

1 SHORT COMMUNICATION

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

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11 For Field Crops Research

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24 **Abstract**

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

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

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49 **1. Introduction**

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

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

66 For long term breeding programs, it is important to periodically evaluate the rate of success
67 or gains for the genetic improvement to identify traits that may require increased efforts by
68 breeders as well as the selection efficiency and associated traits that can be used as criteria for
69 future selection (Cox et al., 1989). For this purpose, historical series of genotypes have been

70 deployed and cultivated together to assess the genetic gains obtained through selection and
71 breeding during a period of time for different traits (Gupta et al., 2016; Laidig et al., 2017;
72 Morgounov et al., 2013). Even though wheat quality has been an integral part of CIMMYT's
73 spring wheat breeding program for decades, only one study (Ortiz-Monasterio et al., 1997) so far
74 was focused on the genetic gains for quality traits of CIMMYT germplasm. As with other
75 agronomic traits, grain quality characteristics of a wheat cultivar will vary with the environment.
76 Hence, estimates of genetic gain must be from diverse environments (Fufa et al., 2005).

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

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80 **2. Materials and methods**

81 *2.1 Plant materials/Agronomic trials*

82 A trial consisting of 54 bread wheat cultivars (Electronic Supplementary Table 1) was
83 sown in the 2012–2013 and the 2013–2014 crop seasons in Ciudad Obregon, Sonora, Mexico.
84 The cultivars (most of them bred either at CIMMYT or with a CIMMYT parent) were selected
85 because they represented unique genetic improvements (e.g., *Sonalika*, *Siete Cerros T66*), were
86 grown on a large area and/or over a long period of time (e.g., *PBW343*, *Inqalab 91*), are of
87 current vital importance for the breeding program (e.g., *Kachu*, *Borlaug100 F2014*), or are
88 promising breeding lines that could be released as varieties by national partners in the near
89 future. For the genotypes released as varieties in several countries the year in which a genotype
90 was first released was used for this study. In certain years only one genotype was released while
91 in other years several genotypes were released; therefore, in order to achieve certain degree of
92 balance, the years of release of the genotypes were grouped in lustrums according to the year

93 they were included in CIMMYT international nurseries or released as varieties. The trial was
94 planted with three replicates in a Randomized Complete Block Design (RCBD) under six
95 different environmental conditions: full drip (optimum conditions) and basin irrigation, medium
96 and severe drought stress, and medium and severe heat stress. All the trials were planted in
97 November, except medium heat stress (January) and severe heat stress (February). All the trials
98 had full irrigation (>500 mm), except the medium drought stress (300 mm) and the severe
99 drought stress (180 mm). The plot size was 6.5 m² and the sowing rate was 120 Kg/ha. Weeds,
100 diseases, and insects were all optimally controlled. In all the trials, N was applied (pre-planting)
101 at a rate of 50 kg of N/ha, and at tillering, 150 additional units of N were applied in all the trials
102 except in severe drought stress (50 N units). Two field replicates of each of the wheat lines were
103 used for analyzing the quality traits.

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105 *2.2 Grain quality evaluation*

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

113 To evaluate the mixing properties such as the optimum dough mixing time (MixT) and
114 torque at that peak (TQ), a mixograph (National Mfg. Co.) equipped with a 35 g bowl according
115 to the AACC method 54-40 (AACC, 2010) was employed. In addition, to measure the visco-

116 elastic properties of the dough, an alveograph (Chopin, France) was used with 60 g flour
117 samples. The energy required to deform the dough-bubble until the point of rupture (AlvW, 10^{-4}
118 J), as well as the dough tenacity and extensibility ratio AlvP/L, were recorded. A basic straight-
119 dough bread-making method was utilized based on the AACC method 10-09 (AACC, 2010) and
120 loaf volume was recorded. The water absorption criteria used for mixograph, alveograph and
121 bread-making tests is described in Guzman et al. (2015).

122

123 *2.4 Statistical Analysis*

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

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

138

139 **3. Results**

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

146 Regressions of the parameters related to grain morphology and, therefore, to potential milling
 147 quality, test weight and thousand kernel weight did not show a significant trend, although it
 148 seems that, in general, grains are larger in genotypes from more recent lustrums. The results
 149 obtained for experimental flour yield showed no genetic gain for this trait, with most of the
 150 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	N° 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).

