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Iron and zinc grain density in common wheat grown in Central Asia

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Abstract Sixty-six spring and winter common wheat genotypes from Central Asian breeding programs were evaluated for grain concentrations of iron (Fe) and zinc (Zn). Iron showed large variation among genotypes, ranging from 25 mg kg^{-1} to 56 mg kg^{-1} (mean 38 mg kg^{-1}). Similarly, Zn concentration varied among genotypes, ranging between 20 mg kg^{-1} and 39 mg kg^{-1} (mean 28 mg kg^{-1}). Spring wheat cultivars possessed higher Fe-grain concentrations than winter wheats. By contrast, winter wheats showed higher Zn-grain concentrations than spring genotypes. Within spring wheat, a strongly significant positive correlation was found between Fe and Zn. Grain protein content was also significantly ($P < 0.001$) correlated with grain Zn and Fe content. There were strong significantly negative correlations between Fe and plant height, and Fe and glutenin content. Similar correlation coefficients were found for Zn. In winter wheat, significant positive correlations were found between Fe and Zn, and between Zn and sulfur (S). Manganese (Mn) and phosphorus (P) were negatively correlated with both Fe and Zn. The additive main effects and multiplicative interactions (AMMI) analysis of genotype × environment interactions for grain Fe and Zn concentrations showed that genotype effects largely controlled Fe concentration, whereas Zn concentration was almost totally dependent on location effects. Spring wheat genotypes Lutescens 574, and Eritrospermum 78; and winter wheat genotypes Navruz, NA160/HEINEVII/BUC/3/F59.71//GHK, Tacika, DUCULA//VEE/MYNA, and JUP/4/CLLF/3/II14.53/ODIN//CI13431/WA00477, are promising materials for increasing Fe and Zn concentrations in the grain, as well as enhancing the concentration of promoters of Zn bioavailability, such as S-containing amino acids.

Keywords Breeding · Central Asia · G × E · Iron · Wheat · Zinc

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Introduction

The Central Asia region comprises five countries (Kazakhstan, Kyrgyzstan, Turkmenistan, Tajikistan and Uzbekistan) which grow a total of more than 15 million ha of wheat (*Triticum aestivum*). In northern Kazakhstan (48–55° N), spring wheat is grown on steppe lands under dry-land conditions. Throughout the southern region (36–44° N), occupying 5–6 million ha, winter or facultative wheat is grown primarily under irrigation (60–70%) (Fig. 1). Rainfed wheat is planted on the remaining 30–40% of the area, mostly on hillsides or mountainous areas where irrigation is not possible (Morgounov et al. 2001).

For both spring and winter wheat improvement, regional and international cooperation have been established with the objectives of strengthening national breeding programs by exchanging information and breeding materials. Since 1994 wheat research in the region was substantially influenced by the development of international linkages, especially in breeding. CIMMYT and ICARDA established germplasm exchange networks through the TURKEY-CIMMYT-ICARDA Winter and Facultative Wheat Improvement Program located in Turkey, and more recently through the Kazakhstan-Siberia Network on Spring Wheat Improvement (KASIB), a CIMMYT Central Asia and Caucasus initiative. By 2003 several wheat lines from both programs were being tested in the region for possible release. The advantages of the new lines are higher grain yield, and better resistance to leaf diseases, especially yellow rust. These efforts contribute significantly to improving food security and self-sufficiency of grain production in these countries. Uzbekistan achieved self-sufficiency in 2002 and 2003, whereas Tajikistan and Turkmenistan have improved national wheat production substantially during the past decade (Morgounov et al. 2005).

However, nutritional problems related to cereal-based diets throughout the region, especially those linked to vitamin and mineral deficiencies in vulnerable groups, such as children under five years and women in reproductive age, are national concerns. UNICEF and the Micronutrient Initiative (2004) estimated iron deficiency anemia ranging from 33% to 49% in children under 5 years of age and 31–63% in women aged 15–49 for countries in the Central Asian region. In Central Asia, as in large parts of the developing world, micronutrient deficiencies are widespread. It is estimated that two billion people worldwide suffer from micronutrient deficiencies, especially children and women (Cakmak et al. 2002; Welch and Graham 2004). High and

