Stability of Quality Traits in Winter Wheat Cultivars

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Abstract

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We investigated the stability of 15 traits of quality in 45 winter wheat cultivars grown in two seasons in the Borovce locality of Slovakia. The gluten swelling, SDS test, starch content, α-amylase (α-AMS) activity, and volume weight were affected simultaneously by the cultivar, growing year, and the country of origin. Other traits were affected by only one or two of these factors. The English cultivars, when compared to the Slovak cultivars, demonstrated lower gluten swelling and volume weight, a higher α-AMS activity, and a longer vegetative period. We observed a higher α-AMS activity in the Czech, a lower starch content in the Austrian, and a longer vegetative period in the German cultivars. In the Hungarian cultivars, we detected a lower starch and a reduced amylose contents. The most stable quality traits in both growing years were identified in the Ilona (gluten swelling), Spartakus (SDS test), Cubus (falling number), Komfort (starch), GK Margit (amylose), GK Verecke (α-AMS), Saturnus (volume weight), and Vanda (thousand-kernel weight) cultivars. Other traits, such as protein, wet gluten, sedimentation index, grain hardness, grain weight per spike, grain yield, and duration of the vegetative period, were strongly affected by the environment (growing year). The foreign cultivars such as the Komfort (AUT), Saturnus (AUT), GK Rába (HUN), GK Csongrád (HUN), Silvius (AUT), GK Bagoly (HUN), and GK Forrás (HUN) were superior for growing in Slovakia. Each of them had more quality traits that were stable, comparable, and ultimately better than the control Slovak cultivars.

Keywords: foreign wheat cultivars; stability of bread quality; environment; traits; growing year; country of origin

Wheat is one of the world's most important crops. The climate conditions in Slovakia traditionally favour the cultivation of wheat with good yields for both food and non-food uses. Annual production reaches 1.4 million tons. Since the integration into the European Union, all cultivars registered in the European Common Catalogue of Vegetable Varieties can now be grown in Slovakia. Foreign wheat cultivars are not necessarily adaptable to the climate conditions in Slovakia. Consequently, their quality may be inferior to the time-proven Slovak cultivars.

The main chemical compounds of wheat grain that determine the quality and grain yield are protein (9–19%) and starch (60–73%). Both the contents and compositions of these high-molecular compounds determine the physico-chemical properties of flour (Graybosch 1996; Branlard *et al.* 2001; Lee *et al.* 2001; Tester & Karkalas 2001; Jing *et al.* 2003; Nowotna *et al.* 2003). The

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baking quality is determined by the character of the protein-starch complex and by the activities of amylolytic and proteolytic enzymes.

Gluten content and composition are the main determinants of the rheological and bread-making properties of wheat flour (Branlard *et al.* 2001); starch is important for the dough structure (Nowotna *et al.* 2003). The amylose/amylopectin ratio plays an important role in wheat quality as it markedly affects the properties of starch (Graybosch 1996; Lee *et al.* 2001; Tester & Karkalas 2001; Sasaki *et al.* 2007). The grain hardness, another important trait that influences the wheat quality, is presumably determined by the degree of adhesion between the starch granules and protein matrix (Morris 2002). The grain hardness affects a range of characteristics including the milling (tempering, milling yield, flour particle size, shape and density of flour particles), baking, and end-use properties (Morris 2002).

Wheat end-use depends upon the cultivar, environment, and their interaction. The wheat flour quality and grain yield are strongly controlled by genetic factors but the environmental conditions during grain filling considerably affect their expression (Peterson *et al.* 1998; Budak *et al.* 2003; Groos *et al.* 2003; Jing *et al.* 2003; Kim *et al.* 2003; Souza *et al.* 2004). The environmental variables (temperature, water availability, light intensity, and fertiliser) influence the rate and duration of wheat grain development and composition (Altenbach *et al.* 2002, 2003; Ozturk & Aydin 2004). Prior to anthesis, the environment affects the germination, photosynthesis, tiller and sprout formation as well as inflorescence development, thereby influencing the grain number. Following anthesis, the environment primarily affects the kernel size and composition (Dupont & Altenbach 2003). The most important period in determining the wheat quality extends from flowering until grain maturity (from April-May to July in Slovakia). After wheat deflowering, nitrogen assimilation from the soil is almost ended. The proteins formed are then transferred to the grain. Starch synthesis and starch accumulation in the grain continues as long as the leaves are green (Dupont & Altenbach 2003).

Field studies indicate that the environmental variables, particularly fertiliser and temperature, affect the content, composition, and/or polymerisation of gluten proteins (Graybosch *et al.* 1995; Luo *et al.* 2000; Smith & Gooding 2008). High temperatures increase the ratio of gliadins to glutenins (Corbellini *et al.* 1997).

High temperatures during grain filling decrease starch synthesis and starch deposit in grain, reduce the final wheat grain weight and diminish the yield (Gibson & Paulsen 1999; Hurkman *et al.* 2003). High temperatures reduce the soluble starch synthase activity (Keeling *et al.* 1993), an effect that is apparently reversible upon short-term exposure to high temperatures. Similarly, ADP-glucose pyrophosphorylase activity is also affected by temperature, which appears to limit the enzymes of starch synthesis (Smidansky *et al.* 2002; Altenbach *et al.* 2003). Apart from temperature, annual rainfall is also very important for starch accumulation (Kim *et al.* 2003).