151
 152 and hardness showed slight but non-significant positive trends, which in the latter case
 153 indicated slightly softer endosperm in more current lustrums.

154 Gluten quality and dough handling characteristics were analyzed by the mixograph and
155 alveograph. The three parameters registered related to gluten strength mixograph optimum
156 mixing time (0.026 min. per year), torque (0.93 per year) and alveograph W (2.31 J*10⁻⁴ per
157 year) had significant and positive coefficients, which means genetic improvement in the last 50
158 years. The genotypes developed in 2000-04 (*Tacupeto F2001* and *Norteña F2007*, among others)
159 showed particularly strong gluten, while genotypes from the two last lustrums (2005-09 and
160 2010-14) also maintained high levels of gluten strength. The gluten tenacity/extensibility ratio
161 (alveograph P/L) did not show significant negative trends across the years, with average values
162 since 1980 lower than 1, meaning that gluten had acceptable extensibility for the elaboration of
163 diverse products. Finally, significant genetic gains were found for bread loaf volume (1.32 mL
164 per year). The genotypes developed during 2005-09 were the best for this trait.

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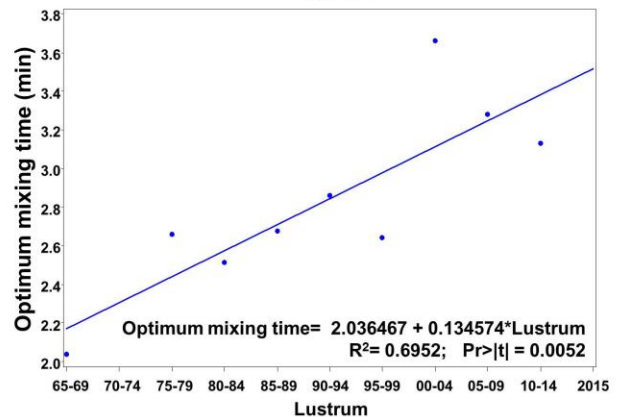
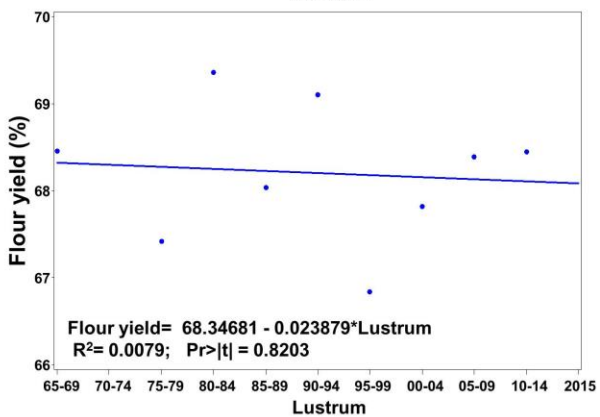
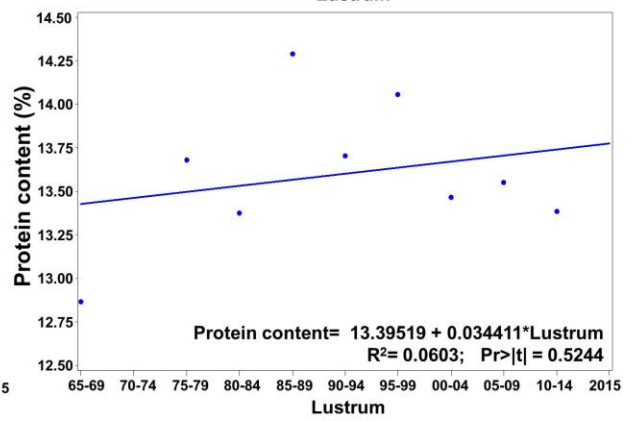
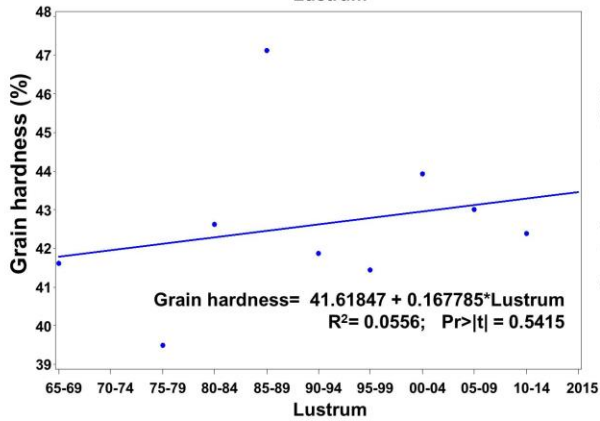
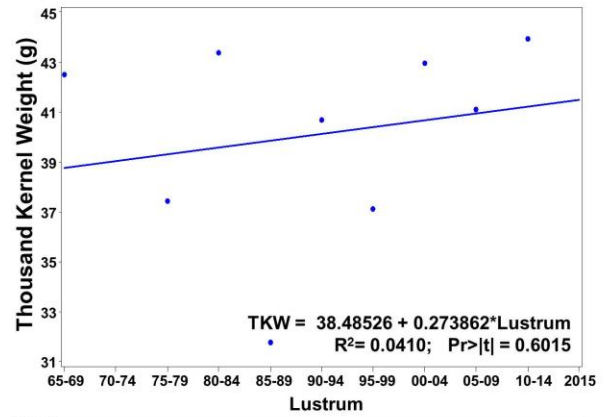
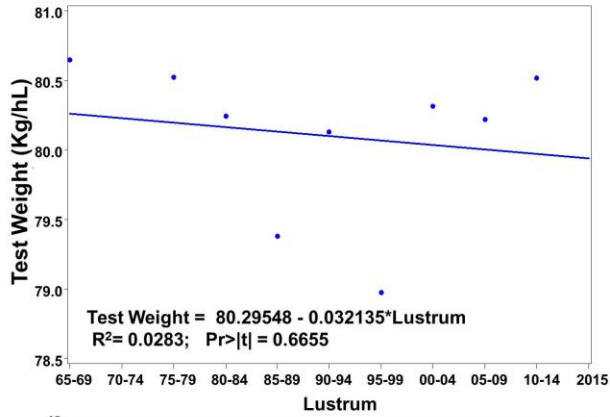
166 **Figure 1.** Genetic gains for test weight, thousand kernel weight, grain hardness, protein content,
167 mixograph optimum mixing time and torque, alveograph W and P/L, and bread loaf volume, in
168 the set of cultivars developed from 1965 to 2015.

