RESEARCH

GENETIC PROGRESS IN WINTER WHEAT CULTIVARS RELEASED IN CHILE FROM 1920 TO 2000

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Wheat (*Triticum aestivum* L.) is the major crop in terms of planted area and presents the largest distribution in the country covering a wide range of climatic regions. This study assesses the changes of various agronomic traits of winter wheat cultivars released in Chile between 1920 and 2000. A total of 117 winter accessions, representing 45 old and 72 modern cultivars were tested in a humid Mediterranean-type climate, with irrigation, in 2003. Old cultivars were those released before 1960 and modern ones were those released after 1960. Principal component (PC) analysis using 10 agronomic traits clearly separate modern from old cultivars of winter wheat. Comparing modern cultivars with old ones, plant height have been reduced by 25.6%, but others traits have increased, like harvest index (21.1%), number of grains per ear (42.6%), sedimentation value (103%), and grain hardness (32.0%). The variation in plant height was negatively correlated with harvest index ($r = -0.30$, $p < 0.001$). Grain yield, a trait not included in PC analysis, was highly correlated with the second PC ($r = 0.81$, $p < 0.0001$). Significant ($p < 0.01$) correlations were found between the year of release of cultivars and agronomic traits: plant height ($r = -0.82$), harvest index ($r = 0.40$), number of grain per ear ($r = 0.69$), sedimentation value ($r = 0.64$), and kernel weight ($r = -0.46$). Those correlations were mostly a consequence of absence or presence of dwarfing genes in the germplasm. Finally, the yield progress was calculated from yield data of yield trial with 15-25 cultivars and advanced lines of winter wheat tested almost every year from 1965 to 2001, showed no increase in yield between 1965 and 1975, but an increment of 246 kg ha^{-1} per year between 1976 and 1998, representing an annual increase of 2.6%.

Key words: Genetic improvement, grain quality, Mediterranean environment, old and new cultivars, principal components, yield progress.

Wheat (*Triticum aestivum* L.) production is of great importance in Chile; is the major crop in terms of planted area and presents the largest distribution in the country covering a wide range of climatic regions, from the semi-arid Mediterranean-type climate (~ 350 mm of rain) of the northern zone to the humid temperate climate (~ 2000 mm) of the southern zone. Winter wheat is mainly sown in southern part of the country where annual rainfall is > 1200 mm.

From the early sixties, grain yield of wheat has increased significantly in both developed and developing countries (Calderini and Slafer, 1998), and worldwide (Miralles and Slafer, 2007). In Chile, before the sixties, the average yield was 1.3 Mg ha^{-1} and the cultivated area ranged between 600 000 and 850 000 ha; from the sixties to the present the average yield has increased significantly reaching 5.7 Mg ha^{-1} in the latest season, but the cultivated area has been reduced to 260 000 ha (ODEPA, 2010).

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Plant breeding has had great impacts on productivity and grain quality of wheat in different countries (Zhou *et al*., 2007; Trethowan *et al*., 2007), including Chile (Mellado, 2007), leading to what has been called genetic progress (Foulkes *et al*., 2007). The introduction of semi-dwarfing genes in the sixties allowed the reduction in plant size, to increase harvest index, number of grains per unit area and grain yield (Flintham *et al*., 1997; Donmez *et al*., 2001; Brancourt-Hulmel *et al*., 2003; Zapata *et al*., 2004; Shearman *et al*., 2005), and to improve grain quality (Ortiz-Monasterio *et al*., 1997; Trethowan *et al*., 2007).

Over 200 cultivars have been released in Chile during the 20th century (Mellado, 2007). The earlier cultivars (before 1950) were mostly introduced from Europe or USA, but afterward cultivars were created by breeding programs in Chile. In this paper we address the following questions: What have been the main changes in agronomic traits of winter wheat germplasm in Chile during the 20th century? How grain quality has been modified by plant breeding? And to what extent genetic improvement and better agronomic practices are responsible of the strong increment in the average grain yield in Chile? Thus, the objectives of this study were: a) to analyze changes in various agronomic traits of winter cultivars released or introduced in the country between 1920 and 2000; b) to identify what traits have contribute most to the genetic improvement of winter wheat cultivars in Chile; and c) to analyze the yield progress in winter bread wheat.

