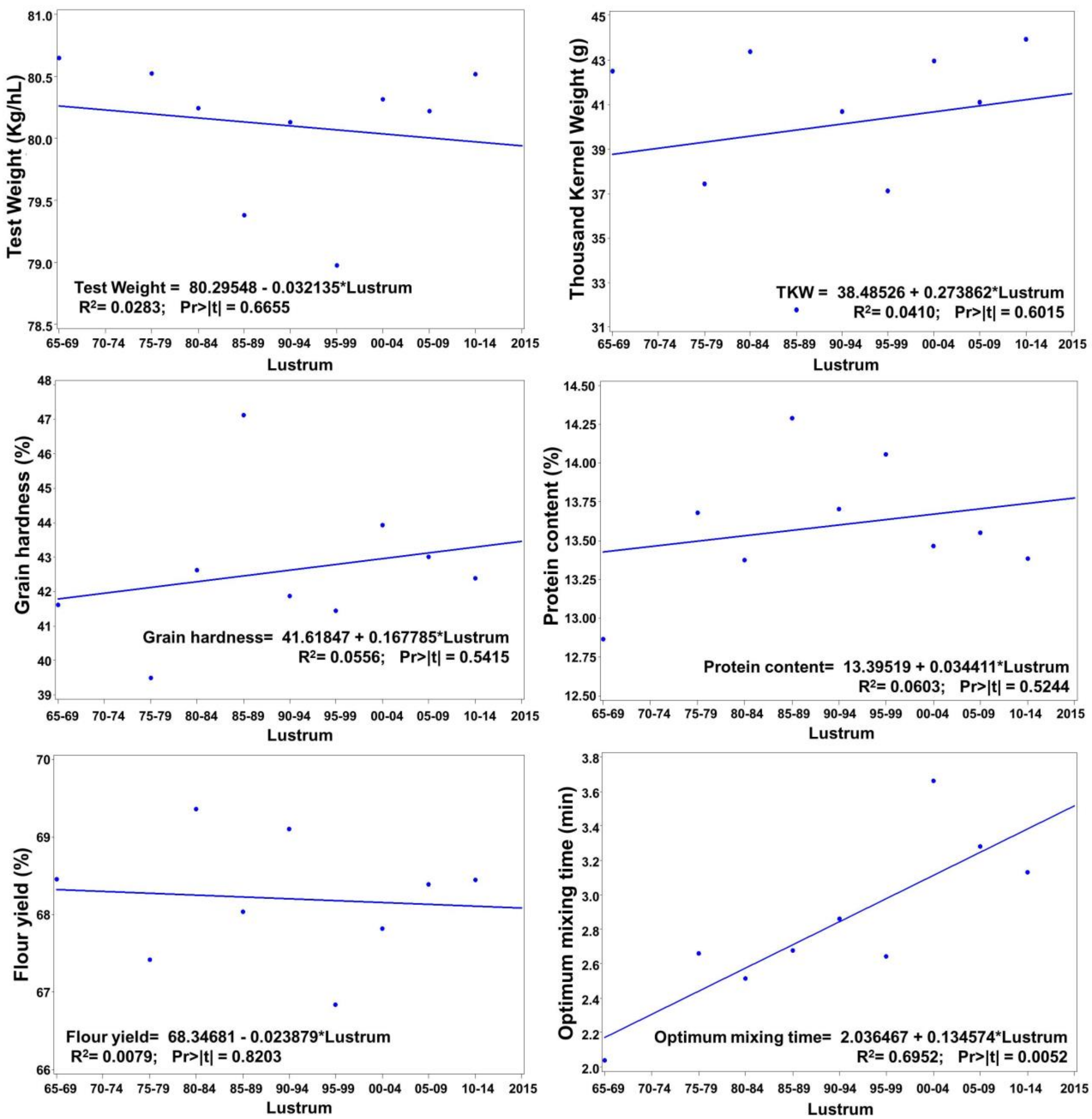
Table 1. Mean values for each quality trait across the whole trial (averaged environment and years) for the cultivars grouped in lustrums (note that letters apply only to comparisons within the same column).

