Canaryseed (*Phalaris canariensis* L.) accessions from nineteen countries show useful genetic variation for agronomic traits

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Cogliatti, M., Bongiorno, F., Dalla Valle, H. and Rogers, W. J. 2011. **Canaryseed (*Phalaris canariensis* L.) accessions from nineteen countries show useful genetic variation for agronomic traits**. Can. J. Plant Sci. **91**: 37–48. Fifty-seven accessions of canaryseed (47 populations and 10 cultivars) from 19 countries were evaluated for agronomic traits in four field trials sown over 3 yr in the province of Buenos Aires, Argentina. Genetic variation was found for all traits scored: grain yield and its components (grain weight, grain number per square meter, grain number per head and head number per square meter), harvest index, percent lodging, and phenological characters (emergence to heading, emergence to harvest maturity and heading to harvest maturity). Although genotype × environment interaction was observed for all traits, the additive differences between accessions were sufficient to enable promising breeding materials to be identified. Accessions superior in performance to the local Argentinean population, which in general gave values close to the overall mean of the accessions evaluated, were identified. For example, a population of Moroccan origin gave good yield associated with elevated values of the highly heritable character grain weight, rather than with the more commonly observed grain number per square meter. This population was also of relatively short stature and resistant to lodging, and, although it performed best when sown within the normal sowing date, tolerated late sowing fairly well. Other accessions were also observed with high grain weight, a useful characteristic in itself, since large grains are desirable from a quality point of view. Regarding phenology, the accessions showed a range of 160 degree days (8 calendar days in our conditions) in maturity, which, while not large in magnitude, may be of some utility in crop rotation management. Some accessions were well adapted to late sowing. Grain yield in general was strongly correlated with grain number per square meter. Principal components analysis (PCA) carried out for all characteristics provided indications of accessions combining useful characteristics and identified three components that explained approximately 70% of the phenotypic variation. Furthermore, a second PCA plus regression showed that approximately 60% of the variation in grain yield could be explained by a component associated with harvest index and grain number per square meter. Pointers were provided to possible future breeding targets.

Key words: *Phalaris canariensis*, *canaryseed*, accessions, yield, phenology, genetics, breeding

Cogliatti, M., Bongiorno, F., Dalla Valle, H. et Rogers, W. J. 2011. **Les obtentions d'alpiste (*phalaris canariensis* l.) de dix-neuf pays révèlent une variation du génotype utile pour les caractères agronomiques**. Can. J. Plant Sci. **91**: 37–48. Les auteurs ont évalué les caractères agronomiques de 57 obtentions d'alpiste (47 populations et 10 cultivars) issues de 19 pays dans le cadre de quatre essais sur le terrain qui ont duré trois ans dans la province de Buenos Aires, en Argentine. Des variations génétiques ont été découvertes pour tous les caractères évalués: le rendement grainier et ses composantes (poids des graines, nombre de graines au mètre carré, nombre de graines par épi et nombre d'épis au mètre carré), l'indice messianique, le pourcentage de verse et la phénologie (nombre de jours entre la levée et l'épiaison, nombre de jours entre la levée et la récolte à maturité et nombre de jours entre l'épiaison et la récolte à maturité). Bien qu'on ait relevé des interactions entre le génotype et l'environnement pour l'ensemble des caractères, les différences cumulatives entre les obtentions étaient suffisantes pour qu'on identifie du matériel génétique prometteur pour l'amélioration. Les auteurs ont déterminé les obtentions dont le rendement était supérieur à celui de la population locale, dont la valeur générale se rapprochait de la moyenne des obtentions exotiques évaluées. Une population du Maroc, par exemple, a donné un bon rendement associé à la valeur élevée du caractère fortement héréditaire qu'est le poids des graines, plutôt qu'au nombre de graines au m^2, ce qui est plus courant. Cette population a aussi produit des plants relativement trapus et résistants à la verse; bien qu'elle donne les meilleurs résultats quand les semis ont lieu à la date usuelle, cette population tolère assez bien une date de semis plus tardive. D'autres obtentions ont également donné un poids élevé de graines, paramètre utile en soi, puisque les grosses graines sont souhaitables sur le plan de la qualité. Du côté de la phénologie, le temps pris par les obtentions pour parvenir à maturité variait dans une plage de 160 degrés-jours (8 jours dans les conditions locales), ce qui, tout en n'étant pas énorme, pourrait avoir son utilité pour les assolements. Quelques obtentions se prêtaient à des semis tardifs. En général, le rendement grainier est étroitement corrélé au nombre de graines par m^2. L'analyse en composantes principales (ACP) effectuée pour tous les caractères a donné une idée des obtentions qui combinent des

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caractères intéressants et permis d'identifier trois composantes qui expliquent environ 70% de la variation phénotypique. D'autre part, une deuxième ACP et une analyse de régression indiquent qu'environ 60% de la variation du rendement grainier s'explique par une composante associée à l'indice messianique et au nombre de graines par m^2. Suivent des conseils sur les objectifs éventuels d'amélioration génétique.

Mots clés: *Phalaris canariensis*, alpiste, obtentions, rendement, phénologie, génétique, amélioration

Canaryseed or annual canarygrass (*Phalaris canariensis* L.) is a winter-spring graminaceous species originating from the Mediterranean basin, and is the only species of its genus grown for grain production. Its crop cycle and management are similar to those of wheat (Robinson 1978; Bodega et al. 1995). The grains are almost exclusively used as feed for song or ornamental caged birds (Miravelles et al. 2002), although a small amount are destined for the elaboration of treatments for fabrics and the distillation of alcoholic beverages, amongst other industrial uses (Yagüez 2002). For many years controversy existed regarding whether the species reproduced by self-fertilization or open pollination, but this has been resolved by Matus-Cadiz and Hucl (2006), who showed that the species is predominantly self-fertilizing, with an upper limit for open pollination of 2.2%.

According to figures obtained over the past 15 yr (SAGPyA 2008), canaryseed production in Argentina is confined to the provinces of Buenos Aires, Entre Rios and La Pampa, 95% of which is concentrated in the center and southeast of the province of Buenos Aires (Fig. 1). Historically, Argentina has played an important role in the global canaryseed market and is currently among the top three producers. Nonetheless, little effort has been directed towards its genetic improvement in the country and no commercial cultivars have been developed, in contrast to the situation in countries such as Canada, the Czech Republic, Holland, Hungary and the United States of America, which have produced their own cultivars, many of which have not yet been evaluated for agronomic performance under Argentinean agro-ecological conditions. Regarding the type of germplasm commercially sown in Argentina, Bodega et al. (1995) found that seeds from different canaryseed-growing regions sown in designed comparative field trials produced crops that did not differ significantly in grain yield and its components, phenology, biological yield and harvest index, and which, therefore, at least from an agronomical point of view, could be considered as belonging to one population. Although adapted to some degree to local conditions, canaryseed shows marked yield instability over seasons, produces low weight grains and tends to lodge in non-limiting conditions for water and nutrients.