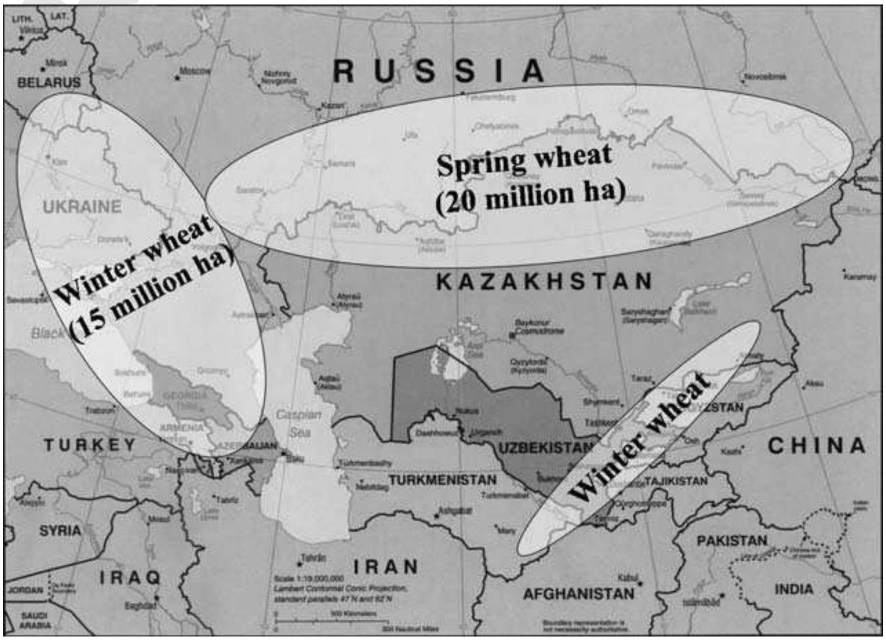

Fig. 1 Wheat-producing areas in the former Soviet Union. Winter wheat is grown during October–June and spring wheat during May–August

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monotonous consumption of cereal-based foods has been shown to be a major reason for such widespread occurrence of micronutrient deficiencies in the developing world. Cereal grains are inherently poor in concentration of micronutrients, and rich in compounds depressing the bioavailability of micronutrients such as phytic acid. In Central Asian countries, wheat is the most important staple food contributing greatly to daily calorie intake. Between 50% (Kazakhstan) and 65% (Tajikistan) of daily calorie intake comes solely from wheat and this rate can be greater than 75% in rural regions (Cakmak et al. 2004).

This situation has led to the formation of the "Anemia Prevention and Control" (APC) program in Kazakhstan, Kyrgyzstan, Uzbekistan, Tajikistan and Turkmenistan under the support of UNICEF, which among other activities fosters the universal fortification of wheat flour with minerals and vitamins (Gleason and Sharmanov 2002). However, fortification efforts are highly dependent on funding, and the scope is restricted to a single geographical area. Standard fortification programs must be sustained at the same level of funding year after year; and if the investments are not sustained, the benefits disappear (Bouis et al. 2000). By contrast, investment in research in plant breeding has multiplicative effects; the benefits may accrue to a number of countries and moreover, the benefits from breeding advances typically do not disappear after initial successful investment and research, as long as an effective domestic agricultural research infrastructure is maintained (Bouis et al. 2000).

Recently, the CGIAR launched the HarvestPlus initiative, a challenge program on biofortification of staple crops (breeding crops with high micronutrient contents). Under this initiative, CIMMYT is developing high yielding disease resistant wheat germplasm with enhanced levels of iron (Fe) and zinc (Zn), and this germplasm is now being tested by national program partners.

The objectives of the present study were to (i) determine the levels of Fe and Zn in the grain of current wheat lines and cultivars used in breeding programs in Central Asia, (ii) analyze the genotype × environment interactions (GE) and relationships with other traits, and (iii) identify promising lines with higher Fe and Zn concentrations in the grain.

Materials and methods

Sixty-six spring and winter wheat cultivars and advanced lines from Central Asian national breeding programs were selected for this study (Table 1). Grain samples from each germplasm included in a Kazakhstan-Siberia Network for Spring Wheat Improvement Regional Nursery (5th KASIB) grown at five locations in Kazakhstan in 2004 were analyzed for Fe and Zn concentration at Waite Analytical Services, University of Adelaide, Australia, based on the nitric/perchloric acid digestion method using an inductively coupled plasma optical emission spectrometer (ICP-OES) (Zarcinas et al. 1987). Grain from field trials, grown at nine locations in Kazakhstan, Kyrgyzstan and Tajikistan in 2005, were also analyzed for micro (Fe, Zn and Mn) and macro-elements (Mg, P, and S) at Sabanci University, Istanbul, Turkey. Measurements of the mineral nutrients were conducted using an ICP-OES after digesting samples in a closed microwave system (Zarcinas et al. 1987; USEPA 1998; Ryan 2005). Agronomic and grain quality data for spring wheat were available from "Results of the 4th and 5th Kazakhstan-Siberia Network Trials for Spring Wheat Improvement" (CIMMYT 2005). For winter wheat, data on grain yield additional to the mineral analyses were available only for Tajikistan.