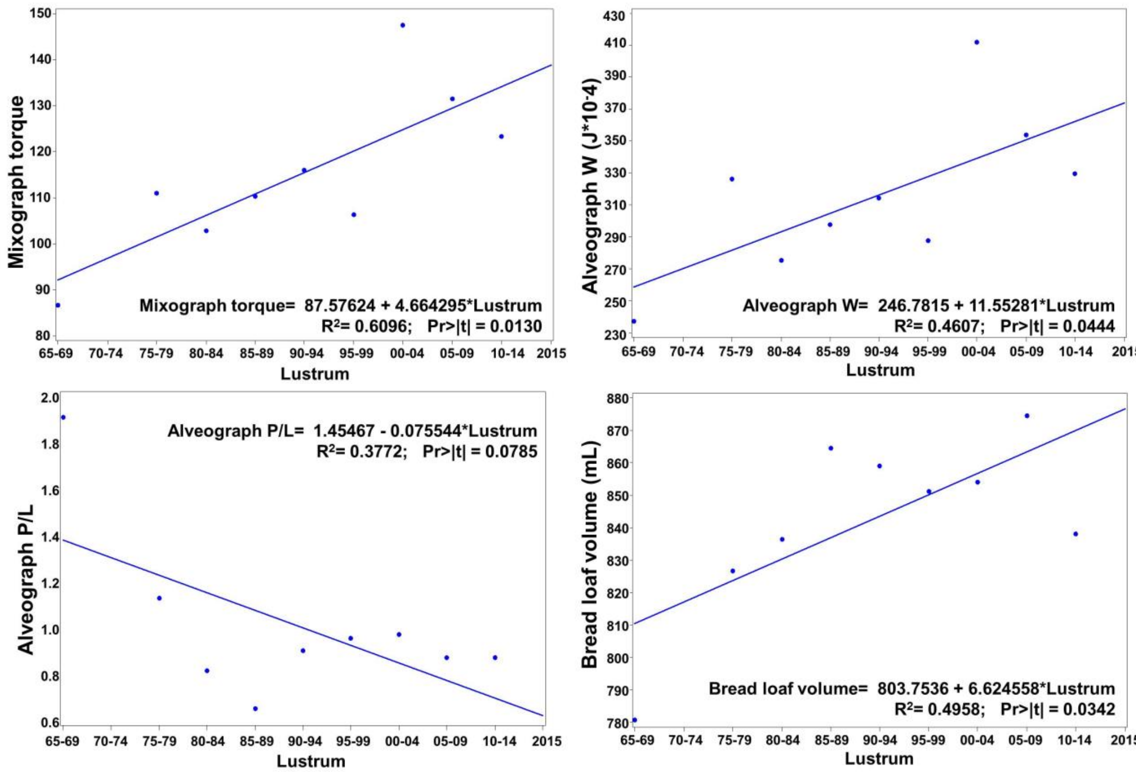
Lustrum	**Nº of cvs.**	**TW (kg/hL)**	**TKW (g)**	**Hardness (%)**	**GPRO (%)**	**Flour yield (%)**	**MixT (min)**	**TQ**	**ALV W ($J*10^{-4}$)**	**ALV P/L**	**Loaf volume (mL)**
1965-69	2	80.6a*	42.5b	41.6ef	12.9e	68.4bc	2.0f	86.7f	237f	1.91e	780e
1975-79	2	80.5ab	37.4d	39.5g	13.7bc	67.4de	2.7de	111.0cde	326bc	1.12b	826d
1980-84	4	80.3ab	43.4ab	42.61cd	13.4d	69.4a	2.5e	102.8e	275e	0.81ef	836cd
1985-89	1	79.4c	31.8e	47.1a	14.3a	68.0cd	2.7de	110.3cde	297cde	0.65f	864ab
1990-94	3	80.1b	40.7c	41.9def	13.7b	69.1ab	2.9d	116.0cd	314cd	0.9cde	859b
1994-99	4	78.9c	37.1d	41.4f	14.1a	66.8e	2.6de	106.3be	287de	0.95cd	851bc
2000-04	5	80.3ba	42.9b	43.9b	13.5cd	67.8cd	3.7a	147.5a	412a	0.97c	854b
2005-09	21	80.2b	41.1c	43.0c	13.5bc	68.4c	3.3b	131.5b	354b	0.87de	874a
2010-14	12	80.5ab	43.9a	42.4de	13.4d	68.4c	3.1c	123.3c	330bc	0.87de	837cd