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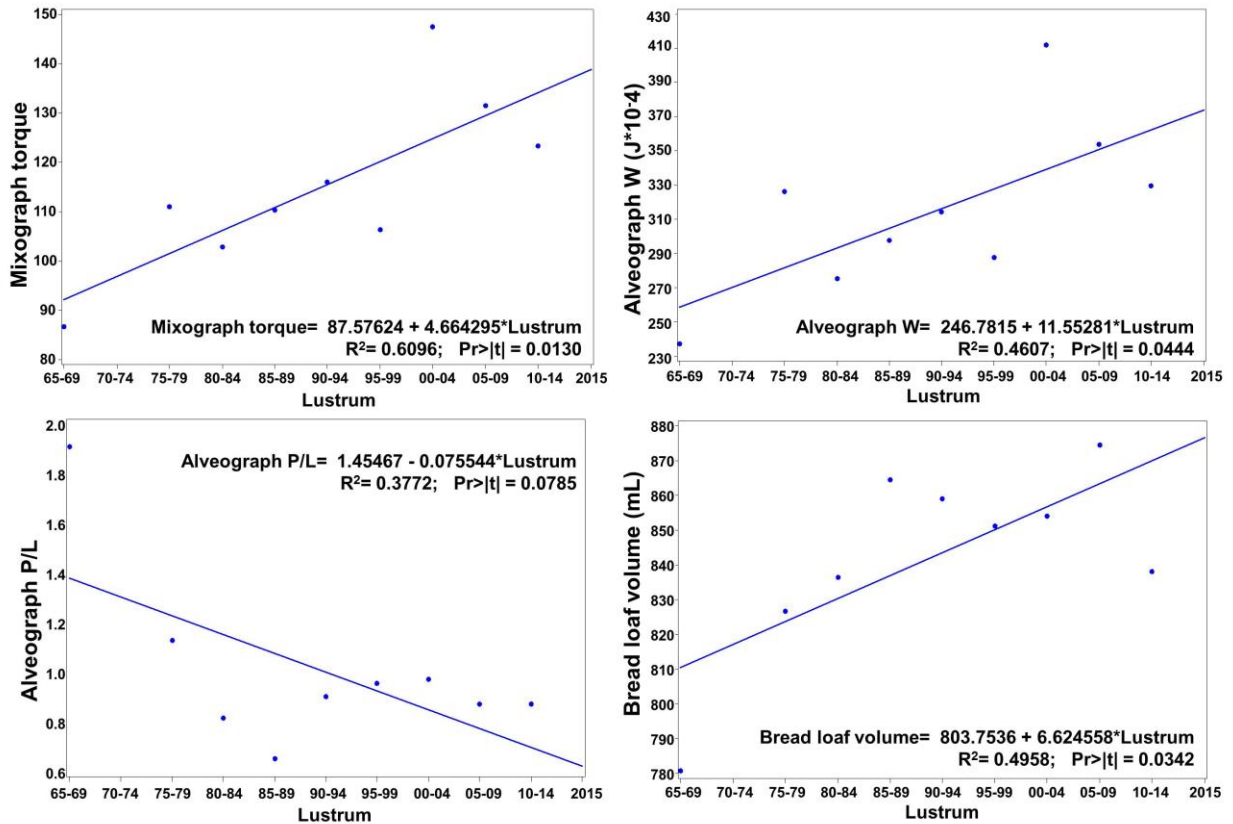
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180 **4. Discussion**