The aim of the study was to evaluate the stability of fifteen quality traits of foreign winter wheat cultivars grown in two seasons in the Borovce area. Additional aims included examining the correlation between the traits; assessing the importance of the growing year, cultivar, and country of origin; and, in particular, identifying the most adaptable superior wheat cultivars for growing in Slovakia.

MATERIALS AND METHODS

Seed samples. Forty-five bread winter wheat (*Triticum aestivum* L.) cultivars from seven countries – Austria (4 cultivars), the Czech Republic (2), Germany (9), Great Britain (5), Hungary (12), Poland (3), and the Slovak Republic (10) – were evaluated. Registered cultivars of good bread-making quality from member countries of the European Union were obtained from the Slovak Republic Gene Bank located in Piešťany. Some were simultaneously evaluated by other research workers within the National Programme of Conservation of Plant Genetic Resources for Food and Agriculture in the Slovak Republic.

Slovak cultivars Ilona and Armelis were selected as standards. Ilona proved to be the best from the early wheat cultivars. Because of its bread-making quality, it ranks among the top-level cultivars. The Armelis cultivar is known to have a high content of wet gluten, high volume and thousand-kernel weight, and a high grain hardness. According to the criteria of the Central Controlling and Testing Institute in Agriculture (ÚKSÚP, Slovak Republic), both wheat cultivars are recognised as level 7 (good bread-making quality).

Climate conditions*.* Wheat cultivars were grown during two seasons (2003–2004 and 2004–2005) in the Borovce locality near Piešťany, an area suitable for the bread wheat production. The soil and climate conditions in Borovce are as follows: soil type – loamy luvic chernozem; average annual air temperature 9.2°C (15.5°C during the growing season); average annual precipitation 595 mm (358 mm during the growing season); altitude 167 m; transitive maize-sugar beet growing region. Monthly climatic characteristics for both growing years as well as 30-year normal values are presented in Table 1.

Laboratory methods*.* The traits of technological quality were determined in flour according to the methods published in the Slovak Technical Norm (STN). The volume weight was determined by gravimetric method (STN 46 1011-5), wet gluten content using 2% sodium chloride (STN 46 1011-9) and SDS test using sodium dodecyl sulphate according to Axford (STN 46 1021). The sedimentation index was determined according to Zeleny (STN ISO 5529). The method is based on suspending the test flour in lactic acid solution in the presence of bromophenol blue. After specified shaking and resting periods, the volume of the deposit is determined. Gluten swelling was measured in slightly acid medium (STN 46 1011-9). The method for falling number evaluation consists in rapid gelatinisation of the suspension of flour milled product in water in a boiling water bath, and subsequent measurement of the liquefaction by alpha-amylase of the starch contained in the sample (STN ISO 3093). Grain protein content was determined by the Dumas method (N concentration × 5.7), and grain hardness using near infrared reflectance spectrometry (NIRS). Starch content was estimated by the polarimetric method according to Ewers (ISO 10520:1997). The amylose ratio was measured using the Amylose/Amylopectin Assay Kit (Megazyme, Ireland). Enzyme activity was ascertained by the Alpha-Amylase Assay Procedure (Megazyme; ICC Standard Method No. 303). One unit of activity was defined as the amount of enzyme, in the presence of excess thermostable α-glucosidase, required to release one micromole of *p*-nitrophenol from the synthetic substrate BPNPG7 (p-nitrophenyl-maltoheptaoside) in one minute under the defined assay conditions, and is referred to as a cereal unit (U). All evaluated parameters were calculated based on the dry weight basis (dwb).

Statistical methods*.* Standard statistical testing was employed for the data evaluation including Analysis of variance (ANOVA), Tukey's HSD test, Waller-Duncan's test and Pearson's correlation coefficient.

Table 1. Average air temperature and sum of precipitation for a month in Borovce

Month	2003–2004		2004–2005		Long-term normal	
	(°C)	(mm)	(°C)	(mm)	(°C)	(mm)
September	15.9	19	15.0	39	14.5	38
October	8.0	58	12.2	61	9.6	42
November	6.7	35	5.2	47	4.6	51
December	0.9	31	1.0	33	0.3	46
January	–3.1	51	–0.5	40	–1.8	32
February	1.3	27	–2.4	52	0.2	33
March	4.4	49	3.0	7	4.2	32
April	11.6	14	11.5	91	9.4	43
May	14.1	16	15.6	33	14.1	54
June	17.9	73	18.2	34	17.7	80
July	20.1	16	20.4	97	18.9	76
August	20.7	45	19.1	99	18.4	68
Average	9.9		9.9		9.2	
Sum		434		633		595

RESULTS AND DISCUSSION

Millers and bakers are primarily concerned with the functional quality of flour, while wheat grain yield is the major target for farmers. Farmers' targets are inversely related to flour-milling targets (a higher grain yield is usually associated with a poorer bread quality and vice-versa). Both are strongly affected by the genotype, environment, and their interaction (Morris *et al.* 1997; Johansson 2002; Budak *et al.* 2003; Jing *et al.* 2003; Barić *et al.* 2004; Williams *et al.* 2008).