Data were evaluated statistically using one-way analyses of variance; means were compared using a least significant difference (LSD) procedure. Associations among variables were evaluated using Pearson correlation and linear regression techniques. Genotype × environment was analyzed independently by trials and country using the additive main effects and multiplicative interactions analysis (AMMI). The AMMI model postulates additive components for the main effects of genotypes (αi) and environments (βj) and multiplicative components for the effect of

Table 1 Concentrations of Fe and Zn in seeds of spring and winter wheat genotypes

Genotype	Fe (mg kg^{-1})[b]	Zn (mg kg^{-1})	Test environments[a]
Spring wheat			
Chelyaba	56	32 (4)	A, B, C, D, E
Lutescense 148-97-16	48	32 (2)	A, B, C, D, E
Iren	48	32 (3)	A, B, C, D, E
Eritrospermum 78	48	29 (11)	A, B, C, D, E
Omskaya 35	47	29 (6)	A, B, C, D, E
Lutescense 574	47	29 (8)	A, B, C, D, E
For a	47	33 (1)	A, B, C, D, E
Eritrospermum 727	47	29 (12)	A, B, C, D, E
Novosibirsk 15	46	29 (7)	A, B, C, D, E
Altaiskaya 50	46	28 (30)	A, B, C, D, E
Tertsia	46	29 (10)	A, B, C, D, E
Lutescense 424	45	29 (9)	A, B, C, D, E
Shortandikskaya uluchshennaya	45	31 (5)	A, B, C, D, E
GVK 1857-9	45	26 (19)	A, B, C, D, E
Lutescense 13	43	27 (15)	A, B, C, D, E
Lutescense 29-94	43	24 (22)	A, B, C, D, E
Lutescense 53-95	43	25 (21)	A, B, C, D, E
GVK 1369-2	43	26 (18)	A, B, C, D, E
Atubenka	42	24 (24)	A, B, C, D, E
Glubokovskaya	41	27 (14)	A, B, C, D, E
Bayterek	41	25 (20)	A, B, C, D, E
Lutescense 54	40	26 (17)	A, B, C, D, E
Stepnaya	40	24 (23)	A, B, C, D, E
Aktobe 32	40	23 (25)	A, B, C, D, E
Astana	39	26 (16)	A, B, C, D, E
Spring wheat mean	45	28	
LSD (0.05)	5.6	12.72	
Winter wheat			
VORONA/HD2402	43	30 (16)	F, G, H
Navruz	42	39 (1)	F, G, H
Tacika	42	34 (6)	F, G, H
Alex	41	34 (7)	F, G, H
Naz	40	29 (19)	L, M
Ormon	39	32 (11)	F, G, H
DUCULA//VEE/MYNA	39	33 (9)	F, G, H
JUP/4/CLLF/3/II14.53/ODIN// CI13431/WA00477	39	32 (12)	F, G, H
Kauz	38	35 (4)	F, G, H
Norman	38	31 (13)	F, G, H
KINACI	38	28 (21)	F, G, H
NA160/HEINE VII/BUC/3/ F59.71//GHK	38	38 (2)	F, G, H
TX71A 1039.1VI*3	38	28 (22)	F, G, H
Chakbol	37	30 (15)	F, G, H
Krasnodar 99	37	36 (3)	F, G, H
Atilla[c]	36	34 (5)	F, G, H
1D13.1/MLT//TUI	36	33 (10)	F, G, H
SHARK/F4105W2.1	36	30 (18)	F, G, H
7C/CNO//CAE/3/YMH/4/VP...	36	27 (25)	F, G, H
MV 218-98	36	34 (8)	F, G, H
Eritrosp.750	35	25 (31)	L, M
BOCRO 4	34	30 (17)	F, G, H
CEBECO 148//CNO/TNIA//...	34	31 (14)	F, G, H
NORKAN/TJB406.892/MON	33	27 (24)	F, G, H
Almaly	33	25 (30)	L, M
Adyr	32	28 (23)	I, J, K
Kazakhstan 10	32	27 (26)	L, M
Zhetisu	32	25 (32)	L, M, N

Table 1 Continued

Genotype	Fe (mg kg^{-1})^{b}	Zn (mg kg^{-1})	Test environments^{a}
Akdan	31	29 (20)	L, N
Tilek	30	24 (36)	I, J, K
Asyl	29	23 (38)	I, J, K
Djamin	29	24 (34)	I, J, K
Nikonia	29	27 (28)	L, N
Intensivanaya	28	26 (29)	I, J, K
Kayrak	27	24 (35)	I, J, K
Kyial	27	23 (39)	I, J, K
Mironovskaya 35	27	25 (33)	L, N
Azibrosh	26	23 (37)	I, J, K
Zubkov	26	22 (40)	I, J, K
Mambo	26	27 (27)	L, N
Swindi	25	20 (41)	I, J, K
Winter wheat mean	34	29	
LSD (0.05)	7.54	7.89	
Grand mean	38	28	