181 From the beginning of the breeding program at CIMMYT, grain yield was considered as the
 182 primary objective because of the urgent need to substantially increase wheat production in many
 183 developing countries. This emphasis on breeding for grain yield has translated into continuous
 184 genetic gains for this trait in CIMMYT materials (Aisawi et al., 2015; Crespo-Herrera et al.,
 185 2017; Lopes et al., 2012; Ortiz-Monasterio et al., 1997), which was also found with the set of
 186 genotypes used in the current study (Mondal et al., 2015). Supplying germplasm with desirable
 187 quality to elaborate diverse products (leavened and flat breads, noodles, etc.) at different
 188 conditions (mechanized, semi-mechanized, and handmade) has been another objective of the
 189 breeding program.

190 Grain characteristics used as indicators of milling quality include grain volume weight,
 191 kernel weight, and experimental flour yield, and did not show a significant trend, indicating the

192 maintenance of these traits over time. The fact that milling quality has not been improved in the
193 last 50 years in CIMMYT spring bread wheat germplasm is due to the fact that it was not a high
194 priority trait since in most important geographical target for the CIMMYT breeding program
195 (South Asia), grain is mainly milled in rural areas by small local mills to produce whole-meal
196 flour (*atta* in India), which is used for the elaboration of different types of flat breads. However,
197 the increase of the urban population in the developing world will possibly increase demands of
198 refined flour for the mechanized food industry. As such, flour extraction should receive more
199 attention in the coming years in the breeding program. This trait has not been improved by other
200 breeding programs where it was supposed to have more importance (Cox et al. 1989; Fufa et al.,
201 2005; Hucl et al. 2015; Souza et al. 1993; Underdahl et al. 2008). This illustrates the difficulty in
202 obtaining genetic gains for the trait. It is also possible that this trait is already optimized to its
203 near maximum genetic potential, making further progress unrealistic. Other traits related to the
204 milling process (grain hardness) did not show a significant trend over the years. In most
205 CIMMYT target areas, hard or semi-hard grains are preferred for the elaboration of diverse
206 products, hence a strong visual selection is made for desired grain hardness, which has resulted
207 in similar characteristics over 5 decades.

208 Interestingly, despite increases in grain yields observed over years for these materials (0.79%
209 per year; Mondal et al., 2015) the trend for protein content was non-significant. This important
210 trait, which is used for market class classification in several countries, is believed to be inversely
211 correlated with grain yield. In this vein, several studies have shown a negative trend for protein
212 content over years of breeding and have attributed this to increased grain yield (Cox et al., 1989;
213 Fufa et al., 2005; Laidig et al., 2017; Sanchez-Garcia et al. 2015; Souza et al., 1993); an
214 undesirable situation for the development of cultivars eligible for market class grades. However,

215 some other studies (De Pauw et al., 2007; Underdahl et al., 2008) have reported results similar to
216 ours, or, even an increase in protein content over time (Hucl et al., 2015). Keeping protein
217 content constant while increasing grain yield is an excellent achievement considering that grain
218 yield improved by 40% since 1965 and it is important for the breeding program to maintain not
219 only industrial quality but nutritional quality of the grain, a paramount objective for CIMMYT.