MATERIALS AND METHODS

Characterization of winter germplasm

A total of 117 winter wheat accessions, representing 45 old and 72 modern cultivars were tested in field experiments in 2003. Seeds were obtained from the Germplasm Bank of CRI-Quilamapu of Instituto de Investigaciones Agropecuarias INIA. Cultivars were released or introduced in the country between 1920 and 2000; old cultivars are those used before 1960 while modern ones are those released after 1960. The experiment was conducted in the experimental field of CRI-Quilamapu, located 25 km from Chillán (36°32’ S; 71°54’ W; 217 m a.s.l.), Chile. The climate corresponds to a humid Mediterranean type; the long term average of the minimum temperature of the coldest month (July) is 3.0 °C; the maximum temperature of warmest month (January) is 28.6 °C; the annual temperature is 13.9 °C; and the annual rainfall is 1270 mm (del Pozo and del Canto, 1999). The soil was a sandy loam, humic Haploxerands (Andisol). Soil chemical characteristics of the top 10 cm were: pH 6.0, 8.87 mg N-$N0_3$ kg^{-1}; 17.05 mg P kg^{-1} (Olsen), 0.45% N-total, 4.5% C and 0.33, 5.75, 0.65, 0.48, cmol kg^{-1} of available K, Ca, Mg and Na, respectively (Zagal *et al*., 2002).

Plots consisted of two rows of 2 m long separated by 0.2 m and the seeding rate was 180 kg ha^{-1}, with no replicates. Sowing date was 2 June. Fertilizer application was done on 1 ha basis of 180 kg N, 52 kg P, 66 kg K, 23 kg Mg, 44 kg S, 1,1 kg B and 1.05 kg Zn. Nitrogen was split into three, 47 kg at planting (Zadoks 00), 80 kg at tillering initiation (Zadoks 20) and 53 kg at the end of tillering (Zadoks 25). Weeds were controlled with MCPA at 750 g a.i. ha^{-1} + metsulfuron methyl 8 g a.i. ha^{-1}. Plots were furrow irrigated according the necessity of the crop.

Ten traits were evaluated: plant height (cm), days to heading, grain yield, harvest index, ear length (average of 20 ears), test weight (kg hL^{-1}), number of grain per ear (average of 20 ear), 1000 kernel weight (g), wet gluten content (%) (Promylograph type TIK, Austria), sedimentation value (cm^3) (Zeleny, 1947), and grain hardness index. The latter determined as the grain resistance to abrasion in a pearler machine (Strong Scott 17810, Seedburo Equipment, Chicago, Illinois, USA), and therefore low values in hardness index (%) means harder grains.

Graphical representation of the estimated genetic similarities between genotypes was obtained by principal component (PC) analysis using the above quantitative traits, excluded grain yield. Only those components with an eigenvalue greater than 1.0 were selected. Correlation values between the original characters and their respective principal components were obtained by multiplying the square root of the eigenvalue for each component by the eigenvector of each character evaluated. Only correlation values ≥ 0.65 were considered as relevant for that principal component.

The PC analysis was done by the procedure PROC PRINCOMP using SAS V 8e (SAS Institute, 2001). One-way ANOVAs were performed to compare traits of old and modern cultivars. Correlation analyses were performed between grain yield and the scores of PCs, and between scores of PCs and the year of cultivar release. Finally, correlations were performed between traits and year of cultivar release.

Yield progress analysis

Grain yield data of 15-25 cultivars and advanced lines of winter wheat tested almost every year from 1965 to 2001, by the wheat breeding program of CRI-Quilamapu, INIA, was used to analyze the yield progress. All the evaluations were conducted at the experimental field of CRI-Quilamapu under irrigated conditions. Plots consisted of six rows of 2 m long separated by 0.2 m with four replicates. Sowing dates were May-June. All plots were fertilized according to soil analysis and weeds controlled with herbicides and/ or manually. To estimate grain yield, an area of 2 m^2 was harvested at maturity.