The aim of the current work was to evaluate the agronomic performance of a collection of accessions (populations and cultivars) of canaryseed and thereby identify sources of genetic variation suitable as a basis for future breeding programs.

MATERIALS AND METHODS

Fifty-seven accessions of canaryseed, comprising 47 populations and 10 cultivars from 19 countries (Table 1) were grown in four field trials carried out in 2004 to 2006, in a randomized complete block design; each of the three replicate blocks were sown on the Experimental Farm of the Faculty of Agronomy in the city of Azul, National University of the Center of the Province of Buenos Aires, Argentina (lat 36°49′53″ South, long. 59°53′23″ West). Each accession was represented by a 3 m × 1.4 m (4.2 m^2) plot in each replicate block with a sowing density of 500 plants m^{-2}. Sowing dates were: Field Trial 1 (FT1), 2004 Aug. 19; FT2, 2005 Aug. 14; FT3, 2006 Jul. 21; and FT4, 2006 Aug. 24.

Diammonium phosphate was applied during land preparation prior to sowing, and urea was applied at Zadoks stage 21 (tillering) (Zadoks et al. 1974). Total soil available nitrogen and phosphorus were 80 kg ha^{-1} and 12 ppm, respectively, for FT1 and FT2, and 120 kg ha^{-1} and 18 ppm for FT3 and FT4. Broad-leaved weeds were controlled by the application at Zadoks stage 13 (three expanded leaves) of 1000 cm^3 ha^{-1} of Weedex 34.6% EC, Bayer Crop Science (34.6 g of bromoxynil octanoate a.i. 100 mL^{-1}), followed by the application at Zadoks stage 21 (tillering) of a mixture composed of 1000 cm^3 ha^{-1} of MCPA 28% SL, Syngenta (28 g of the sodium salt of 2-methyl 4-chlorophenoxyacetic acid 100 mL^{-1}) + 120 cm^3 ha^{-1} of Banvel 57.71% SL, Syngenta (57.71 g of dicamba-dimethylammonium 100 mL^{-1}). The dosages applied were those recommended by Cámara de Sanidad Agropecuaria y Fertilizantes (2005).

In the four trials, grain yield, single grain weight, grain number m^{-2}, harvest index (HI) and plant height were determined. In trials FT3 and FT4, grain number per head, head number m^{-2}, percent lodging and the duration of the following phenological stages in calendar time and thermal time expressed in degree days (°D) (base temperature 0°C) were also determined: emergence to heading (°D E-H), heading to harvest maturity (°D H-M) and emergence to harvest maturity (°D E-M). Data were analyzed by analysis of variance [applied to individual trials and combined over trials according to McIntosh (1983)], Fisher's test for treatment differences and Pearson's correlation coefficient between variables. In trials FT3 and FT4, principal component analysis (PCA) was also applied to study relationships between characters and grouping between accessions, as well as, when combined with regression analysis, to study the relationship between grain yield

Table 1. Type of canaryseed germplasm, country of origin, seed source, original accession number and commercial name of the entries comprising cultivars

Accession number	Type of germplasm	Country of origin	Seed source[z]	Original accession number	Commercial name
1	Population	Brazil	USDA	PI 163357	
2	Population	Mexico	USDA	PI 165429	
3	Population	Mexico	USDA	PI 189547	
4	Population	Mexico	USDA	PI 203913	
5	Population	Turkey	USDA	PI 180864	
6	Population	Turkey	USDA	PI 1700027	
7	Population	Turkey	USDA	PI 179397	
8	Population	Turkey	USDA	PI 251475	
9	Population	Turkey	USDA	PI 170624	
10	Population	Turkey	USDA	PI 180863	
11	Population	Turkey	USDA	PI 179398	
12	Population	Turkey	USDA	PI 175812	
13	Population	Turkey	USDA	PI 175811	
14	Population	Turkey	USDA	PI 174299	
15	Population	Turkey	USDA	PI 170634	
16	Population	Turkey	USDA	PI 170622	
17	Population	Turkey	USDA	PI 170625	
18	Population	Turkey	USDA	PI 177026	
19	Population	Turkey	USDA	PI 170633	
20	Population	Turkey	USDA	PI 322734	
21	Population	Turkey	USDA	PI 167261	
22	Population	Turkey	USDA	PI 170629	
23	Population	Turkey	USDA	PI 170627	
24	Population	Turkey	USDA	PI 170626	
25	Population	Turkey	USDA	PI 170623	
26	Population	Iran	USDA	PI 251390	
27	Population	Iran	USDA	PI 223398	
28	Population	Iran	USDA	PI 223397	
29	Population	Iran	USDA	PI 250741	
30	Population	Iran	USDA	PI 249998	
31	Population	Iran	USDA	PI 223396	
32	Population	Iran	USDA	PI 249999	
34	Population	Iran	USDA	PI 229768	
36	Population	Egypt	USDA	PI 250097	
37	Population	Egypt	USDA	PI 251274	
38	Population	Morocco	USDA	PI 266186	
39	Population	Morocco	USDA	PI 284180	
40	Population	Morocco	USDA	PI 284182	
41	Population	Morocco	USDA	PI 284183	
42	Population	Morocco	USDA	PI 284184	
43	Population	Sweden	USDA	PI 284185	
44	Population	Italy	USDA	PI 284186	
45	Population	Portugal	USDA	PI 368984	
46	Population	Switzerland	USDA	PI 415822	
48	Cultivar	USA	USDA	PI 578798	Alden
49	Cultivar	USA	USDA	PI 578799	Keet
50	Cultivar	USA	USDA	PI 578800	Elias
51	Population	Syria	USDA	PI 181780	
52	Cultivar	Canada	SK		CDC-Maria
54	Cultivar	Hungary	CGB	13G 7200005	Lizard
56	Cultivar	Hungary	CGB	13G 7200003	Karcsu
57	Cultivar	Hungary	CGB	13G 7200007	Kisvardai-41
58	Cultivar	Hungary	CGB	13G 7200006	Abad
60	Cultivar	Holland	CGB	13G 7200004	Cantate
62	Cultivar	Czech Republic	CGB	13G 7200008	Judita
63	Population	Spain	UNMdP		
73	Population	Argentina	HJN		

[z]HJN, cereal commercialization company H. J. Navas & Cía. S. A., Azul, Province of Buenos Aires, Argentina; UNMdP, Faculty of Agrarian Sciences, National University of Mar del Plata, Argentina; CGB, Czech Gene Bank, Research Institute of Crop Production, Prague, Czech Republic; SK, University of Saskatchewan, Canada; USDA, National Genetic Resources Program, United States Department of Agriculture.

and the remaining traits. Analyses were carried out using the program INFOSTAT version 2007p (Infostat 2007).