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

238 quality) was found, probably because the increase in protein quality was not enough to mitigate
239 the effect of the reduction on protein content due to higher grain yield (Laidig et al., 2017).

240

241 **5. Conclusions**

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

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247 **Acknowledgements**

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307 **Abstract**

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331 **1. Introduction**

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352 deployed and cultivated together to assess the genetic gains obtained through selection and
353 breeding during a period of time for different traits (Gupta et al., 2016; Laidig et al., 2017;
354 Morgounov et al., 2013). Even though wheat quality has been an integral part of CIMMYT's
355 spring wheat breeding program for decades, only one study (Ortiz-Monasterio et al., 1997) so far
356 was focused on the genetic gains for quality traits of CIMMYT germplasm. As with other

357 agronomic traits, grain quality characteristics of a wheat cultivar will vary with the environment.
358 Hence, estimates of genetic gain must be from diverse environments (Fufa et al., 2005).

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

361

362 **2. Materials and methods**

363 *2.1 Plant materials/Agronomic trials*

364 A trial consisting of 54 bread wheat cultivars (Electronic Supplementary Table 1) was
365 sown in the 2012–2013 and the 2013–2014 crop seasons in Ciudad Obregon, Sonora, Mexico.
366 The cultivars (most of them bred either at CIMMYT or with a CIMMYT parent) were selected
367 because they represented unique genetic improvements (e.g., *Sonalika*, *Siete Cerros T66*), were
368 grown on a large area and/or over a long period of time (e.g., *PBW343*, *Inqalab 91*), are of
369 current vital importance for the breeding program (e.g., *Kachu*, *Borlaug100 F2014*), or are
370 promising breeding lines that could be released as varieties by national partners in the near
371 future. For the genotypes released as varieties in several countries the year in which a genotype
372 was first released was used for this study. In certain years only one genotype was released while
373 in other years several genotypes were released; therefore, in order to achieve certain degree of
374 balance, the years of release of the genotypes were grouped in lustrums according to the year
375 they were included in CIMMYT international nurseries or released as varieties. The trial was
376 planted with three replicates in a Randomized Complete Block Design (RCBD) under six
377 different environmental conditions: full drip (optimum conditions) and basin irrigation, medium
378 and severe drought stress, and medium and severe heat stress. All the trials were planted in
379 November, except medium heat stress (January) and severe heat stress (February). All the trials

380 had full irrigation (>500 mm), except the medium drought stress (300 mm) and the severe
381 drought stress (180 mm). The plot size was 6.5 m² and the sowing rate was 120 Kg/ha. Weeds,
382 diseases, and insects were all optimally controlled. In all the trials, N was applied (pre-planting)
383 at a rate of 50 kg of N/ha, and at tillering, 150 additional units of N were applied in all the trials
384 except in severe drought stress (50 N units). Two field replicates of each of the wheat lines were
385 used for analyzing the quality traits.

386

387 *2.2 Grain quality evaluation*

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

395 To evaluate the mixing properties such as the optimum dough mixing time (MixT) and
396 torque at that peak (TQ), a mixograph (National Mfg. Co.) equipped with a 35 g bowl according
397 to the AACC method 54-40 (AACC, 2010) was employed. In addition, to measure the visco-
398 elastic properties of the dough, an alveograph (Chopin, France) was used with 60 g flour
399 samples. The energy required to deform the dough-bubble until the point of rupture (AlvW, 10⁻⁴
400 J), as well as the dough tenacity and extensibility ratio AlvP/L, were recorded. A basic straight-
401 dough bread-making method was utilized based on the AACC method 10- 09 (AACC, 2010) and

402 loaf volume was recorded. The water absorption criteria used for mixograph, alveograph and
403 bread-making tests is described in Guzman et al. (2015).