Genotypes are listed in descending order for Fe. Numbers in parentheses indicate Zn ranking

[a] Spring wheat environments in Kazakhstan: A = Almaty 2004, B = Kartabalyk 2004, C = Pavlodar 2004, D = Astana 2004, and E = Aktobe 2004. Winter wheat environments in Tajikistan: F = Gissar 2005, G = Isfara 2005 and H = Vakhsh 2005. Winter wheat environments in Kyrgyzstan: I = Karasu-Osh 2005, J = Sokuluk-Chu 2005, and K = Bakay-Atip-Talas 2005. Winter wheat environments in Kazakhstan: L = Uzun-Agash 2005, M = Almalibak 2005, and N = Shymkent 2005

[b] Environment B (Karabalyk 2004) was not included in the Fe analysis for spring wheat

[c] Spring wheat genotype Atilla performed well under autumn-sowing conditions in Tajikistan, therefore it was included with winter wheat in our study

the interaction (ϕij). Thus, the mean response of genotype i in environment j is modeled by

$$\hat{Y} = \mu + \alpha i + \beta j + \sum_{k=1}^{m} \lambda k \gamma i k \delta j k + \rho i j + \varepsilon i j$$

where μ is the grand mean, αi is the main effect of the ith genotype, βj is the main effect of the jth environment, and ϕij is the interaction between genotype i and environment j; in which ϕij is represented by

$$\sum_{k=1}^{m} \lambda k \gamma i k \delta j k$$

where λk is the size, γik is the normalized genotype vector of the genotype scores or sensitivities, δjk is the normalized environmental vector of the scores describing environments, ρij are the AMMI residuals, and εij is the error term. All calculations were performed by IRRISTAT 4.3 software (International Rice Research Institute 2003).

Results and discussion

Wheat grain composition

Table 1 shows mean concentrations of Fe and Zn in mature grain from 66 genotypes. The amount of Fe in the grain showed a large variation among genotypes and ranged from 25 mg kg^{-1} to 56 mg kg^{-1} (mean 38 mg kg^{-1}). As with Fe, the concentration of Zn varied among genotypes and ranged from 20 mg kg^{-1} to 39 mg kg^{-1} (mean 28 mg kg^{-1}).

Comparing the 12 spring and 12 winter wheat genotypes with the highest iron and zinc concentrations, it was clear that spring wheat genotypes possessed higher grain Fe concentrations. By contrast, grain Zn concentrations were higher in winter wheat than spring wheat. Comparing the top 12 Fe genotypes with the best 12 Zn genotypes for winter wheat, there were six genotypes in common (Navruz, Tacika, Alex, Ormon, NA160/HEINE VII/BUC/3/ F59.71//GHK and JUP/4/CLLF/3/II14.53/ODIN//CI13431/WA00477). For spring wheat, 11 genotypes were among the top 12 for high Fe and high Zn concentrations. Table 2 and Fig. 2A show that the concentration of Fe and Zn in the grain of spring wheat cultivars were strongly and positively correlated [Fe = (17.2011) + (0.9917) Zn, $R^2 = 0.6335$; $P = < 0.001$]. A strong correlation between grain Zn and Fe concentrations occurred in germplasm containing both wild wheat (Cakmak et al. 2004) and cultivated wheats (Peterson et al. 1986). In winter wheat this association was equally strong [Table 3 and Fig. 2B; Fe = (8.5300) + (0.8855) Zn, $R^2 = 0.6270$; $P < 0.001$]. The relationship between Fe and Zn was not so strong for the combined spring and winter wheat data [Fig. 2C; Fe = (16.8126) + (0.7452) Zn, $R^2 = 0.1856$; $P < 0.001$]. Considering independently spring and winter wheat, our findings support other findings, that it is possible to combine high-iron and high-zinc traits during breeding (Monasterio and Graham 2000; Cakmak et al. 2004).