RESULTS AND DISCUSION

In the current work and in spite of previous reports that the genetic variation observed in canaryseed is low

(Poverene et al. 1994; Bodega et al. 1995, 2003; Putnam et al. 1996; Miravalles et al. 2002; Matus-Cadiz and Hucl 1999, 2002), significant differences were found between the accessions for all evaluated characters (grain yield and its components, plant height and phenology) as described in the following sections (Table 2), although the combined analyses of variance over trials also demonstrated the presence of significant genotype (accession) × environment (trial) interaction ($P \leq 0.05$).

Grain Yield

Significant differences were found between the accessions in three of the four trials (FT1, FT3 and FT4) and in the combined analysis ($P = 0.0052$). The overall mean over the four trials was 1369 kg ha^{-1}, with a range of 1130 (accession 46, Swiss population) to 1557 kg ha^{-1} (accession 13, Turkish population). This latter population was significantly higher in yield than the local population (accession 73, yield 1324 kg ha^{-1}). Second in ranking for yield was the US cultivar Elias (accession 50) with 1533 kg ha^{-1}, and third was a Moroccan population (accession 42) with 1530 kg ha^{-1}, of which further mention is made below. In agreement with Hucl et al. (2001), the US cultivar Keet (accession 49) yielded 15% higher than the glabrous seeded Canadian cultivar CDC Maria (accession 52).

Since two trials, FT3 and FT4, were sown in the same year at different times (2006 Jul. 21 and 2006 Aug. 24), the effect of sowing date upon grain yield for the 57 accessions could be observed (Table 2). Important ranking changes were observed for the accessions over dates and the accession × trial interaction was correspondingly highly significant (Table 3). For example, accession 57 (cultivar Kisvardai-41 from Hungary) was second in ranking in FT3, but 52nd in FT4, suggesting that this cultivar would require early sowing in our conditions. The Moroccan population mentioned above (accession 42) was ranked first in FT3 and maintained a reasonably high ranking in FT4 (eighth), implying it tolerated late sowing reasonably well. Three accessions, 2 and 4 from Mexico and 20 from Turkey, ranked poorly in FT3 (57th, 53rd and 54th, respectively), but were the three top yielding accessions in FT4 (2nd, 1st and 3rd, respectively). These populations were amongst the first accessions to flower in both trials, and their extremely low yield in FT3 might be explained by the fact that their flowering period coincided with a brief spell of sub-zero temperatures that appeared to reduce their grain number per square meter. This implies that they should be sown later than the majority of the accessions studied in order to avoid late season sub-zero temperatures, and that they might constitute material of some agronomic interest due to being well adapted for yield to late sowing.

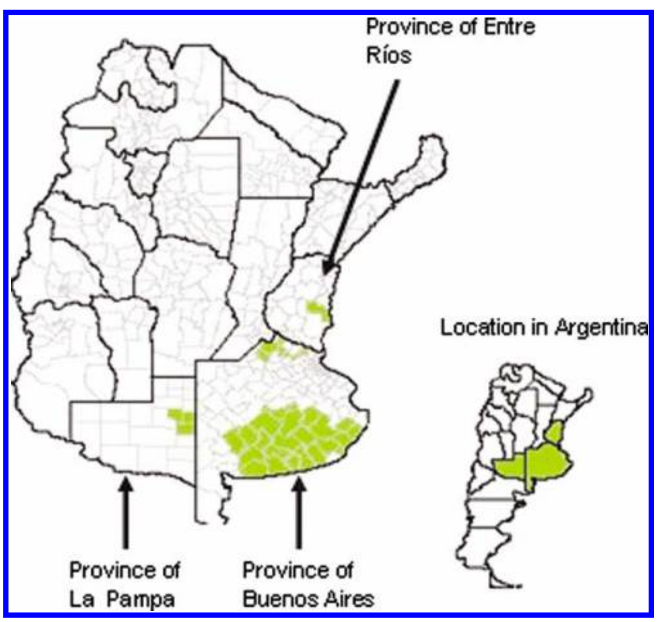

Fig. 1. Production regions for canaryseed in Argentina (SAGPyA 2008).

Yield Components

For grain weight, significant differences were found between the accessions in all four trials and in the combined analysis ($P < 0.0001$). The overall mean over the four trials was 7.1 mg, with a range of 5.9 mg (accession 43, Swedish population) to 8.5 mg (accession 60, Dutch cultivar Cantate). The local population (accession 73) gave a relatively low value of 6.7 mg, which was within the range observed by Bodega et al. (1995) for this accession of 6.3 to 7.3 mg. From a breeding point of view, it is noteworthy that accessions 60 (Cantate), 42 (the Moroccan population previously mentioned), 39 (a population also from Morocco) and 38 (Jordanian population) gave high grain weight in all four trials (results not shown).

For grain number per square meter, significant differences were found between the accessions in three of the four trials (FT1, FT3 and FT4) and in the combined analysis ($P < 0.0001$). The overall mean over the four trials was 19432 grains m^{-2}, with a range of 15 788 (accession 12, Turkish population) to 22 003 grains m^{-2} (accession 3, Mexican population). The local population 73 gave 19 769 grains m^{-2}, similar to the overall mean and below the range of values found by Bodega et al. (1995) for this accession (22 670 to 28 940). It is interesting to observe that the grain number of the Moroccan population, previously noted for its high yield and grain weight (accession 42), was relatively low (18 622 grains m^{-2}); thus this promising population appeared to achieve its high yield through large grains rather than through the more commonly observed high grain number.

For harvest index, which for canaryseed is relatively low compared with other cereal crops such as wheat (30 to 40%) and maize (43 to 50%) (Carcova et al.