We evaluated the traits of quality in winter wheat cultivars originating from different countries which were grown in two seasons in the locality of Borovce. The growing years were markedly differ-

Table 2. MS from analysis of variance for traits in relation to year, cultivar, and origin

Traits	Source	Year		Cultivar		Origin	
		df	MS	df	MS	df	MS
Protein	between groups	1	40.71**	44	1.35	6	1.52
	within groups	88	0.99	45	1.53	83	1.43
Wet gluten	between groups	1	1 137.99**	44	21.10	6	34.39
	within groups	88	15.09	45	34.16	83	27.22
Gluten swelling	between groups	1	21.51*	44	7.91**	6	20.47**
	within groups	88	4.39	45	1.33	83	3.44
SDS test	between groups	1	1 033.61**	44	200.95**	6	354.91**
	within groups	88	120.21	45	61.57	83	114.25
Falling number	between groups	1	3 4261.51**	44	2 505.76*	6	3 287.80
	within groups	88	1643.67	45	1 525.58	83	1 917.80
Sedimentation index	between groups	1	2 942.83**	44	33.65	6	41.70
	within groups	88	20.57	45	72.73	83	54.25
Starch	between groups	1	87.93**	44	6.52**	6	13.77**
	within groups	88	3.65	45	2.72	83	3.94
Amylose	between groups	1	0.41	44	11.69**	6	18.79**
	within groups	88	6.26	45	0.82	83	5.28
α-Amylase	between groups	1	10 514.02**	44	905.22**	6	3 023.60**
	within groups	88	503.68	45	333.52	83	442.12
Volume weight	between groups	1	21 808.90**	44	2 000.92**	6	9 752.61**
	within groups	88	1110.53	45	699.88	83	735.17
Hardness	between groups	1	5 152.90**	44	85.62	6	115.76
	within groups	88	50.91	45	130.35	83	107.69
TKW	between groups	1	3.89	44	46.58**	6	104.97
	within groups	88	25.48	45	4.37	83	19.48
Grain weight per spike	between groups	1	4.73**	44	0.14	6	0.18
	within groups	88	0.08	45	0.13	83	0.13
Vegetative period	between groups	1	877.34**	44	12.07	6	66.57**
	within groups	88	7.74	45	22.83	83	13.97
Grain yield	between groups	1	16.62**	44	0.87	6	0.78
	within groups	88	0.56	45	0.62	83	0.74

**significant at the 0.01 level, *significant at the 0.05 level, MS – mean squares ent in terms of weather, most notably during the vegetation period (Table 1). The year 2005 was characterised by higher daily temperatures during May and extremely heavy rainfall during July (97 mm) when compared to the year 2004. In the third decade of May 2005, the average temperature recorded was as high as 19.6°C. Consequently, the temperatures in 2005 had a negative impact on wheat baking quality. On the other hand, this allowed us to evaluate objectively the stability of foreign wheat cultivar qualitative traits under unfavourable environmental conditions. The rainfall during harvest results in the absorption of water by the grain endosperm, which stimulates the production of a range of plant hormones associated with the germination process. Grain starch quality (but not protein content) is affected when α-amylase enters the starch granule where it attacks and degrades the starch molecules. Flour milled from weather-damaged wheat has a poor starch quality rendering it unsuitable for many processes including bread making (Noda *et al.* 2003). Others have noted the negative effect of summer rainfall on wheat grain quality (Kettlewell *et al.* 2003).

Analysis of variance highlighted the differences in the value of growing year, cultivar, and country of origin on individual traits of quality (Table 2). Gluten swelling, SDS test, starch content, α-AMS activity, and volume weight were simultaneously affected by the cultivar, growing year, and country of origin. Other traits were influenced by only one or two of these factors.

The adverse weather in the year 2005 had a negative effect on most qualitative traits (Table 2), but positively affected important farmers' targets. Statistically significant decreases ($P < 0.01$) were observed in protein, wet gluten, SDS test, falling number (FN), volume weight, grain hardness, and duration of vegetative period. Significant ($P < 0.01$) increases were recorded in sedimentation index, starch, α-amylase (α-AMS) activity, grain weight per spike and grain yield. Gluten swelling also significantly increased ($P < 0.05$). The effect of the growing year on amylose and thousand kernel weight (TKW) was not statistically significant.

From Table 2 is it evident that the cultivar significantly influenced ($P < 0.01$) gluten swelling, SDS test, starch, amylose, α-AMS, volume weight, TKW as well as FN ($P < 0.05$). The greatest intra-cultivar variation was observed with gluten swelling (*CV* 12.1%), SDS (*CV* 36.3%), α-AMS (*CV* 17.6%) and TKW (*CV* 14.1%) while the smallest variation appeared in the duration of the vegetative period (*CV* 0.9%).

The greatest effect of the country of origin was observed with gluten swelling, SDS test, starch, amylose, α-AMS, volume weight, and the duration of the vegetative period (Table 2).