RESULTS

Agronomic traits and year of cultivar release

The first three PCs explained 72.4% of the total variance (Table 1). The first component explained 43.2% of the total variance and in general separated modern from old cultivars (Figure 1); the former were located on the left side of PC 1 and were characterized by lower plant height, greater number of grains per ear and better grain quality, i.e., higher values of wet gluten and sedimentation value,

Table 1. Eigenvectors and cumulative variance of the most important principal components (PC) for 10 quantitative traits of winter (45 old and 72 modern) cultivars of wheat, evaluated at the experimental field of CRI-Quilamapu in 2003. In bold are the relevant traits for each PC.

	Principal components		
Traits	PCI	PC2	PC3
Plant height, cm	**0.84**	-0.08	0.24
Days to heading	0.26	-0.62	-0.34
Ear length, cm	**-0.66**	0.14	-0.09
Harvest index	-0.18	**0.84**	-0.28
Test weight, kg hL^{-1}	0.61	0.55	0.41
Number of grains per ear	**-0.66**	0.44	-0.42
1000 kernel weight, g	0.68	0.49	0.13
Wet gluten content, %	**-0.79**	-0.18	0.38
Sedimentation value, cm^3	**-0.77**	0.05	0.45
Hardness index	**0.76**	-0.01	-0.24
% variance explained	43.3	18.8	10.3
Cumulative variance	43.3	62.1	72.4

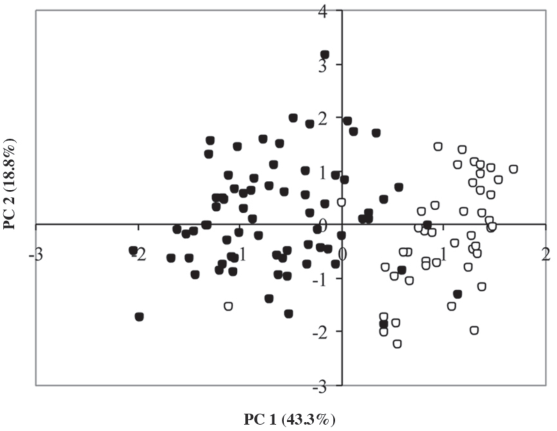

Figure 1. Scatter diagram of the first two principal components (PC) for 45 old (○) and 72 modern (●) winter wheat cultivars evaluated at the experimental field of CRI-Quilamapu in 2003. PC 1 and PC 2 explained 43.3 and 18.8 % of the variance, respectively.

and lower hardness index (harder grains) (Table 1). The second PC explained 18.8% of the total variance and was positively correlated with harvest index (Table 1). Significant differences (ANOVAs; $p < 0.001$) between old (released before 1960) and modern (released after 1960) cultivars of winter wheat were found for all evaluated traits (Table 2). In modern cultivars plant height and 1000 kernel weight were reduced by 25.6 and 20.9%, respectively, whereas harvest index, ear length, number of grains per ear were increased by 21, 18.8 and 42.6%, respectively. Regarding grain quality, wet gluten content and sedimentation value were augmented by 54.4 and 103%, respectively; however test weight and hardness index were reduced by 20.9 and 32%, respectively. Days to heading was slightly reduced in modern cultivars (Table 2). Grain yield, a trait not included in PC analysis, was highly correlated with PC 2 (Table 3). The year of release was negatively correlated with PC 1, indicating that those agronomic traits related with PCs are contributing to the yield improvement of wheat. In fact, the year of release was positively correlated with harvest index, ear length and number of grain per ear (Table 4). Traits related with grain quality were also positively correlated with the year of release, like wet gluten and sedimentation value (Table 4). However, as expected, plant height was negatively correlated with year of release and so do 1000 kernel weight, test weight and hardness index (Table 4). The number of grain per ear was positively ($r = 0.49$; $p < 0.01$) with ear length, but negatively correlated ($r = -0.28$; $p < 0.01$) with 1000 kernel weight.