Table 2. Trial means and combined mean for each canaryseed accession, for the characters grain yield, single grain weight, grain number, harvest index, plant height and the three phenological phases: emergence to heading (°D E-H), heading to harvest maturity (°D H-M) and emergence to harvest maturity (°D E-M)[z]

	Grain yield (kg ha^{-1})					Single grain weight (mg)					Grain number (grains m^{-2})					Harvest index				
A no.[z]	FT1	FT2	FT3	FT4	Com	FT1	FT2	FT3	FT4	Com	FT1	FT2	FT3	FT4	Com	FT1	FT2	FT3	FT4	Com
1	840	884	2276	1725	1431	6.5	6.8	7.0	6.6	6.7	12876	13039	32381	26260	21139	18	25	21	22	21
2	757	709	1561	2277	1326	6.9	7.0	6.5	7.1	6.9	10876	10121	23767	32140	19226	19	23	21	23	21
3	969	692	1934	2081	1419	6.3	6.6	6.3	6.6	6.4	15368	10470	30504	31672	22003	17	22	19	20	19
4	714	651	1670	2653	1422	7.0	7.7	7.0	7.4	7.3	10052	8541	23882	35765	19560	15	27	19	24	21
5	828	611	1915	2000	1338	7.1	6.9	7.2	7.2	7.1	11725	8868	26448	27842	18721	18	22	20	23	21
6	1074	697	1783	2002	1389	6.6	6.9	7.1	7.1	6.9	16198	10124	25197	28458	19994	15	24	21	23	21
7	1028	887	1971	1564	1363	7.1	6.7	7.0	6.8	6.9	14562	13222	28073	22850	19677	20	24	18	23	21
8	877	791	2044	1964	1419	6.8	7.0	6.9	6.8	6.9	12797	11229	29484	28860	20593	16	26	20	20	21
9	673	595	2246	1870	1346	6.5	7.0	7.4	7.0	7.0	10374	8506	30664	26642	19046	15	25	20	21	20
10	1065	763	2123	2017	1492	7.0	7.1	7.1	6.8	7.0	15100	10779	29895	29643	21354	18	28	21	22	22
11	808	816	2096	1795	1379	7.1	7.3	7.5	7.2	7.3	11443	11197	27970	24950	18890	17	24	21	22	21
12	582	665	1621	1680	1137	6.9	7.5	7.1	7.3	7.2	8482	8874	22626	23172	15788	17	27	18	21	21
13	1036	754	2520	1917	1557	7.2	7.1	7.5	7.3	7.3	14342	10607	33374	26396	21180	19	24	21	25	22
14	592	776	2135	1660	1291	6.4	6.9	7.0	6.8	6.8	9208	11296	30531	24288	18831	19	27	22	20	22
15	722	604	1880	1544	1187	6.8	7.2	6.9	7.0	7.0	10669	8447	27233	21990	17085	15	24	19	22	20
16	1020	909	2021	1629	1395	7.4	7.3	7.4	7.1	7.3	13928	12474	27127	22964	19123	15	29	23	19	21
17	768	672	2287	2026	1438	7.2	7.1	7.3	7.0	7.2	10701	9304	31146	28759	19978	18	24	23	20	21
18	1045	873	2456	1710	1521	7.2	7.2	7.3	6.9	7.2	14484	12115	33456	24619	21168	18	27	21	21	22
19	651	796	2368	1774	1397	6.8	6.8	6.9	6.6	6.8	9649	11641	34577	26885	20688	14	27	21	21	21
20	662	868	1642	2085	1314	7.4	7.6	6.8	7.4	7.3	8894	11342	23994	28270	18125	18	30	23	19	22
21	700	698	1753	1853	1251	7.0	6.9	7.2	7.2	7.0	10012	10106	24317	25649	17521	15	28	21	18	21
22	688	800	2226	1815	1383	6.8	7.3	7.3	7.0	7.1	10055	10927	30421	25930	19333	14	27	21	24	21
23	751	699	2045	1946	1360	7.0	7.0	7.3	7.0	7.1	10633	10035	27954	27752	19093	17	25	22	21	21
24	784	716	2041	1894	1359	6.9	7.0	7.2	7.0	7.0	11410	10103	28314	27043	19217	17	24	19	22	21
25	700	550	2084	1816	1287	7.0	7.0	7.3	6.8	7.0	9937	7849	28405	26669	18215	15	21	17	22	19
26	829	763	2013	1815	1355	7.2	7.1	7.1	6.9	7.1	11569	10744	28162	26146	19155	16	27	20	20	21
27	791	913	2165	1921	1447	7.1	7.3	7.3	6.9	7.1	11170	12468	29643	27837	20279	17	24	21	21	21
28	781	557	2156	1651	1286	7.1	7.1	6.8	7.1	7.0	10708	7895	31671	23425	18425	15	24	21	22	20
29	771	734	2164	1998	1417	6.8	7.4	7.1	7.0	7.1	11513	9954	30521	28373	20090	17	25	22	23	22
30	1017	718	2362	1763	1465	7.2	7.1	7.2	6.8	7.1	14171	10051	32867	25827	20729	16	22	18	18	19
31	786	821	2528	1836	1493	7.1	7.1	7.3	6.9	7.1	11032	11537	34388	26653	20903	16	21	20	21	20
32	1008	703	2438	1877	1506	7.2	7.0	7.5	6.9	7.2	14043	10018	32492	27181	20934	16	23	23	18	20
34	1034	734	2271	1596	1409	7.3	7.2	7.2	6.7	7.1	14198	10185	31390	23718	19873	15	24	23	22	21
36	949	806	2093	1808	1414	7.4	7.3	7.3	6.9	7.2	12943	11029	28853	26404	19807	19	24	20	21	21
37	752	584	2351	1918	1401	6.9	6.9	6.8	6.7	6.8	10944	8409	34831	28681	20716	16	21	20	20	19
38	776	767	1800	1906	1312	8.5	8.0	7.6	7.8	8.0	9143	9644	23691	24383	16715	17	21	20	20	20
39	672	737	2043	2034	1372	7.8	8.3	8.0	7.6	7.9	8533	8889	25456	26652	17382	17	25	20	21	21
40	977	622	2340	1401	1232	6.3	6.2	6.4	6.2	6.3	15507	10046	31045	22081	19670	18	24	21	23	21
41	939	689	2405	1892	1481	6.7	7.2	7.1	7.0	7.0	13803	9496	33602	27138	21010	19	24	23	21	22
42	806	660	2619	2033	1530	8.0	8.1	8.3	8.1	8.1	10091	8156	31104	25137	18622	17	24	22	22	22
43	594	553	2158	1382	1172	5.5	6.1	6.1	5.9	5.9	10807	9029	35532	23257	19656	15	18	21	20	19
44	701	732	2064	1550	1189	6.8	7.3	7.3	6.8	7.0	10243	10057	28321	22684	16872	17	26	21	20	21
45	904	902	1781	2052	1410	7.0	7.2	6.6	6.9	6.9	12902	12483	26818	29673	20469	18	17	22	23	20
46	861	611	1617	1429	1130	7.0	7.1	7.0	7.0	7.0	12242	8563	23239	20461	16126	17	22	19	20	20
48	891	846	2170	1514	1355	6.5	7.3	7.3	6.6	6.9	13895	11528	29573	22857	19463	13	23	22	24	21
49	819	835	2297	2044	1499	7.2	7.3	7.2	7.0	7.2	11444	11485	31739	29023	20923	18	27	23	21	22
50	772	908	2381	2073	1533	7.2	7.5	7.6	7.2	7.3	10767	12197	31443	28788	20799	19	28	21	23	22
51	762	631	2271	1724	1347	7.1	7.2	7.4	6.8	7.1	10734	8748	30897	25577	18989	15	25	22	21	21