Table 2 shows the Pearson correlations between Fe, Zn and other nine agronomic and grain quality traits for spring wheat. A strong positive significant correlation was found between Fe and grain protein content ($r = 0.65$). Strong negative significant correlations occurred between Fe and plant height ($r = -0.6$), and Fe and glutenin content ($r = -0.48$), indicating that shorter plants with lower glutenin content favor higher grain-Fe concentration. Weak but significant negative correlations between Fe and grain yield ($r = -0.41$), and Fe and grain number per m^2 ($r = -0.38$), confirmed that modern cultivars with high grain yield and grain yield component traits tend to have lower concentrations of micronutrients in the grain. Similar correlation coefficients were found between Zn and other traits (Table 2), but the negative correlations between Zn and yield ($r = -0.64$), and Zn and grain number per m^2 ($r = -0.55$) were stronger than those observed for Fe. Another slight difference was the positive significant correlation between Zn and gliadin content ($r = 0.44$). For Zn, the strongest correlation was with protein ($r = 0.68$***). A very strong correlation between grain Zn and grain protein was also shown previously (Peterson et al. 1986; Feil and Fossati 1995), indicating that grain protein may be a sink for Zn. In agreement with these results, Distelfeld et al. (2006) recently showed that a locus (e.g., *Gpc-B1* affecting grain protein concentration) on the short arm of chromosome 6B in wheat was also effective in increasing accumulation of Zn and Fe in grain. In wheat seed, Zn is predominantly localized in the embryo and aleurone layer (up to 150 mg per kg seed) whereas endosperm contains much less (around 15 mg Zn per kg seed) (Ozturk et al. 2006). The embryo and aleurone are rich in protein, supporting the suggestion that high protein in seed represents an important sink for Zn. This association

Table 2 Pearson correlation coefficients among grain iron content (Fe), grain zinc content (Zn), grain yield, grain protein content, glutenin content, gliadin content, days to heading, plant height, thousand-grain weight (1000-K), grain number per m^2 (KNO), and test weight of 25 spring wheat genotypes grown across locations in Kazakhstan in 2004

	Zn	Yield	Grain protein	Glutenin	Gliadin	Days to heading	Height	1000-K	KNO	Test weight
Fe	0.79***	–0.41*	0.65***	–0.48**	0.34	0.05	–0.60***	0.05	–0.38*	–0.26
Zn		–0.64***	0.68***	–0.51**	0.44*	–0.13	–0.62***	0.03	–0.55**	–0.37
Yield			–0.46*	0.32	–0.18	0.53**	0.73***	–0.04	0.87***	0.65***
Grain Protein				–0.85***	0.29	–0.11	–0.61***	–0.35	–0.22	–0.50**
Glutenin					–0.20	–0.03	0.51**	0.45*	0.04	0.51**
Gliadin						0.02	–0.06	0.03	–0.17	–0.10
Days to Heading							0.57**	0.18	0.37	0.57**
Height								0.10	0.57**	0.72***
1000-K									–0.52**	0.15
KNO										0.46*

*Significant at $P = 0.05$; **significant at $P = 0.01$; ***significant at $P = 0.001$

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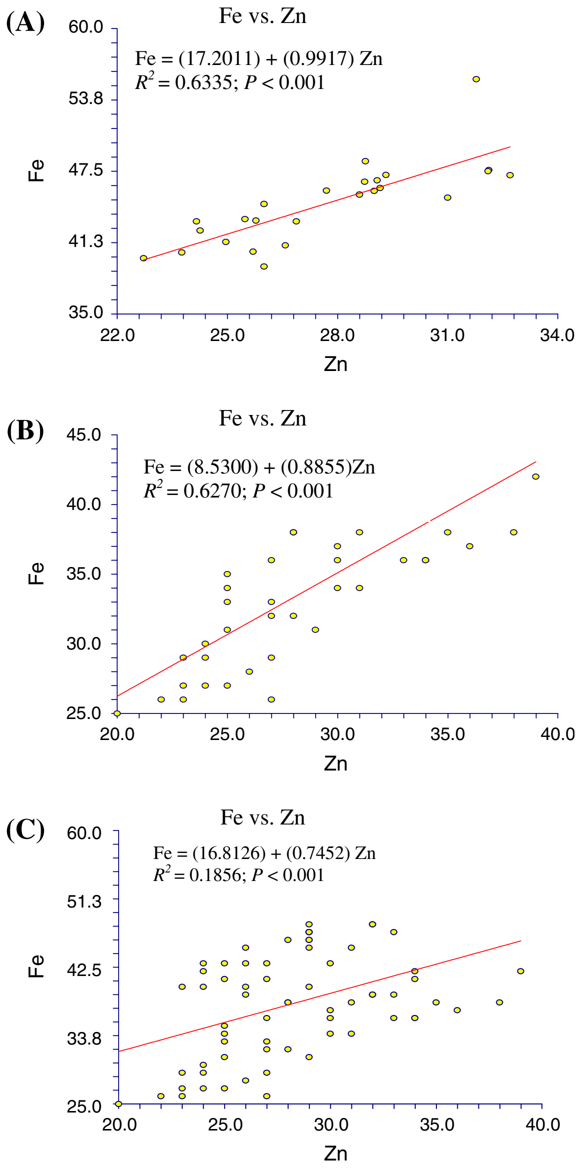