Table 2. Mean (standard error) values of traits of old and modern winter cultivars evaluated at the experimental field of CRI-Quilamapu in 2003.

Trait	Old (N = 45)	Modern (N = 72)	F	P
Plant height, m	136.1 (1.8)	101.3 (1.5)	179.9	0.000
Days to heading	163.0 (0.9)	159.3 (0.7)	9.3	0.003
Harvest index	0.19 (0.01)	0.23 (0.01)	14.6	0.000
Ear length, cm	8.5 (0.2)	10.1 (0.2)	33.2	0.000
Number of grains per ear	28.9 (1.1)	41.2 (0.9)	73.7	0.000
1000 kernel weight, g	39.3 (1.1)	31.1 (0.9)	32.4	0.000
Test weight, kg hL^{-1}	76.1 (0.6)	72.3 (0.5)	23.9	0.000
Wet gluten content, %	17.1 (1.0)	26.4 (0.8)	49.5	0.000
Sedimentation value, cm^3	8.8 (1.0)	17.9 (0.8)	45.9	0.000
Hardness index	41.9 (1.3)	28.5 (1.0)	68.4	0.000

Table 3. Pearson correlation values for the relationship between the year of release of cultivars and grain yield with the scores of principal components (PC).

Principal component	Year of release	Grain yield
PC 1	-0.85**	-0.01
PC 2	0.24	0.81**
PC 3	-0.09	-0.14

**Correlations are significant at the 0.005 level.

Table 4. Correlations between year of release and traits of winter wheat cultivars evaluated at the experimental field of CRI-Quilamapu in 2003.

	Winter (N = 117)
Plant height, cm	-0.82*
Days to heading	-0.29*
Harvest index	0.40*
Ear length, cm	0.53*
Number of grains per ear	0.69*
1000 kernel weight, g	-0.46*
Test weight, kg hL^{-1}	-0.39*
Wet gluten content, %	0.60*
Sedimentation value, cm^3	0.63*
Hardness index	-0.66*
Grain yield, Mg ha^{-1}	0.24*

*Correlations are significant at the 0.01 level.

Yield progress

Frequency distribution of grain yield indicate higher grain yield in modern cultivars than in older ones (Figure 2). As a consequence, grain yield was positively correlated with year of release (Table 4). Using a more extensive set of data available from INIA trials, average yield values of commercial cultivars and experimental lines of winter wheat evaluated from 1965 to 2001, show a null yield progress from 1965 to 1975 (average yield 4.2 Mg ha^{-1}), then an increase in yield from 1976 to the middle nineties, with 2 yr (1996 and 1998) with average yields higher than 10 Mg ha^{-1} (Figure 3).

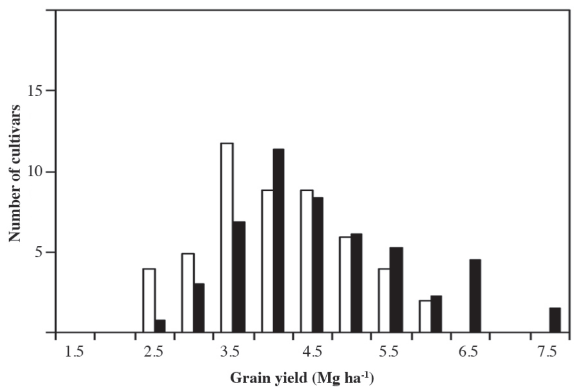

Figure 2. Frequency distribution of grain yield of old (○) and modern (●) winter wheat cultivars evaluated at the experimental field of CRI-Quilamapu in 2003.