404

405 *2.4 Statistical Analysis*

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

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

420

421 **3. Results**

422 Grain samples from the 54 bread wheat genotypes cultivated in six different environmental
423 conditions over two years were completely characterized for quality traits. Table 1 shows the
424 mean values for each quality trait obtained from the wheat genotypes grouped in different

425 lustrums depending on the year they were released. Visual impressions of the different patterns
 426 of change for the different quality traits are provided in the regression plots (Fig. 1), in which the
 427 genetic gains for each trait obtained in the last 50 years are given.

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

435

436 Gluten quality and dough handling characteristics were analyzed by the mixograph and
 437 alveograph. The three parameters registered related to gluten strength mixograph optimum
 438 mixing time (0.026 min. per year), torque (0.93 per year) and alveograph W (2.31 J*10⁻⁴ per
 439 year) had significant and positive coefficients, which means genetic improvement in the last 50
 440 years. The genotypes developed in 2000-04 (*Tacupeto F2001* and *Norteña F2007*, among others)

441 showed particularly strong gluten, while genotypes from the two last lustrums (2005-09 and
442 2010-14) also maintained high levels of gluten strength. The gluten tenacity/extensibility ratio
443 (alveograph P/L) did not show significant negative trends across the years, with average values
444 since 1980 lower than 1, meaning that gluten had acceptable extensibility for the elaboration of
445 diverse products. Finally, significant genetic gains were found for bread loaf volume (1.32 mL
446 per year). The genotypes developed during 2005-09 were the best for this trait.

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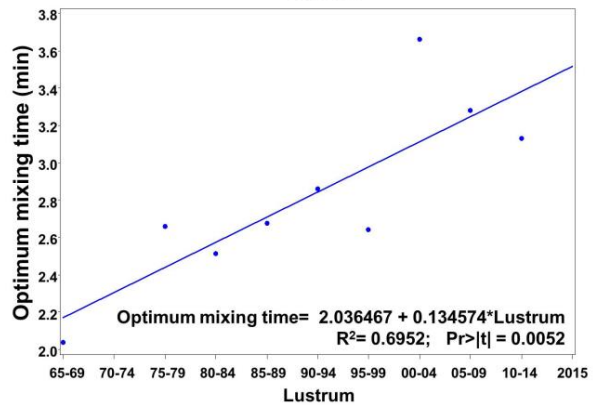
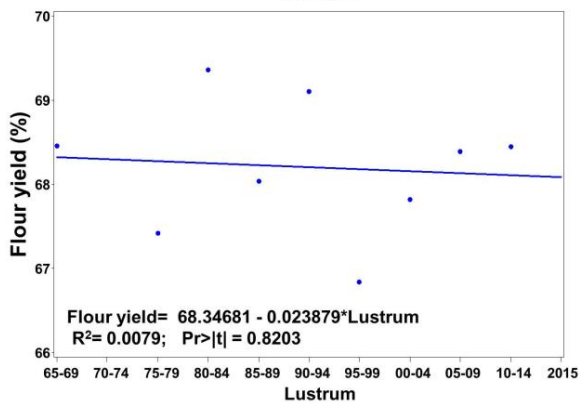
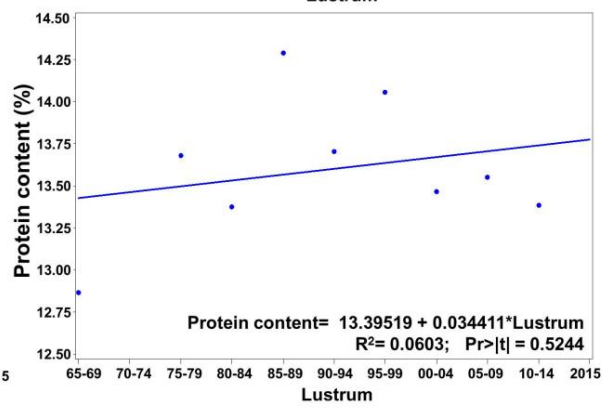
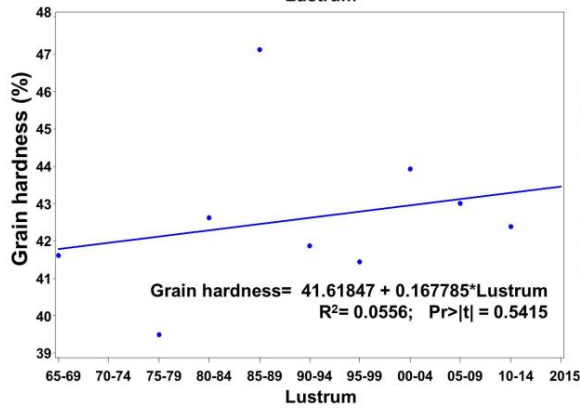
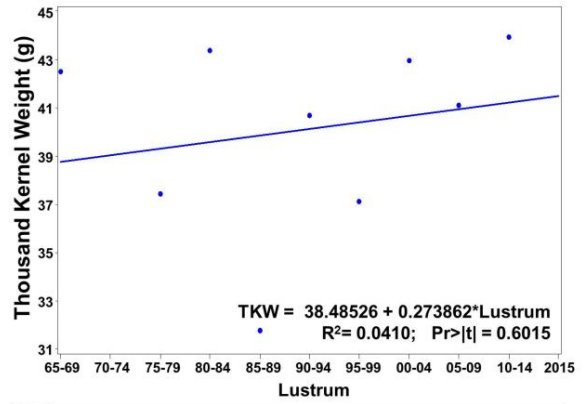
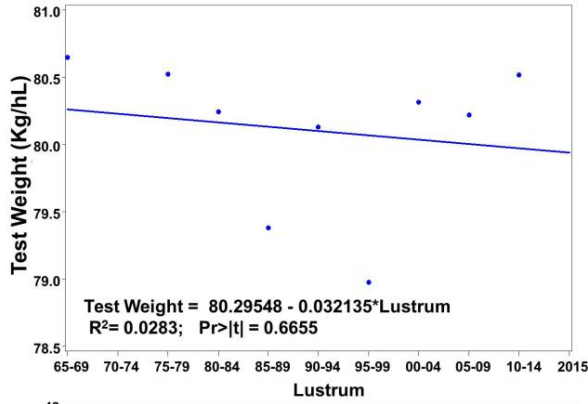
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459 **Figure 1.** Genetic gains for test weight, thousand kernel weight, grain hardness, protein content,
460 mixograph optimum mixing time and torque, alveograph W and P/L, and bread loaf volume, in
461 the set of cultivars developed from 1965 to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