Table 2 (*Continued*)

	Grain yield (kg ha^{-1})					Single grain weight (mg)					Grain number (grains m^{-2})					Harvest index				
A no.[z]	FT1	FT2	FT3	FT4	Com	FT1	FT2	FT3	FT4	Com	FT1	FT2	FT3	FT4	Com	FT1	FT2	FT3	FT4	Com
52	756	650	1804	1878	1272	6.9	7.5	7.0	7.2	7.1	11027	8644	25837	26048	17889	15	23	16	24	19
54	931	799	2398	1910	1300	7.3	7.2	7.3	7.0	7.2	12688	11111	33383	27099	21070	18	25	20	23	22
56	872	685	2150	1765	1368	6.6	7.0	6.9	6.7	6.8	13228	9833	31248	26466	20194	15	25	19	19	19
57	715	780	2607	1537	1410	6.7	7.0	7.0	6.6	6.9	10641	11095	37166	23270	20543	15	24	19	22	20
58	791	946	2021	1731	1372	7.0	7.4	7.2	6.9	7.1	11335	12804	28127	24880	19286	17	26	19	23	21
60	1085	672	2512	1796	1516	8.4	8.8	8.5	8.2	8.5	12838	7597	29639	21953	18007	18	24	21	21	21
62	568	621	2266	1284	1185	5.8	6.6	6.6	6.1	6.3	9721	9433	34390	21010	18638	12	20	18	23	18
63	762	738	2145	1767	1353	6.9	7.2	7.3	6.9	7.1	11113	10154	29228	25772	19067	16	27	24	20	21
73	965	737	1924	1670	1324	6.9	6.5	6.5	6.8	6.7	13986	10965	29573	24553	19769	17	24	20	21	20
LSD[y]	310	263	589	388	224	0.5	0.4	0.4	0.2	0.2	4138	3513	7467	5299	2685	4	7	4	5	2
Means	824	736	2123	1822	1369	7.0	7.2	7.1	7.0	7.1	11803	10271	29607	26114	19432	16	24	21	21	21
Max	1085	946	2619	2653	1557	8.5	8.8	8.5	8.2	8.5	16198	13222	37166	35765	22003	20	30	24	25	22
Min	568	550	1561	1284	1130	5.5	6.1	6.1	5.9	5.9	8482	7597	22626	20461	15788	12	17	16	18	18

	Plant height (cm)					°D E-H			°D P-M			°D E-M		
A no.[z]	FT1	FT2	FT3	FT4	Com	FT3	FT4	Com	FT3	FT4	Com	FT3	FT4	Com
1	91	80	122	110	88	1136	1041	1089	671	640	656	1807	1681	1744
2	79	68	108	104	90	1102	985	1043	570	639	605	1672	1624	1648
3	87	69	113	104	90	1088	998	1043	631	642	636	1719	1640	1679
4	82	70	108	104	91	1095	998	1047	577	634	605	1672	1632	1652
5	96	79	123	110	91	1173	1071	1122	657	610	633	1830	1681	1755
6	104	81	124	112	93	1194	1076	1135	673	605	639	1867	1681	1774
7	98	87	123	115	93	1160	1054	1107	693	627	660	1853	1681	1767
8	96	79	123	113	93	1198	1086	1142	706	601	653	1904	1687	1795
9	92	79	125	115	95	1194	1060	1127	673	622	647	1867	1681	1774
10	96	79	124	115	96	1159	1025	1092	654	663	658	1813	1687	1750
11	99	84	120	110	97	1159	1076	1118	638	605	621	1797	1681	1739
12	75	64	105	107	97	1042	958	1000	630	681	655	1672	1640	1656
13	97	82	127	111	97	1155	1070	1113	691	611	651	1846	1681	1764
14	77	75	118	110	97	1119	1010	1064	703	607	655	1821	1617	1719
15	94	75	111	109	98	1038	971	1004	707	115	411	1745	1627	1686
16	102	78	118	113	98	1186	1054	1120	689	621	655	1875	1675	1775
17	94	76	127	113	99	1146	1065	1106	683	616	650	1830	1681	1755
18	102	81	125	114	99	1191	1071	1131	661	610	635	1852	1681	1766
19	87	77	120	114	99	1201	1065	1133	666	616	641	1867	1681	1774
20	81	72	108	105	99	1119	992	1056	576	633	604	1695	1625	1660
21	95	76	114	109	99	1118	1037	1078	641	644	642	1759	1681	1720
22	95	83	125	114	99	1151	1054	1102	670	627	648	1820	1681	1751
23	92	83	124	112	99	1155	1060	1107	690	622	656	1845	1681	1763
24	95	75	120	114	99	1146	1054	1100	606	627	616	1752	1681	1717
25	96	76	122	108	99	1191	1081	1136	719	625	672	1910	1706	1808
26	90	74	119	112	99	1189	1071	1130	700	610	655	1889	1681	1785
27	89	76	119	105	100	1226	1111	1168	664	589	626	1890	1699	1795
28	91	72	123	112	100	1226	1116	1171	685	577	631	1911	1693	1802
29	89	72	120	107	100	1214	1106	1160	660	587	624	1875	1693	1784
30	97	78	125	108	100	1231	1117	1174	679	576	627	1910	1693	1802
31	90	74	125	107	100	1216	1117	1167	674	564	619	1890	1681	1785

Table 2 (*Continued*)