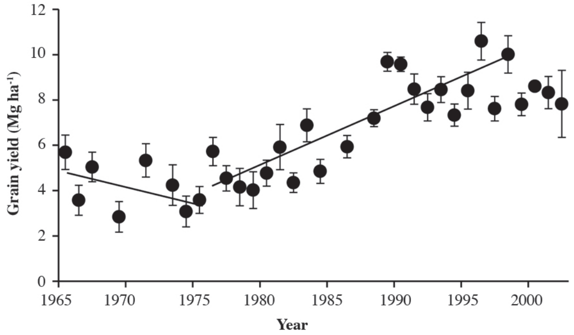

Figure 3. Yield progress in winter wheat. Values are the mean of 15-25 cultivars tested each year at the experimental field of CRI-Quilamapu between 1965 and 2001. The lineal regression between 1976 and 1998 is: y = 0.2461x - 482.11; R^2 = 0.70.

DISCUSSION

Comparing modern cultivars with old ones (released before the sixties) a number of traits have changed in winter cultivars (Table 2); plant height have been reduced by 25.6%, but others traits have increased, like harvest index (21.1%) and number of grain per ear (42.6%). Similar changes in these agronomic traits have been observed with genetic improvement in UK (Flintham *et al*., 1997; Shearman *et al*., 2005), France (Brancourt-Hulmel *et al*., 2003), North America (Donmez *et al*., 2001), Italia (Guarda *et al*., 2004) and Argentina (Slafer and Andrade, 1989). The variation in plant height was negatively correlated with harvest index ($r = -0.30$, $p < 0.001$), as has been reported by other authors (Richards, 1992; Evans, 1993; Mellado, 2000).

The reduction of plant height is a consequence of the introduction of semi-dwarfing genes which were introduced in Chile in 1956 (Zapata *et al*., 2004). As a consequence, the significant correlations between year of release and plant height, harvest index or number of kernel per ear, observed in winter cultivars (Table 4), as well as in other studies (e.g. Shearman *et al*., 2005; Zhou *et al*., 2007), is mostly due to the absence or presence of dwarfing genes in the germplasm. In fact, the correlations are not significant when the analysis is performed for year of release from 1970 onwards, i.e. for wheat germplasm with dwarfing genes. The increase in number of grains per ear is a consequence of *Rht* pleiotropy (Flintham *et al*., 1997), which in the case of the Chilean germplasm the dwarfing genes derive mainly from the cultivar Norin 10 (Mellado, 2007).

In Chile crosses of spring by winter types have been performed, and the selection has been driven to facultative type. As a consequence a slight reduction in days to heading has been obtained in modern winter cultivars (Table 2). Kernel weight has been reduced in modern cultivars (Tables 2 and 4), and this can be explained because kernel weight has not been a selection target by breeders in Chile, and also due to the strong increase in the number of grains per ear. In Italy, kernel weight of winter wheat also decreased between 1900 and 1994 (Guarda *et al*., 2004). In North China, kernel weight of bread wheat was not modified between the sixties and the year 2000 (Zhou *et al*., 2007). But, in durum wheat growing in a Mediterranean environment in Turkey, kernel weight was superior in modern cultivars (Koç *et al*., 2003).

The yield progress has been extensively analyzed by different authors, either as trends of national averages (e.g. Calderini and Slafer, 1998) or as progress of yield potential (e.g. Sayre *et al*., 1997; Fischer, 2007; Foulkes *et al*., 2007). The later has been estimated comparing the yield of cultivars from different year of release; in Centro Internacional de Mejoramiento de Maíz y Trigo (CIMMYT), Mexico, under irrigated conditions, the genetic progress for spring bread wheat was 0.41% per year between 1966 and 2003 (Fischer, 2007), and 0.88% per year comparing eight cultivars released between 1962 and 1988 (Sayre *et al*., 1997). For durum wheat, the rate of progress has been estimated in 0.49% per year between 1966 and 2003 (Fischer, 2007). In North China, the annual genetic progress ranged 0.48-1.05% (32.0-72.1 kg ha^{-1}), in three Provinces, for cultivars released between the sixties and the nineties (Zhou *et al*., 2007). In this study, the yield progress, calculated from yield data of winter cultivars tested from 1965 to 2001, is 246 kg ha^{-1} yr^{-1} (2.6%) between 1976 and 1998, but in this evaluation there are confounded both genetic and agronomic improvements. For the same period (1976-1998) the average grain yield in Chile increased at the rate of 118 kg ha^{-1} yr^{-1} (from 1.5 to 3.2 Mg ha^{-1}; ODEPA, 2010), that is an increase of 3.7% per year. Therefore, the yield gap (calculated as the yield obtained in experimental trials – average country yield) increased from 2.7 Mg ha^{-1} in 1976 to 6.4 Mg ha^{-1} in 1998.