The results we obtained are in agreement with the observations of other authors. Jing *et al.* (2003) described a significant effect of the environment on the sedimentation value and wet gluten and protein contents, at the same time showing that the starch/amylose ratio was insensitive to the environment. Hudec *et al.* (2006) verified the effect of simulated intensive pre-harvest rainfall on the yield and technological quality of winter wheat. Intensive rainfall during the phase between the milk and wax grain ripeness influenced more expressively all the parameters in comparison with later rainfall between the wax and technological grain ripeness. Schillinger *et al.* (2008) found that for wheat grain yield, rainfall during the months of May and June is more beneficial than during April. The importance of annual rainfall for the accumulation of starch in wheat grain was also noted (Kim *et al.* 2003).

The amylose to amylopectin ratio in starch is presumably inherited. Matsuki *et al.* (2003) examined this by isolating starches from four wheat cultivars grown to maturation in chambers at various daytime temperatures. Amylose content was not significantly altered at high maturation temperatures in some cultivars, whereas in others a slight increase was observed.

In determining the best foreign cultivars suitable for growing in Slovakia, the results shown in Table 2 prove the effects of the cultivar and year on the means of individual traits. Using Tukey's HSD or Waller-Duncan's test, mean differences were determined as well as standard deviations. Thus, the stable quality was preferred to the absolute quality. The baking quality traits (Table 3) and milling quality traits along with the traits associated with the yield (Table 4) are given in addition. These tables provide information regarding different traits of each cultivar. The cultivars having a mean value of good quality in both years and simultaneously the smallest standard deviation within them were considered as the best cultivars possessing stability in the given trait. These were considered the best cultivars (Table 3) with stable high grain protein (GK Csongrád, Armelis, GK Bagoly), wet gluten

Table 3. Mean values of baking quality traits in two years (Tukey's HSD test)

Cultivar	Origin	GP		WG		GS		SDS		FN		SI		TS		AMY		αAMS	
		$\bar{x}$	S.D.	$\bar{x}$	S.D.	$\bar{x}$	S.D.	$\bar{x}$	S.D.	$\bar{x}$	S.D.	$\bar{x}$	S.D.	$\bar{x}$	S.D.	$\bar{x}$	S.D.	$\bar{x}$	S.D.
Komfort	AUT	13.0	0.1	34.9	1.7	8.5^{bcdef}	0.7	41.5^{ab}	0.7	323^{ab}	35	45.0	9.9	61.0	1.7	23.1	0.2	120	5
Saturnus	AUT	12.9	0.6	37.2	4.0	8.0^{bcdef}	0.0	51.0^{ab}	7.1	357^{ab}	32	46.7	3.9	61.8	0.9	20.0	0.2	160	20
Silvius	AUT	11.7	1.5	31.2	7.7	9.5^{cdef}	0.7	43.5^{ab}	12.0	323^{ab}	24	53.1	5.1	64.1	1.6	24.5	0,2	139	14
Spartakus	AUT	12.8	1.7	32.4	10.2	8.5^{bcdef}	0.7	52.5^{b}	16.3	296^{ab}	46	47.6	4.8	63.1	1.9	24.4	1.1	115	19
Meritto	CZE	11.6	1.4	27.5	6.3	5.5^{abcdef}	0.7	31.5^{ab}	6.4	289^{ab}	8	49.2	7.4	66.6	2.5	22.8	3.5	154	17
Rheia	CZE	12.7	0.5	34.9	2.0	5.0^{abcde}	1.4	34.0^{ab}	2.8	359^{ab}	4	47.9	5.9	63.5	1.5	21.3	0.4	162	33
Biscay	DEU	12.1	0.4	33.1	2.5	3.5^{ab}	0.7	23.5^{ab}	0.7	345^{ab}	6	47.6	7.4	65.6	0.3	23.4	1.8	136	11
Centrum	DEU	12.4	0.3	33.7	3.6	7.0^{abcdef}	1.4	37.5^{ab}	0.7	316^{ab}	9	44.1	8.4	67.5	0.7	25.2	0.3	167	10
Cubus	DEU	12.3	0.8	32.9	4.2	8.5^{bcdef}	0.7	46.0^{ab}	2.8	374^{b}	0	46.3	7.3	67.3	0.0	24.4	1.3	122	19
Grandios	DEU	11.5	1.6	32.7	8.4	9.5^{cdef}	0.7	35.5^{ab}	9.2	355^{ab}	9	50.1	6.4	62.7	2.4	25.3	0.9	126	7
Karpos	DEU	11.5	1.8	32.5	8.4	8.0^{bcdef}	0.0	41.0^{ab}	15.6	298^{ab}	6	48.1	8.3	62.5	1.1	21.3	0.2	117	15
Maltop	DEU	10.7	2.3	29.6	6.7	6.5^{abcdef}	0.7	24.5^{ab}	14.9	278^{ab}	19	46.5	9.9	65.5	1.8	24.8	0.2	142	19
Tiger	DEU	13.0	0.2	34.5	2.3	8.5^{bcdef}	0.7	49.5^{ab}	6.4	317^{ab}	19	48.3	8.2	63.2	0.7	22.0	1.1	122	22
Trend	DEU	12.6	0.6	31.5	2.6	9.0^{bcdef}	1.4	40.0^{ab}	0.0	361^{b}	11	51.0	7.0	65.9	1.6	23.7	0.2	136	4
Wasmo	DEU	11.6	1.6	29.9	5.7	6.0^{abcdef}	0.0	16.5^{ab}	3.5	311^{ab}	6	48.2	11.1	64.0	0.9	27.2	0.5	151	28
Coxwain	GBR	14.2	0.8	39.0	5.8	7.5^{abcdef}	0.7	49.0^{ab}	5.7	323^{ab}	66	47.2	10.6	63.4	1.8	22.5	0.1	172	7
Eclipse	GBR	12.5	1.5	34.5	3.8	3.5^{ab}	0.7	13.5^{a}	0.7	302^{ab}	15	46.0	14.2	65.0	1.6	24.9	1.4	143	15
Griffen	GBR	12.7	1.8	35.8	8.1	2.0^{a}	1.4	16.0^{ab}	8.5	272^{ab}	39	49.9	11.6	64.1	1.7	28.5	0.2	183	13
Odyssey	GBR	12.3	2.7	34.3	10.7	6.5^{abcdef}	0.7	30.5^{ab}	12.0	259^{ab}	74	51.1	7.8	64.4	0.9	23.1	0.1	152	33
Orton	GBR	10.9	2.5	30.2	11.2	4.0^{abc}	1.4	27.5^{ab}	9.2	313^{ab}	47	53.9	9.5	61.8	1.3	21.6	0.7	135	21
GK Attila	HUN	14.0	0.9	41.3	4.5	6.0^{abcdef}	0.0	44.5^{ab}	16.3	259^{ab}	103	55.4	2.7	62.0	2.7	22.3	0.2	121	25
GK Bagoly	HUN	13.1	0.0	34.8	3.0	6.0^{abcdef}	0.0	42.0^{ab}	1.4	286^{ab}	87	47.4	8.4	61.5	1.8	24.4	0.1	139	23
GK Csongrád	HUN	13.7	0.1	38.6	1.1	5.5^{abcdef}	2.1	31.0^{ab}	1.4	309^{ab}	33	44.3	8.5	62.7	2.0	23.4	1.0	114	13
GK Forrás	HUN	13.9	0.9	41.9	1.9	7.0^{abcdef}	0.0	35.0^{ab}	2.8	317^{ab}	51	61.3	13.0	61.3	1.0	20.2	1.3	103	19