Fig. 2 Linear regressions: (**a**) Fe vs. Zn for 25 spring genotypes, (**b**) Fe vs. Zn for 42 winter wheat genotypes, and (**c**) Fe vs. Zn for the combined spring–winter wheat genotypes

Table 3 Pearson correlation coefficients among grain iron content (Fe), grain zinc content (Zn), grain manganese content (Mn), grain magnesium content (Mg), grain phosphorous content (P), and grain sulfur content of 42 winter wheat genotypes across locations in central Asia in 2005

	Zn	Mn	Mg	P	S
Fe	0.79***	–0.46***	0.29*	–0.18	0.67***
Zn		–0.46***	0.16	–0.11	0.71***
Mn			0.31*	0.59***	0.05
Mg				0.50***	0.47***
P					0.04

*Significant at $P = 0.05$; **significant at $P = 0.01$; ***significant at $P = 0.001$

between Zn and protein should be considered in breeding programs aimed at improving cereal grains for Zn and Fe contents.

For winter wheat, only data on micro and macro-nutrient concentrations in grain were available for all trials. Significant positive correlation coefficients were found between Fe and Zn, S, and Mg; between Zn and S; and between Mn, Mg and P. An important point was the negative correlation between P and both Fe and Zn ($r = –0.18$ and $r = –0.11$, respectively (Table 3, Fig. 3C). The contents of P in winter wheat analyzed ranged from 2627 mg kg^{-1} to 3694 mg kg^{-1} (mean 3177 mg kg^{-1}). Approximately 75% of total P in wheat grain is stored as phytic acid, particularly in the germ and aleurone layers (Lott and Spitzer 1980; Raboy 2000). At physiological pH, phytic acid is a polyanion, with each molecule containing six to eight negative charges distributed among six phosphate esters. This relatively small molecule with a high charge density is a strong chelator of positively charged mineral cations such as calcium, iron and zinc (Raboy 2000). In terms of human health and nutrition, dietary phytate can have both negative and positive outcomes. It can contribute to mineral depletion and deficiency in populations that rely on whole grains and legume-based products as staple foods; however, phytic acid can also function as an antioxidant and anticancer agent and may have other beneficial effects on health (Cakmak et al. 2002; Welch and Graham 2004).

Welch and Graham (2004) highlighted the importance of promoters, mostly organic acids and S-containing amino acids, for the bioavailability of Zn. Biologically, increasing the content of promoters which serve as catalysts, is an attractive option to increase Zn bioavailability, because marginal increases are likely to have large effects. Minor changes in the promoter content are unlikely to have negative effects on the food quality. This is in contrast to selecting for a lower anti-nutrient content, which may have negative effects on food quality due to potential anti-carcinogenic and anti-mutant functions.