	Plant height (cm)					°D E-H			°D P-M			°D E-M		
A no.[z]	FT1	FT2	FT3	FT4	Com	FT3	FT4	Com	FT3	FT4	Com	FT3	FT4	Com
32	91	75	122	112	100	1205	1111	1158	712	583	647	1917	1693	1805
34	99	78	118	107	100	1201	1081	1141	696	606	651	1897	1687	1792
36	93	81	121	111	101	1169	1071	1120	728	610	669	1896	1681	1789
37	94	80	121	113	101	1159	1041	1100	687	640	663	1846	1681	1764
38	89	79	117	110	101	1153	1027	1090	573	648	611	1726	1675	1700
39	85	82	126	116	101	1182	1016	1099	675	601	638	1857	1617	1737
40	95	73	121	111	101	1205	1060	1132	648	622	635	1853	1681	1767
41	88	77	123	111	101	1135	1010	1073	670	671	671	1805	1681	1743
42	80	67	120	104	101	1178	1041	1110	693	640	667	1871	1681	1776
43	86	74	121	107	102	1258	1180	1219	659	519	589	1917	1699	1808
44	97	76	121	114	102	1195	1071	1121	631	610	618	1826	1681	1739
45	82	72	105	101	102	1164	991	1077	538	626	582	1702	1617	1659
46	93	69	119	109	102	1199	1016	1108	697	671	684	1897	1687	1792
48	96	80	120	110	102	1190	1087	1139	677	594	635	1867	1681	1774
49	85	73	115	109	102	1145	1050	1097	685	632	658	1830	1681	1755
50	91	74	120	112	103	1184	1060	1122	711	622	666	1895	1681	1788
51	97	75	120	111	103	1187	1070	1129	695	617	656	1882	1687	1784
52	88	75	125	113	103	1142	1037	1090	591	588	589	1733	1625	1679
54	89	75	120	110	103	1159	1023	1091	722	659	690	1882	1681	1781
56	92	81	121	114	103	1145	1046	1095	619	636	627	1764	1681	1723
57	90	76	121	113	103	1173	1046	1109	702	636	669	1875	1681	1778
58	88	78	121	112	104	1153	1027	1090	660	598	629	1813	1625	1719
60	85	69	115	102	104	1216	1086	1151	701	595	648	1917	1681	1799
62	88	74	129	103	105	1212	1093	1153	699	588	643	1911	1681	1796
63	89	77	121	109	105	1183	1070	1127	675	611	643	1858	1681	1770
73	95	77	115	109	106	1125	1029	1077	637	658	647	1761	1687	1724
LSD	8	7	8	6	4	26	19	16	58	23	31	60	14	31
Means	91	76	120	110	99	1148	1036	1111	655	599	627	1802	1644	1723
Max	104	87	129	116	106	1258	1180	1219	728	681	690	1917	1706	1808
Min	75	64	105	101	88	1038	958	1000	538	115	411	1672	1617	1648

[z]A no., accession number; FT1, field trial sown in 2004; FT2, field trial sown in 2005; FT3, field trial sown in 07/2006; and FT4, field trial sown in 08/2006. Com, combined analysis. °D, degree days.
LSD, Fisher's least significant difference ($P \leq 0.05$).

Table 3. Combined ANOVA for grain yield for the field trials sown in 2006 (FT3 and FT4[z])

Sources of variation	Sum of squares	df	Mean squares	F	*P* value	Error
Trial	7409194.45	1	7409194.45	4.57	0.0993	(Block within trial)
Accession	8004735.69	56	142941.71	1.53	0.0173	
Trial × Accession	12234231.15	56	218468.41	2.33	<0.0001	
Block within trial	6483018.27	4	1620754.57	17.29	<0.0001	
Error	20712469.73	221	9372.58			
Total	54843649.29	338				

[z]FT3, field trial sown in July 2006; FT4, field trail sown in August 2008.

2003), significant differences were detected between the accessions only for FT3 ($P = 0.0428$). In the combined analysis, the overall mean was 20.7% and the mean of the local population 73 was 20.5%, higher than the upper limit of the range observed by Bodega et al. (1995) of 8.8 to 18.8%. Nonetheless, a clear breeding aim for this crop would be to increase harvest index to a value approaching that in other cereals.

Plant Height

Significant differences were found for this character in all four trials and in the combined analysis ($P < 0.0001$). The overall range observed was 88 cm (accession 12, Turkish population) to 106 cm (accession 7, Turkish population), the overall mean was 99 cm and the mean of the local population was 99.1 cm. In spite of the significant genotype × interaction observed, it was possible to identify accessions that maintained low stature over the four trials (accessions 2, 3 and 4 from Mexico). Two of the accessions identified for their high grain weight (accession 60, cultivar Cantate, and accession 42, the promising Moroccan population) were also relatively low in stature. This observation for the high-yielding accession 42 is interesting since, in the context of lodging, it is a potentially useful exception to the generally observed positive correlation between height and yield (see below).

Phenology

In FT3 and FT4, sown in 2006, significant differences were found in both trials for the three phenological phases scored [emergence to heading (°D E-H), heading to harvest maturity (°D H-M) and emergence to harvest maturity (°D E-M)]. In the combined analysis for °D E-M (equivalent to the total cycle of the crop), significant differences between the accessions were found and the range observed was 1648 for accession 2 (Mexican population) to 1808°D for accession 43 (Swedish population), where the difference of 160°D between them was equivalent to 8 calendar days. Although significant genotype × environment interaction was observed, it was possible to identify a homogeneous group of five relatively short-cycled accessions [2 and 4 (Mexican populations), 12 and 20 (Turkish populations) and 45 (Portuguese population)]. The early maturation of accession 12 from Turkey was also observed by Norton and Ford (2002).

The mean duration of trials FT3 (sown 2006 Jun. 21) and FT4 (sown 2006 Aug. 24) was 144 and 110 d, respectively. The difference of 34 d was precisely the difference between sowing dates, i.e., in spite of the fact the trials were sown more than a month apart, they reached harvest maturity simultaneously.

The identification of early-maturing accessions is of interest since it potentially allows early sowing of the subsequent crop species. Besides the range of 8 d mentioned above, the local population 73 gave a cycle length close to the overall mean of the accessions, 4 d longer that the earliest population (accession 2). While these differences are not large, they may be of practical use in rotation management.

Correlations Between Characters

The correlation calculated between grain yield and grain number per square meter showed that there was a very strong positive association between them ($r = 0.99$, Fig. 2), in agreement with Bodega et al. (2002, 2003) for this species and Peltonen-Sainio et al. (2007) for wheat, barley, oats and rice. One of the few exceptions to this general relationship was, as mentioned above, the

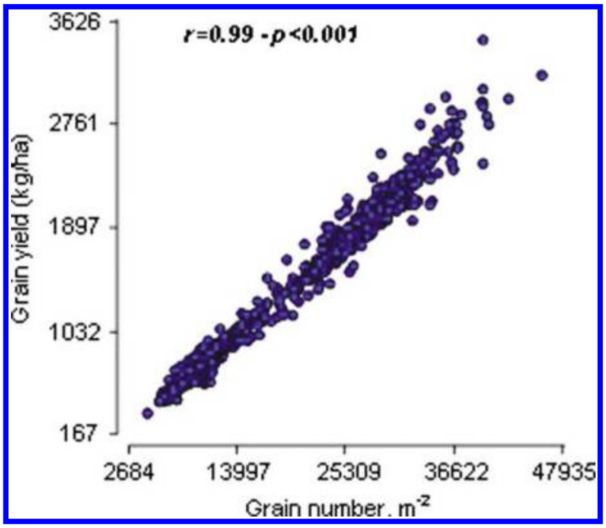

Fig. 2. Relationship between grain yield and grain number per square meter. Plot values.