Table 3 to be continued

Cultivar	Origin	GP		WG		GS		SDS		FN		SI		TS		AMY		αAMS	
		$\bar{x}$	S.D.	$\bar{x}$	S.D.	$\bar{x}$	S.D.	$\bar{x}$	S.D.	$\bar{x}$	S.D.	$\bar{x}$	S.D.	$\bar{x}$	S.D.	$\bar{x}$	S.D.	$\bar{x}$	S.D.
GK Héja	HUN	12.8	1.2	36.8	7.0	5.0^{abcde}	0.0	38.0^{ab}	9.9	279^{ab}	56	44.0	5.3	62.8	1.0	20.6	0.5	124	19
GK Holló	HUN	12.4	1.6	34.6	5.6	6.5^{abcdef}	0.7	26.0^{ab}	9.9	311^{ab}	17	45.2	10.9	64.6	1.8	19.8	0.1	136	7
GK Jaszság	HUN	12.9	1.2	33.8	3.4	7.5^{abcdef}	0.7	26.5^{ab}	7.8	301^{ab}	62	38.5	10.7	64.7	2.6	20.2	0.9	114	33
GK Margit	HUN	12.2	1.9	34.6	9.0	5.5^{abcdef}	2.1	21.5^{ab}	10.6	294^{ab}	31	43.0	12.0	64.9	2.0	18.7	0.7	136	11
GK Rába	HUN	12.0	1.0	31.2	5.9	10.5^{ef}	2.1	41.5^{ab}	6.4	281^{ab}	76	49.3	8.5	63.4	1.2	19.0	0.2	108	20
GK Szálka	HUN	13.3	1.6	35.8	4.8	5.5^{abcdef}	0.7	26.5^{ab}	7.8	322^{ab}	28	45.1	7.9	62.5	1.6	20.4	0.5	122	40
GK Szivarvány	HUN	11.3	0.1	29.5	2.2	9.0^{bcdef}	1.4	40.5^{ab}	5.0	327^{ab}	13	47.8	7.3	65.1	1.4	25.2	0.5	115	19
GK Verecke	HUN	11.8	0.1	32.4	1.6	8.5^{bcdef}	2.1	42.0^{ab}	4.2	353^{ab}	21	52.3	10.8	67.8	1.6	28.1	1.0	94	7
Liryka	POL	11.8	0.8	30.0	1.6	4.5^{abcd}	0.7	23.0^{ab}	2.8	279^{ab}	45	52.6	9.9	63.9	0.2	19.1	1.0	122	24
Symfonia	POL	12.3	0.2	34.2	3.3	4.5^{abcd}	0.7	25.0^{ab}	1.4	336^{ab}	4	49.5	7.6	63.7	1.1	23.7	0.6	97	6
Torija	POL	11.6	2.5	31.3	11.3	7.5^{abcdef}	2.1	34.0^{ab}	11.3	347^{ab}	35	46.2	6.7	63.5	2.3	22.2	0.1	113	16
Arida	SVK	13.2	0.5	38.0	4.6	9.0^{bcdef}	1.4	45.5^{ab}	3.5	278^{ab}	13	43.5	9.3	64.1	1.8	23.9	0.6	132	15
Armelis	SVK	13.3	0.0	35.9	7.5	8.0^{bcdef}	1.4	48.5^{ab}	0.7	323^{ab}	45	43.5	3.7	64.0	4.0	24.4	0.5	113	5
Venistar	SVK	11.6	0.4	31.3	2.6	7.5^{abcdef}	0.7	25.5^{ab}	2.1	289^{ab}	25	41.5	7.1	65.4	0.9	25.3	0.5	126	9
Petrana	SVK	12.2	1.5	31.3	8.0	8.0^{bcdef}	2.8	37.0^{ab}	4.2	340^{ab}	31	48.9	11.4	63.7	1.4	21.4	1.3	101	4
Velta	SVK	11.4	0.3	28.5	1.8	8.0^{bcdef}	0.0	30.0^{ab}	4.2	324^{ab}	19	41.2	9.4	65.5	0.3	28.0	0.2	119	24
Astella	SVK	11.3	0.7	29.2	3.0	10.0^{def}	0.0	28.5^{ab}	9.2	171^{a}	13	45.5	8.0	67.5	0.5	24.1	1.7	167	21
Ilona	SVK	12.1	0.6	31.1	5.9	11.0^{f}	1.4	40.5^{ab}	10.6	276^{ab}	0	50.9	8.2	66.2	2.5	25.5	0.1	120	2
Torysa	SVK	13.2	0.5	35.2	3.3	5.5^{abcdef}	0.7	35.0^{ab}	1.4	309^{ab}	20	44.1	4.6	66.0	0.6	24.9	0.3	118	15
Vanda	SVK	13.0	0.5	30.3	1.6	7.0^{abcdef}	0.0	41.5^{ab}	3.5	311^{ab}	54	44.9	6.9	65.2	1.4	22.2	0.1	100	11
Malyska	SVK	11.8	1.6	31.3	8.4	6.0^{abcdef}	1.4	21.0^{ab}	11.3	291^{ab}	23	43.7	0.6	67.7	1.4	23.5	0.6	103	5