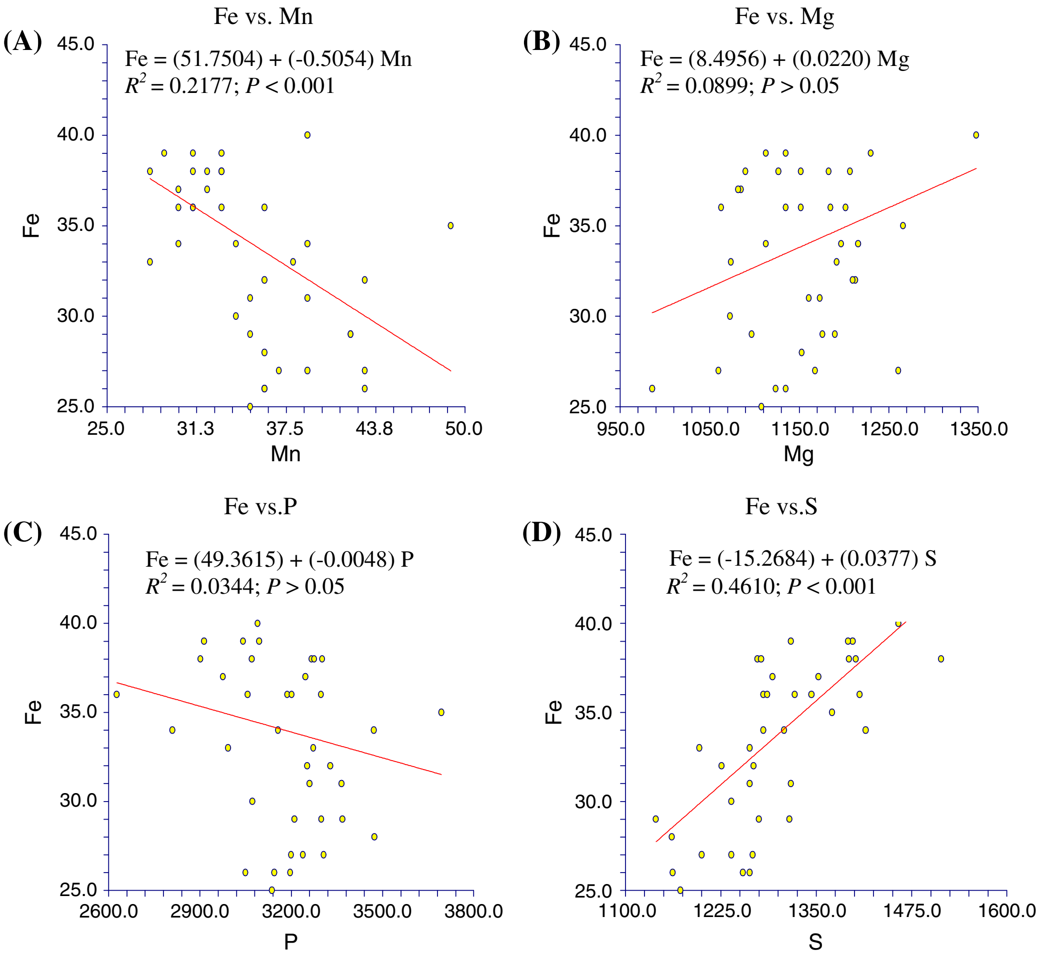

Fig. 3 Linear regressions of 42 winter wheat genotypes: (**a**) Fe vs. Mn, (**b**) Fe vs. Mg, (**c**) Fe vs. P, and (**d**) Fe vs. S

In this study, Fe-grain and S-grain, and Zn-grain and S-grain, were positively and significantly correlated, suggesting a possible positive correlation between high grain micronutrients and high S-containing amino acid concentrations in grain. From the best 12 genotypes with S-grain content ranging from 1140 mg kg^{-1} to 1558 mg kg^{-1}, seven were among the best 12 Fe-grain genotypes (Navruz, Naz, DUCULA//VEE/MYNA, NA160/HEINEVII/BUC/3/F59.71//GHK, Norman, JUP/4/CLLF/3/II14.53/ODIN//CI13431/WA00477, and Tacika), and nine were within the top 12 Zn-grain genotypes (Navruz, NA160/HEINEVII/BUC/3/F59.71//GHK, Kauz, DUCULA//VEE/MYNA, JUP/4/CLLF/3/II14.53/ODIN// CI13431/WA00477, Atilla, Krasnodar 99, MV 218-98 and Tacika). Five genotypes with high S-grain concentration were among both high Fe-grain and high Zn-grain groups. Thus, the development of new winter wheat genotypes with higher grain Fe and grain Zn concentrations and promoters that affect both Fe and Zn bioavailability appears feasible.

Genotype × environment interactions

The AMMI analysis of variance of Fe and Zn grain concentrations (mg kg^{-1}) carried out independently for each trial and presented in Tables 4 and 5, show the relative magnitudes of the genotype (G), location (L), and genotype × location (GL) variance terms. Generally, the expressions of Fe and Zn levels were controlled to a large extent by location (especially true for Zn). However, for Fe in spring wheat, and in winter wheat in Kazakhstan (trial 1), genotype (G) was

Table 4 Additive main effects analysis of variance from the AMMI model for grain iron density (mg kg^{-1}) of the genotypes for independent trials

Source	df	SS	MS	Explained (%)
Spring wheat, Kazakhstan				
Genotypes	24	1213.09	50.55	50.53
Locations	3	758.53	252.84	31.59
Genotypes × location	72	428.91	5.96	17.86
Total	99	2400.53		
Winter wheat, Tajikistan				
Genotypes	21	405.98	19.33	22.72
Locations	2	752.38	376.19	42.11
Genotypes × location	42	628.21	14.95	35.16
Total	65	1786.58		
Winter wheat, Kyrgyzstan				
Genotypes	9	124.43	13.82	22.23
Locations	2	283.08	141.54	50.58
Genotypes × location	18	152.11	8.45	27.18
Total	29	559.62		
Winter wheat, Kazakhstan				
Genotypes[a]	4	83.26	20.81	51.31
Locations	1	16.03	16.03	9.88
Genotypes × location	4	62.96	15.74	38.80
Total	9	162.27		
Genotypes[b]	4	34.73	8.68	22.83
Locations	1	43.37	43.37	28.51
Genotypes × location	4	73.98	18.49	48.64
Total	9	152.10		

[a] Trial 1: locations Uzun-Agash and Almalibak; and genotypes Almaly, Naz, Kazakhstan 10, Eritrosp.750, and Zhetisu

[b] Trial 2: locations Uzun-Agash and Shymkent; and genotypes Zhetisu, Akdan, Mambo, Nikonia, and Mironovskaya 35

the most important source of grain Fe concentration accounting for over 50% of the G + L + GL. For all trials, the grain Fe- genotype effect was never less than 22% indicating that genotype was an important contributor to overall variability.