Other important traits modified by plant breeding are those related to grain quality; the sedimentation value and wet gluten have increased in modern cultivars (103% and 54.4%, respectively; Table 2) and were positively correlated with year of release (Table 4). In a previous study, where cultivars of spring (10 cultivars) and winter (11 cultivars) wheat released between 1968 and 1993 were compared, the sedimentation value showed no progress during that period, but it did grain protein content which increased 0.5-1.0% (Mellado, 2001). The analysis of 37 cultivars released between 1955 and 2005 in the former Yugoslavia, revealed that plant breeding increased grain protein content (close related to sedimentation value), but reduced wet gluten (Dencic *et al*., 2005).

CONCLUSIONS

Changes in a number of traits have occurred in winter wheat cultivars in Chile as a consequence of plant breeding; plant height and kernel weight has been reduced but harvest index and number of grain per ear have increased. Also, grain quality traits have been modified; higher sedimentation values and lower hardness index (harder grains) are observed in modern's wheat. The yield progress in Chile between 1976 and 1998 has been very high which explains the strong increment in the average grain yield of the country, in the last decades.

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Progreso genético en cultivares de trigo de invierno liberados en Chile desde 1920 a 2000. El trigo (*Triticum aestivum* L.) es el cultivo más importante en Chile en términos de superficie sembrada y áreas geográficas en las cuales se siembra, cubriendo una gran diversidad de condiciones climáticas. Este estudio evaluó los cambios de varias características agronómicas de variedades de trigo de invierno liberadas en el país entre 1920 y 2000. Un total de 117 genotipos de trigos de invierno, que representa 45 cultivares antiguos y 72 cultivares modernos, se evaluaron en un clima húmedo de tipo mediterráneo, en condiciones de riego, en el año 2003. Los cultivares antiguos corresponden a aquellos liberados antes del año 1960 y los modernos a los liberados después del año 1960. Mediante un análisis de componentes principales (CP) usando 10 características agronómicas, permitió separar claramente los cultivares modernos de los antiguos. Al comparar los cultivares modernos con los antiguos se determinó que la altura de la planta se ha reducido un 25,6%, pero en otras características se produjo un aumento, como el índice de cosecha (21,1%), número de granos por espiga (42,6%), valor de sedimentación (103%) y la dureza del grano (32,0%). La variación en la altura de la planta se correlacionó negativamente con el índice de cosecha ($r = -0{,}30$, $p < 0{,}001$). El rendimiento de grano, una característica no incluida en el análisis de PC, estuvo altamente correlacionado con el segundo PC ($r = 0{,}81$, $p < 0{,}0001$). Correlaciones significativas ($p < 0{,}01$) se encontraron entre el año de la liberación de los cultivares y las características agronómicas: altura de planta ($r = -0{,}82$), índice de cosecha ($r = 0{,}40$), número de granos por espiga (0,69), valor de sedimentación ($r = 0{,}64$), y peso del grano ($r = -0{,}46$). Estas correlaciones fueron en su mayoría una consecuencia de ausencia o presencia de genes de enanismo en el germoplasma. Finalmente el avance en rendimiento, calculado a partir de datos de rendimiento de ensayos en los que se probaron entre 15 y 25 cultivares y líneas avanzadas de trigo de invierno evaluados casi todos los años entre 1965 y hasta 2001, no mostró ningún aumento en el rendimiento entre 1965 y 1975, pero sí un aumento de 246 kg ha^{-1} por año entre 1976 y 1998, lo que representa un incremento anual de 2,6%.

Palabras clave: mejoramiento genético, calidad del grano, clima mediterráneo, cultivares antiguos y mejorados, componentes principales, avance genético del rendimiento.

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