GP – grain protein (%); WG – wet gluten (%); GS – gluten swelling (ml); SDS – sedimentation test (ml); FN – falling number (s); SI – sedimentation index (ml); TS – total starch (%); AMY – amylose (% of starch); αAMS – α-amylase (U/g); $\bar{x}$ – mean; S.D. – standard deviation; $^{a–x}$ $P \leq 0.1$

Table 4. Mean values of milling quality traits and traits associated with yield in two years (Tukey's HSD test)

Cultivar	Origin	VW		HA		TKW		GWS		VP		GY	
		$\bar{x}$	S.D.	$\bar{x}$	S.D.	$\bar{x}$	S.D.	$\bar{x}$	S.D.	$\bar{x}$	S.D.	$\bar{x}$	S.D.
Komfort	AUT	815^{abc}	24.7	75.00	14.1	38.6^{ab}	4.4	2.27	0.27	288	4	9.69	0.4
Saturnus	AUT	860^{c}	21.2	80.47	9.6	45.7^{ab}	1.3	1.90	0.28	284	6	8.47	0.7
Silvius	AUT	840^{bc}	0.7	79.57	9.4	36.0^{ab}	0.1	2.07	0.52	287	7	7.60	1.1
Spartakus	AUT	837^{bc}	31.1	73.40	9.7	40.9^{ab}	2.6	1.89	0.23	285	5	8.23	0.3
Meritto	CZE	816^{abc}	22.6	77.58	10.1	36.6^{ab}	1.9	2.28	0.66	287	6	9.34	0.7
Rheia	CZE	812^{abc}	8.5	78.80	9.0	45.2^{ab}	4.0	2.13	0.21	285	4	9.16	1.1
Biscay	DEU	776^{abc}	7.8	73.37	14.5	38.7^{ab}	2.5	2.05	0.18	287	7	10.30	1.5
Centrum	DEU	812^{abc}	20.5	82.24	10.8	42.5^{ab}	1.1	2.34	0.56	290	5	9.41	0.9
Cubus	DEU	819^{abc}	4.2	70.62	6.0	34.9^{ab}	1.0	2.02	0.59	284	3	9.20	1.0
Grandios	DEU	787^{abc}	6.4	61.22	17.9	33.1^{ab}	1.1	1.97	0.49	286	1	8.90	1.0
Karpos	DEU	802^{abc}	17.0	72.28	17.7	37.2^{ab}	0.6	1.88	0.43	289	5	8.86	0.3
Maltop	DEU	785^{abc}	18.4	60.55	15.1	34.6^{ab}	0.1	1.80	0.30	289	5	7.94	0.8
Tiger	DEU	816^{abc}	20.5	86.29	9.4	43.5^{ab}	2.6	2.37	0.69	287	7	8.32	0.9
Trend	DEU	780^{abc}	9.9	66.27	9.5	36.6^{ab}	0.5	2.03	0.21	287	6	9.12	0.8
Wasmo	DEU	769^{abc}	26.9	61.28	15.2	29.5^{ab}	0.7	1.51	0.33	287	6	8.23	1.0
Coxwain	GBR	746^{abc}	3.5	72.17	15.4	33.0^{ab}	0.0	1.94	0.22	287	6	9.06	0.8
Eclipse	GBR	745^{abc}	24.0	66.35	17.4	34.1^{ab}	0.8	2.16	0.27	290	5	8.65	0.2
Griffen	GBR	701^{a}	9.9	62.98	13.6	28.9^{b}	2.5	1.82	0.31	289	6	7.75	0.9
Odyssey	GBR	731^{abc}	2.8	67.84	16.6	27.9^{ab}	0.1	1.51	0.21	289	5	7.59	0.8
Orton	GBR	793^{abc}	17.7	67.41	15.5	36.0^{ab}	1.4	2.32	0.30	288	4	9.03	0.0
GK Attila	HUN	826^{abc}	42.4	81.04	11.1	36.0^{ab}	0.6	1.38	0.02	283	7	7.92	0.0
GK Bagoly	HUN	823^{abc}	43.8	73.34	10.5	43.6^{ab}	5.3	1.95	0.28	282	5	7.77	0.7
GK Csongrád	HUN	807^{abc}	23.3	77.23	9.7	33.3^{ab}	2.0	1.76	0.34	281	4	8.93	1.1
GK Forrás	HUN	833^{bc}	42.4	68.90	12.8	32.1^{ab}	0.4	1.23	0.02	283	2	7.94	0.3