In contrary to Fe, in the AMMI analysis of variance of grain Zn concentrations, genotype (G) was the most important source of variation only in Tajikistan, accounting for 35.13% of the G + L + GL. For the other trials (with the exception of Kyrgyzstan where G accounted for about 32%) the genotypic effect was minor, explaining 4–9% of the G + L + GL variation. The genotype × location effect (GL) was important for both Fe and Zn. For Fe, GL ranged from 17.6% to 48.64% across the trials, and for Zn, from about 7.3% to 48.77%. This implies that for both Fe and Zn, the rankings of winter wheat genotypes in Tajikistan and Kazakhstan were influenced by location.

Conclusions

There were strong positive correlations between the Fe and Zn grain concentrations for both spring and winter materials. For spring wheat, positive correlations between grain Fe and grain Zn concentrations and grain protein content indicated that breeding and selection for one of these traits could simultaneously improve the others. Negative correlations between the micronutrient concentrations, plant height and grain yield does not necessarily imply that a strategy for reducing plant height could produce gains in grain yield and grain element concentrations. The observed negative correlations between grain element concentrations, plant height and grain yield might be at least partially explained in that shorter and lower yielding genotypes have a lower dilution effect of minerals in the grain, and thus express higher grain Fe and Zn concentrations.

Table 5 Additive main effects analysis of variance from the AMMI model for grain zinc density (mg kg^{-1}) of the genotypes for independent trials

Source	df	SS	MS	Explained (%)
Spring wheat, Kazakhstan				
Genotypes	24	976.58	40.69	8.67
Locations	4	9443.27	2360.82	83.88
Genotypes × location	96	836.96	8.72	7.43
Total	124	11256.80		
Winter wheat, Tajikistan				
Genotypes	21	703.49	33.49	35.13
Locations	2	636.51	318.25	31.79
Genotypes × location	42	662.51	15.77	33.08
Total	65	2002.52		
Winter wheat, Kyrgyzstan				
Genotypes	9	125.40	13.93	32.59
Locations	2	162.50	81.25	42.24
Genotypes × location	18	96.80	5.38	25.16
Total	29	384.69		
Winter wheat, Kazakhstan				
Genotypes[a]	4	25.80	6.45	8.58
Locations	1	128.28	128.28	42.65
Genotypes xlocation	4	146.69	36.67	48.77
Total	9	300.77		
Genotypes[b]	4	15.88	3.97	4.68
Locations	1	209.56	209.56	61.73
Genotypes × location	4	114.01	28.50	33.59
Total	9	339.46		

[a] Trial 1: locations Uzun-Agash and Almalibak; and genotypes Almaly, Naz, Kazakhstan 10, Eritrosp.750, and Zhetisu

[b] Trial 2: locations Uzun-Agash and Shymkent; and genotypes Zhetisu, Akdan, Mambo, Nikonia, and Mironovskaya 35

However, some genotypes with optimum plant height and above average Fe and Zn (Lutescens 574 and Eritrospermum 78) were found.

In the winter wheats, the strong positive correlations among grain Fe, grain Zn and grain S together with high concentrations of each (Navruz, NA160/HEINEVII/BUC/3/F59.71//GHK, Tacika, DUCULA//VEE/MYNA, and JUP/4/CLLF/3/II14.53/ODIN//CI13431/WA00477) should be important for the development of new breeding populations targeting the enhancement of Fe and Zn bioavailability by increasing the concentration of promoters such as S-containing amino acids (i.e., methionine, histidine, and lysine).

Breeding for increased grain yield may simultaneously increase grain element concentration and could take three approaches: (i) to identify lines with improved ability to allocate mineral nutrients into the grain without changes in root uptake of nutrients, (ii) to select lines with greater ability for root uptake of mineral nutrients, whilst maintaining current high efficiencies of partitioning to the grain, and (iii) to identify lines that have both features (Calderini and Ortiz-Monasterio 2003). Regarding genotype × environment interactions grain Fe concentration was to an important extent, controlled by genotype effects, whereas grain Zn concentration was almost totally dependent on location. Thus, genotypes having a greater genetic ability for root uptake of Fe and Zn (CIMMYT 2005) could be important sources of germplasm for increasing micronutrient concentration in Central Asian wheats.

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