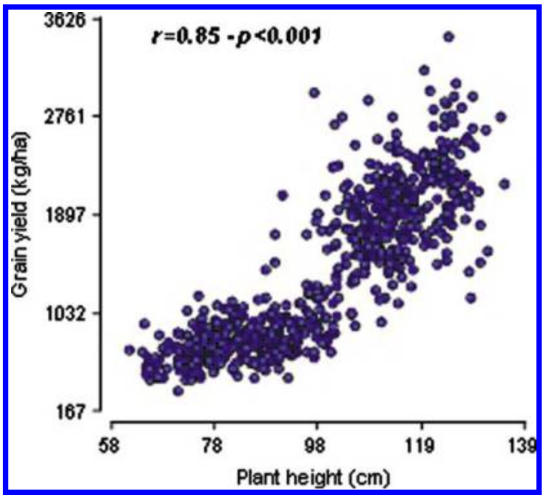

Fig. 3. Relationship between grain yield and plant height. Plot values.

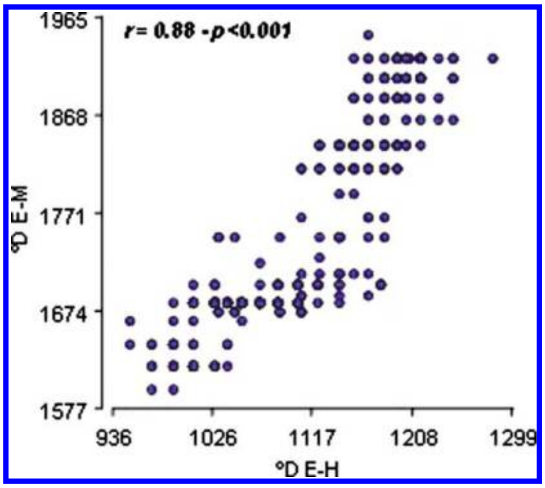

Fig. 4. Relationship between degree-days from emergence to heading (°D E-H) and emergence to harvest maturity (°D E-M). Plot values.

promising Moroccan population 42, the high yield of which was due to its high grain weight; this was also the case for the Dutch cultivar Cantate (accession 60).

The positive association observed between yield and plant height (Fig. 3) is in general undesirable due to the tendency for tall plants to lodge in this crop, in the same way that older cultivars of wheat and barley did prior to the introduction of dwarfing genes. Accessions 42 and 60 were exceptions to this general relationship, combining low stature with good yield.

Regarding phenology, the strong positive relationship between °D E-H and °D E-M (Fig. 4) demonstrated that the differences in the total cycle length was principally due to those in emergence to heading. On average, emergence to heading occupied 63% of the total life cycle, coinciding with the report of Bodega et al. (2003).

Principal Component Analysis

The first three principal components (PC1, PC2 and PC3) identified in an analysis that included all characters scored in trials FT3 and FT4 explained 72% of the total phenotypic variation (40.1, 18.6 and 12.5%, respectively). PC1 was positively associated with the degree-days to heading and maturity of the crop and grain number per head, and negatively associated with head number per square meter (Table 4). A group of six accessions (2, 3, 4, 15, 45 and 20) was separated from

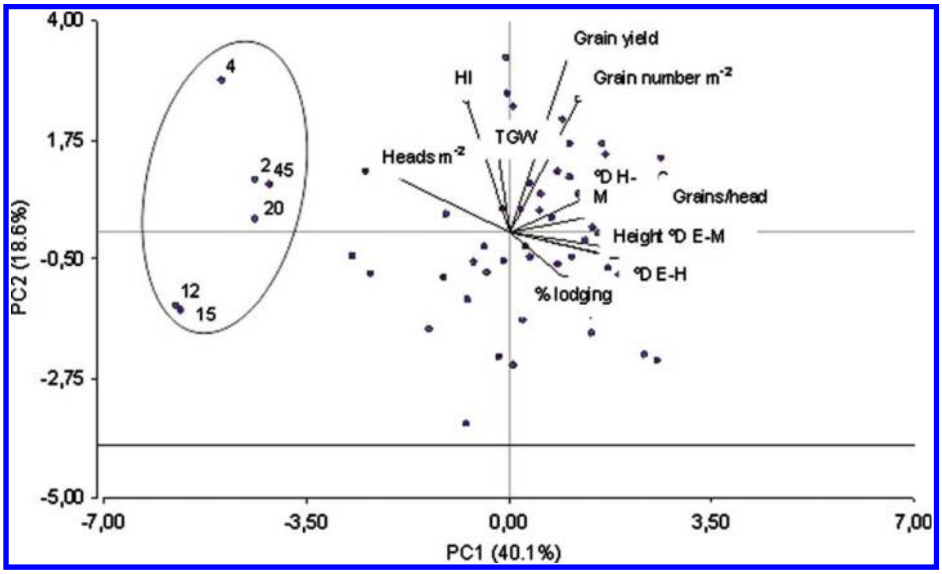

Fig. 5. Relationship between principal component 1 (PC1) and principal component 2 (PC2) in the principal component analysis including all traits. For explanation of circled accessions, see text.

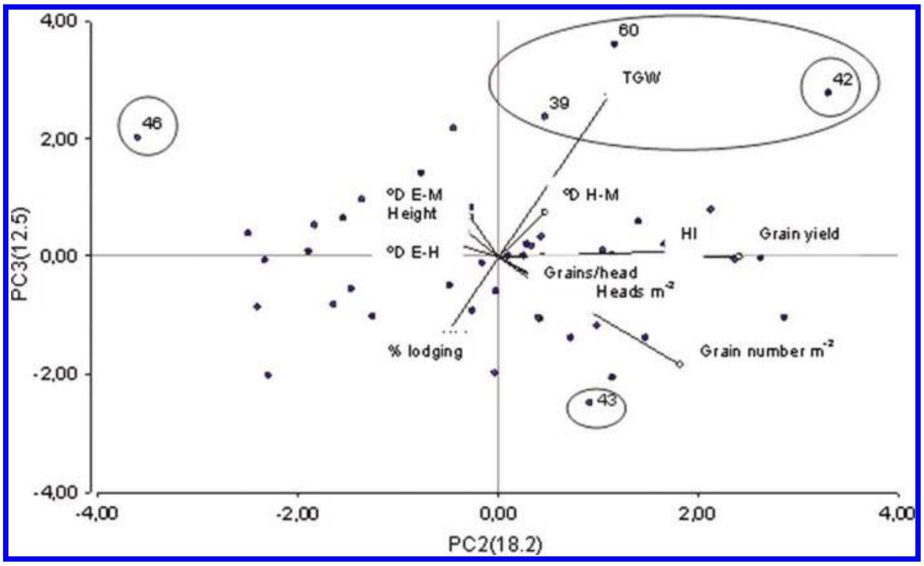

Fig. 6. Relationship between principal component 2 (PC2) and principal component 3 (PC3) in the principal component analysis including all traits. For explanation of circled accessions, see text.