GK Héja	HUN	838^{bc}	36.8	73.30	10.6	40.4^{ab}	0.6	1.79	0.16	285	4	9.27	0.9
GK Holló	HUN	838^{bc}	24.0	65.98	10.6	32.4^{ab}	1.4	2.00	0.56	283	1	9.17	0.3
GK Jaszság	HUN	807^{abc}	31.8	76.90	8.6	36.8^{ab}	4.2	1.66	0.25	282	6	8.31	0.6
GK Margit	HUN	819^{abc}	35.4	69.95	13.0	37.9^{ab}	2.0	1.72	0.32	284	0	8.90	0.6
GK Rába	HUN	825^{abc}	41.0	70.56	7.5	43.9^{ab}	0.8	2.21	0.37	283	4	9.47	0.3
GK Szálka	HUN	822^{abc}	21.9	73.72	11.5	37.0^{ab}	3.2	1.67	0.23	283	6	8.71	2.0
GK Szivarvány	HUN	832^{bc}	14.8	71.11	14.1	42.3^{ab}	1.4	2.30	0.45	282	4	9.76	0.6
GK Verecke	HUN	822^{abc}	39.6	62.95	8.8	44.5^{a}	1.4	1.80	0.17	283	4	8.33	0.6
Liryka	POL	801^{abc}	13.4	69.87	15.2	37.2^{ab}	3.4	1.81	0.42	284	4	9.07	1.3
Symfonia	POL	819^{abc}	18.4	77.40	4.3	37.3	0.1	1.90	0.41	286	7	8.06	0.8
Torija	POL	806^{abc}	18.4	77.04	12.2	31.9	1.6	1.69	0.40	287	7	7.71	0.6
Arida	SVK	822^{abc}	54.4	68.45	5.4	44.3	2.8	1.74	0.01	282	3	8.33	0.3

Table 4 to be continued

Cultivar	Origin	VW		HA		TKW		GWS		VP		GY	
		$\bar{x}$	S.D.	$\bar{x}$	S.D.	$\bar{x}$	S.D.	$\bar{x}$	S.D.	$\bar{x}$	S.D.	$\bar{x}$	S.D.
Armelis	SVK	826^{abc}	41.7	79.48	3.7	44.6	1.0	1.87	0.41	283	4	9.30	0.1
Venistar	SVK	825^{abc}	26.9	61.59	3.6	38.8	0.4	2.20	0.16	282	3	9.70	0.5
Petrana	SVK	810^{abc}	42.4	71.38	14.4	34.2	0.6	1.70	0.15	283	1	8.19	0.5
Velta	SVK	834^{bc}	33.2	66.51	5.0	39.4	1.9	1.78	0.16	284	2	9.38	0.4
Astella	SVK	786^{abc}	5.7	58.42	4.2	36.4	0.8	1.74	0.21	283	2	9.19	0.7
Ilona	SVK	781^{abc}	1.4	70.85	6.4	38.2	0.0	1.78	0.37	284	4	8.80	0.1
Torysa	SVK	757^{abc}	7.1	75.99	5.5	45.2	4.0	2.22	0.53	285	4	8.78	0.7
Vanda	SVK	808^{abc}	43.8	76.46	8.6	46.9	1.3	2.09	0.50	283	5	8.78	0.4
Malyska	SVK	813^{abc}	7.8	78.73	7.7	37.0	2.5	1.61	0.46	284	3	8.03	1.2

VW – volume weight (g/l); HA – grain hardness; TKW – thousand kernel weight (g); GWS – grain weight per spike (g); VP – duration of vegetative period (day); GY – grain yield (t/ha); $\bar{x}$ – mean; S.D. – standard deviation; $^{a-x}$ $P \leq 0.05$

(GK Csongrád, GK Forrás, Komfort), gluten swelling (Ilona, GK Rába, Astella), SDS test (Spartakus, Saturnus, Tiger), falling number (Cubus, Trend, Rheia), sedimentation index (GK Attila, Silvius, Grandios), and stable low starch content (Komfort, GK Forrás, GK Bagoly) and amylose (GK Margit, GK Rába, Liryka) and α-AMS activities (GK Vereczke, Symfonia, Vanda). Similarly, the cultivars