TW, test weight; TKW, thousand kernel weight; GPRO, grain protein content; MixtT, mixograph optimum mixing time; TQ, mixograph torque; ALV W, alveograph W; ALV P/L, alveograph P/L.
*Means with different letters are significantly different ($p<0.05$) (LSD test).

Gluten quality and dough handling characteristics were analyzed by the mixograph and alveograph. The three parameters registered related to gluten strength mixograph optimum mixing time (0.026 min. per year), torque (0.93 per year) and alveograph W (2.31 J*10-4 per year) had significant and positive coefficients, which means genetic improvement in the last 50 years. The genotypes developed in 2000-04 (*Tacupeto F2001* and *Norteña F2007*, among others) showed particularly strong gluten, while genotypes from the two last lustrums (2005-09 and 2010-14) also maintained high levels of gluten strength. The gluten tenacity/extensibility ratio (alveograph P/L) did not show significant negative trends across the years, with average values since 1980 lower than 1, meaning that gluten had acceptable extensibility for the elaboration of diverse products. Finally, significant genetic gains were found for bread loaf volume (1.32 mL per year). The genotypes developed during 2005-09 were the best for this trait.

Figure 1. Genetic gains for test weight, thousand kernel weight, grain hardness, protein content, mixograph optimum mixing time and torque, alveograph W and P/L, and bread loaf volume, in the set of cultivars developed from 1965 to 2015.


Test Weight (Kg/hL)
Test Weight = 80.29548 - 0.032135*Lustrum
R²= 0.0283; Pr>|t| = 0.6655
Thousand Kernel Weight (g)
TKW = 38.48526 + 0.273862*Lustrum
R²= 0.0410; Pr>|t| = 0.6015
Grain hardness (%)
Grain hardness= 41.61847 + 0.167785*Lustrum
R²= 0.0556; Pr>|t| = 0.5415
Protein content (%)
Protein content= 13.39519 + 0.034411*Lustrum
R²= 0.0603; Pr>|t| = 0.5244
Flour yield (%)
Flour yield= 68.34681 - 0.023879*Lustrum
R²= 0.0079; Pr>|t| = 0.8203
Optimum mixing time (min)
Optimum mixing time= 2.036467 + 0.134574*Lustrum
R²= 0.6952; Pr>|t| = 0.0052
Lustrum
65-69
70-74
75-79
80-84
85-89
90-94
95-99
00-04
05-09
10-14
2015



4. Discussion

From the beginning of the breeding program at CIMMYT, grain yield was considered as the primary objective because of the urgent need to substantially increase wheat production in many developing countries. This emphasis on breeding for grain yield has translated into continuous genetic gains for this trait in CIMMYT materials (Aisawi et al., 2015; Crespo-Herrera et al., 2017; Lopes et al., 2012; Ortiz-Monasterio et al., 1997), which was also found with the set of genotypes used in the current study (Mondal et al., 2015). Supplying germplasm with desirable quality to elaborate diverse products (leavened and flat breads, noodles, etc.) at different conditions (mechanized, semi-mechanized, and handmade) has been another objective of the breeding program.