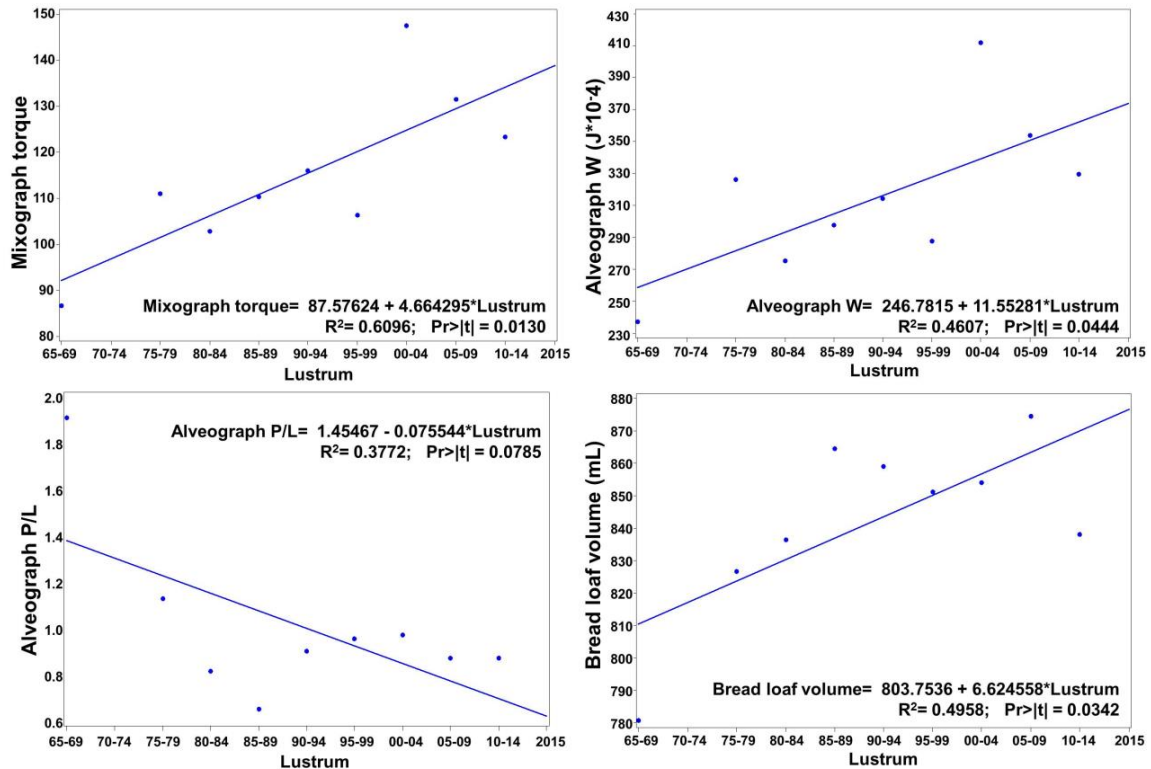
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467 4. Discussion