the main group because they had low values for PC1 (Fig. 5); these were generally early-maturing accessions. PC2 was positively associated with grain yield, grain number per square meter and HI (Table 4). The Moroccan population 42, while not outstanding for grain number or HI, gave a high value for this component due to its high yield, whereas the Swiss population 46 gave a low value due to its low yield and grain number per square meter (Fig. 6). PC3 was positively associated with grain weight and negatively associated with grain number per square meter and percent lodging (Table 4). The Moroccan populations 39 and 42 and the Dutch cultivar 60 gave high values for this component due to their high grain weight and low percent lodging, whereas the Swedish population 43 gave a low value due to its poor grain weight (Fig. 6). The PCA did not in general separate the accessions according to their geographic origin.

In order to explore the relationship between grain yield and the remaining characteristics, an additional analysis was carried out in which all characteristics except grain yield were subjected to PCA and then grain yield was regressed onto these components (Table 5). Of all possible regression models, the best fitting was the one where grain yield was regressed onto PC1 and PC3 ($R^2 = 0.7$), although the regression onto PC3 alone

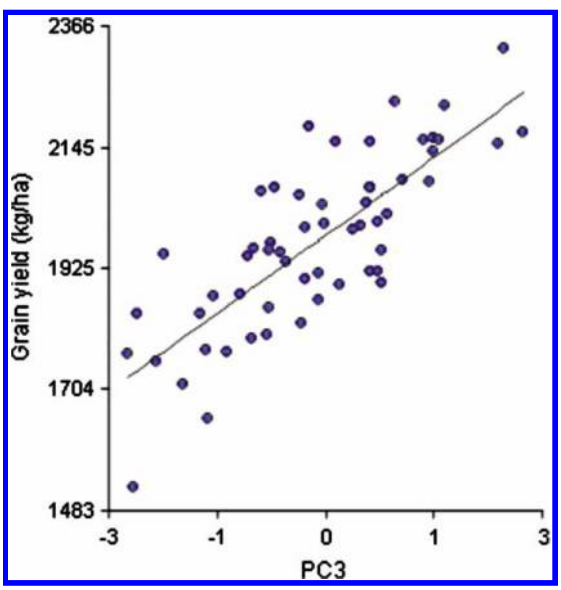

Fig. 7. Relationship between grain yield and principal component 3 (PC3) obtained in the principal component analysis without grain yield.

Table 4. Correlations between the traits evaluated in field trials sown in 2006 (FT3 and FT4[z]) and the first three principal components (PC) for the principal component analysis including all traits[z]

Traits	PC1	PC2	PC3
Grain yield	0.19	**0.61**	−4.90E–04
Grain weight	−0.04	0.28	**0.7**
Grain number m^{-2}	0.22	**0.46**	**−0.47**
Head number m^{-2}	**−0.4**	0.21	−0.19
Grain number/head	**0.43**	0.09	−0.11
Harvest index	−0.14	**0.46**	0.02
Plant height	0.33	−0.08	0.11
% lodging	0.18	−0.16	**−0.41**
Degree-days E-M[y]	**0.43**	−0.07	0.17
Degree-days E-H[y]	**0.4**	−0.1	0.05
Degree-days H-M[y]	0.24	0.12	0.19

[z]FT3, field trial sown in July 2006; FT4, field trial sown in August 2006.
[y]E-M, emergence to harvest maturity; E-H, emergence to heading; H-M, heading to harvest maturity.

Table 5. Correlations between the traits evaluated in 2006 (FT3 and FT4[z]) and the first three principal components (PC) for the principal component analysis excluding grain yield[z]

Traits	PC1	PC2	PC3
Grain weight	−0.12	0.82	0.28
Grain number m^{-2}	0.38	−0.54	0.66
Head number m^{-2}	−0.87	−0.22	0.15
Grain number /head	0.89	−0.13	0.25
Harvest index	−0.35	0.03	0.76
Plant height	0.71	0.13	−0.07
% lodging	0.39	−0.48	−0.26
Degree-days E-M[y]	0.92	0.20	0.02
Degree-days E-H[y]	0.86	0.06	−0.03
Degree-days H-M[y]	0.48	0.23	0.24

[z]FT3, field trial sown in July 2006; FT4, field trial sown in August 2006.
[y]E-M, emergence to harvest maturity; E-H, emergence to heading; H-M, heading to harvest maturity.

(strongly associated with HI and grain number m^{-2}) fitted almost as well ($R^2 = 0.62$, Fig. 7). This verified the important role that grain number per square meter in general plays in determining grain yield, as previously observed for all four trials (Fig. 7).

CONCLUSIONS

Useful genetic variation was found for all traits evaluated, and, although genotype × environment interaction was observed for all traits, differences between accessions were sufficient to allow promising breeding materials to be identified. Accessions superior in performance to the local Argentinean population, which in general gave values close to the overall mean of the accessions evaluated, were identified. For example, the Moroccan population 42 gave high yield associated with high values of the highly heritable character grain weight (Cogliatti 2009), rather than with the more commonly observed grain number per square meter. This population was also of relatively short stature and resistant to lodging, and, although it performed best when sown at the normal sowing date, it tolerated late sowing reasonably well. Other accessions were also observed with high grain weight, a useful characteristic in itself, since large grains are desirable from a quality point of view. Regarding phenology, the accessions showed a range of 160 degree days (8 calendar days in our conditions) in maturity, which, while not large in magnitude, may be of some utility in crop rotation management. Some accessions (for example, populations 2, 4 and 20) were well adapted to late sowing. Grain yield in general was strongly correlated with grain number per square meter. Principal component analysis provided indications of accessions combining useful characteristics, and identified three components that explained approximately 70% of the phenotypic variation. Furthermore, a second PCA plus regression showed that approximately 60% of the variation in grain yield could be explained by a component associated with harvest index and grain number per square meter.

Possible future breeding targets might be the introduction of the recessive allele responsible for glabrous seeds (Matus-Cádiz et al. 2003) to the high-yielding accessions identified in this study, especially to the Moroccan population 42 that achieved its good yield performance through elevated grain weight (highly heritable) rather than by high seed number. The glabrous character would potentially allow canaryseed grains to be used for human consumption (Matus-Cádiz et al., 2003).

In the longer term, it would be beneficial to direct effort towards breeding for lodging resistance through shorter stature and stronger stems, and towards increasing harvest index, which is low compared to others cereals (Carcova et al. 2003).

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