Grain characteristics used as indicators of milling quality include grain volume weight, kernel weight, and experimental flour yield, and did not show a significant trend, indicating the maintenance of these traits over time. The fact that milling quality has not been improved in the last 50 years in CIMMYT spring bread wheat germplasm is due to the fact that it was not a high priority trait since in most important geographical target for the CIMMYT breeding program (South Asia), grain is mainly milled in rural areas by small local mills to produce whole-meal flour (*atta* in India), which is used for the elaboration of different types of flat breads. However, the increase of the urban population in the developing world will possibly increase demands of refined flour for the mechanized food industry. As such, flour extraction should receive more attention in the coming years in the breeding program. This trait has not been improved by other breeding programs where it was supposed to have more importance (Cox et al. 1989; Fufa et al., 2005; Hucl et al. 2015; Souza et al. 1993; Underdahl et al. 2008). This illustrates the difficulty in obtaining genetic gains for the trait. It is also possible that this trait is already optimized to its near maximum genetic potential, making further progress unrealistic. Other traits related to the milling process (grain hardness) did not show a significant trend over the years. In most CIMMYT target areas, hard or semi-hard grains are preferred for the elaboration of diverse products, hence a strong visual selection is made for desired grain hardness, which has resulted in similar characteristics over 5 decades.

Interestingly, despite increases in grain yields observed over years for these materials (0.79% per year; Mondal et al., 2015) the trend for protein content was non-significant. This important trait, which is used for market class classification in several countries, is believed to be inversely correlated with grain yield. In this vein, several studies have shown a negative trend for protein content over years of breeding and have attributed this to increased grain yield (Cox et al., 1989; Fufa et al., 2005; Laidig et al., 2017; Sanchez-Garcia et al. 2015; Souza et al., 1993); an undesirable situation for the development of cultivars eligible for market class grades. However, some other studies (De Pauw et al., 2007; Underdahl et al., 2008) have reported results similar to ours, or, even an increase in protein content over time (Hucl et al., 2015). Keeping protein content constant while increasing grain yield is an excellent achievement considering that grain yield improved by 40% since 1965 and it is important for the breeding program to maintain not only industrial quality but nutritional quality of the grain, a paramount objective for CIMMYT.

Despite the absence of an increase in grain protein content, we found improvements for physical properties of dough and loaf volumes in this historical set of cultivars. Optimum mixing time (0.026 min per year) and gluten strength (2.31 $J*10^{-4}$ per year for alveograph W) increased constantly until the 00`s. Other breeding programs have also been successful to genetically improve these traits at similar rates (Morgounov et al. 2013; Sanchez-Garcia et al. 2015; Souza et al. 1993). Part of this progress could probably be explained by changes in protein quality or composition of glutenins (Morgounov et al. 2013), for which profiles are determined routinely for all the lines included in the crossing block (Guzman et al. 2016). For gluten extensibility, while the trend found was not statistically significant, there was a trend to decrease tenacity and increase extensibility (alveograph P/L ratio) that can be clearly observed. Balanced doughs are required for the elaboration of any bread wheat products, which explains the better values in alveograph P/L found in more recent genotypes compared to the oldest ones. Therefore, although breeding efforts could not produce an increase of protein concentration when raising yield level, breeding was successful in increasing protein quality, which ensures better dough handling properties in CIMMYT materials. Finally, and probably more important, bread-making quality expressed as loaf volume showed significant genetic gains (1.32 mL per year). This is in agreement with data from other breeding programs (Cox et al., 1989; Souza et al., 1993), but in others a non-significant (Underdahl et al., 2008) or negative trend for loaf volume (bread-making quality) was found, probably because the increase in protein quality was not enough to mitigate the effect of the reduction on protein content due to higher grain yield (Laidig et al., 2017).

5. Conclusions

Genetic gains in the grain yield performance of CIMMYT spring wheat cultivars (Mondal et al., 2015) were not at the expense of processing nor end-use quality traits. Both types of traits have been improved in the last 50 years through direct selection ensuring the acceptability of CIMMYT germplasm in the target countries by all wheat value chain stakeholders.

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