468 From the beginning of the breeding program at CIMMYT, grain yield was considered as the
 469 primary objective because of the urgent need to substantially increase wheat production in many
 470 developing countries. This emphasis on breeding for grain yield has translated into continuous
 471 genetic gains for this trait in CIMMYT materials (Aisawi et al., 2015; Crespo-Herrera et al.,
 472 2017; Lopes et al., 2012; Ortiz-Monasterio et al., 1997), which was also found with the set of
 473 genotypes used in the current study (Mondal et al., 2015). Supplying germplasm with desirable
 474 quality to elaborate diverse products (leavened and flat breads, noodles, etc.) at different
 475 conditions (mechanized, semi-mechanized, and handmade) has been another objective of the
 476 breeding program.

477 Grain characteristics used as indicators of milling quality include grain volume weight,
 478 kernel weight, and experimental flour yield, and did not show a significant trend, indicating the

479 maintenance of these traits over time. The fact that milling quality has not been improved in the
480 last 50 years in CIMMYT spring bread wheat germplasm is due to the fact that it was not a high
481 priority trait since in most important geographical target for the CIMMYT breeding program
482 (South Asia), grain is mainly milled in rural areas by small local mills to produce whole-meal
483 flour (*atta* in India), which is used for the elaboration of different types of flat breads. However,
484 the increase of the urban population in the developing world will possibly increase demands of
485 refined flour for the mechanized food industry. As such, flour extraction should receive more
486 attention in the coming years in the breeding program. This trait has not been improved by other
487 breeding programs where it was supposed to have more importance (Cox et al. 1989; Fufa et al.,
488 2005; Hucl et al. 2015; Souza et al. 1993; Underdahl et al. 2008). This illustrates the difficulty in
489 obtaining genetic gains for the trait. It is also possible that this trait is already optimized to its
490 near maximum genetic potential, making further progress unrealistic. Other traits related to the
491 milling process (grain hardness) did not show a significant trend over the years. In most
492 CIMMYT target areas, hard or semi-hard grains are preferred for the elaboration of diverse
493 products, hence a strong visual selection is made for desired grain hardness, which has resulted
494 in similar characteristics over 5 decades.

495 Interestingly, despite increases in grain yields observed over years for these materials (0.79%
496 per year; Mondal et al., 2015) the trend for protein content was non-significant. This important
497 trait, which is used for market class classification in several countries, is believed to be inversely
498 correlated with grain yield. In this vein, several studies have shown a negative trend for protein
499 content over years of breeding and have attributed this to increased grain yield (Cox et al., 1989;
500 Fufa et al., 2005; Laidig et al., 2017; Sanchez-Garcia et al. 2015; Souza et al., 1993); an
501 undesirable situation for the development of cultivars eligible for market class grades. However,

502 some other studies (De Pauw et al., 2007; Underdahl et al., 2008) have reported results similar to
503 ours, or, even an increase in protein content over time (Hucl et al., 2015). Keeping protein
504 content constant while increasing grain yield is an excellent achievement considering that grain
505 yield improved by 40% since 1965 and it is important for the breeding program to maintain not
506 only industrial quality but nutritional quality of the grain, a paramount objective for CIMMYT.

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

525 quality) was found, probably because the increase in protein quality was not enough to mitigate
526 the effect of the reduction on protein content due to higher grain yield (Laidig et al., 2017).

527

528 **5. Conclusions**

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

533

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536

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