Table 5. Cultivars with the best traits stability in both years

Traits	Rank			Note
	1.	2.	3.	
Protein	GK Csongrád (HUN)	Armelis (SVK)	GK Bagoly (HUN)	low variability, relative high value
Wet gluten	GK Csongrád (HUN)	GK Forrás (HUN)	Komfort (AUT)	
Gluten swelling	Ilona (SVK)**	GK Rába (HUN)	Astella (SVK)	
SDS test	Spartakus (AUT)**	Saturnus (AUT)*	Tiger (DEU)	Tukey HSD
Falling number	Cubus (DEU)**	Trend (DEU)**	Rheia (CZE)*	
Sedimentation index	GK Attila (HUN)	Silvius (AUT)	Gradios (DEU)	low variability, relative high value
Starch	Komfort (AUT)**	GK Forrás (HUN)	GK Bagoly (HUN)	Waller-Duncan
Amylose	GK Margit (HUN)**	GK Rába (HUN)	Liryka (POL)	
α–amylase	GK Verecke (HUN)**	Symfonia (POL)	Vanda (SVK)	Tukey HSD
Volume weight	Saturnus (AUT)**	Silvius (AUT)	GK Holló (HUN)	
Grain hardness	Armelis (SVK)	Symfonia (POL)	Tiger (DEU)	low variability, relative high value
TKW	Vanda (SVK)**	Saturnus (AUT)	Torysa (SVK)	Tukey HSD
Grain weight per spike	Venistar (SVK)	Biscay (DEU)	Komfort (AUT)	low variability, relative high value
Vegetative period	GK Forrás (HUN)	Arida (SVK)	Venistar (SVK)	low variability, relative low value
Grain yield	Armelis (SVK)	GK Rába (HUN)	Komfort (AUT)	low variability, relative high value

$^{**}P \leq 0.01$, $^{*}P \leq 0.05$

were distinguished (Table 4) for stable volume weight (Saturnus, Silvius, GK Holló), grain hardness (Armelis, Symfonia, Tiger), thousand-kernel weight (Vanda, Saturnus, Torysa), grain weight per spike (Venistar, Biscay, Komfort), duration of vegetative period (GK Forrás, Arida, Venistar) and grain yield (Armelis, GK Rába, Komfort). The best stable quality of more than one trait was identified in the Komfort (AUT), Saturnus (AUT), GK Rába (HUN), GK Csongrád (HUN), Silvius (AUT), GK Bagoly (HUN), GK Forrás (HUN), and Venistar (SVK) cultivars. The Slovak control Armelis cultivar demonstrated three best stable traits (grain protein, grain hardness, and grain yield).

Statistical significance of the cultivars with the best stability in both years is summarised in Table 5. The best stable quality traits for both growing years were identified in the Ilona (gluten swelling), Spartakus (SDS test), Cubus (falling number), Komfort (low starch), GK Margit (low amylose), GK Verecke (low α-AMS), Saturnus (volume weight), and Vanda (thousand-kernel weight) cultivars. Other traits, such as protein, wet gluten, sedimentation index, grain hardness,

Table 6. Significant differences between origins (Tukey's HSD test)

Traits	(I) Origin	(J) Origin	Mean Difference (I–J)	S.D.Error
Gluten swelling	AUT	GBR	3.93*	0.88
		POL	3.13*	1.00
	DEU	GBR	2.69*	0.73
	HUN	GBR	2.18*	0.70
	SVK	GBR	3.30*	0.72
SDS test	AUT	GBR	19.83*	5.07
		POL	19.79*	5.77
Starch	SVK	AUT	3.04*	0.83
		HUN	1.92*	0.60
Amylose	HUN	DEU	–2.30*	0.72
	SVK	HUN	2.45*	0.70
α–amylase	HUN	CZE	–38.75*	11.36
		GBR	–37.93*	7.91
	POL	CZE	–47.34*	13.57
		GBR	–46.52*	10.86
	SVK	CZE	–37.82*	11.52
		GBR	–37.00*	8.14
Volume weight	AUT	DEU	43.97*	11.52
		GBR	94.75*	12.86
	CZE	GBR	71.00*	16.04
	DEU	GBR	50.78*	10.69
	HUN	DEU	30.39*	8.45
		GBR	81.17*	10.21
	POL	GBR	65.50*	14.00
	SVK	GBR	63.00*	10.50
Vegetative period	HUN	DEU	–4.42*	1.17
		GBR	–5.72*	1.41
	SVK	DEU	–3.90*	1.21
		GBR	–5.20*	1.45

grain weight per spike, grain yield, and the duration of the vegetative period were strongly affected by the environment (growing year).

Using Tukey's HSD test, significant differences were noted between the different Slovak cultivars (Table 6). English wheat cultivars had lower gluten swelling and volume weight while, at the same time, higher α-AMS activity and a longer vegetative period. A higher α-AMS activity in the Czech, a lower starch content in the Austrian, and a longer vegetative period in the German cultivars were observed. In the Hungarian cultivars, significantly lower starch content and amylose ratio were detected. However, only few cultivars from each country were evaluated and therefore the results can not be generalised for all the cultivars from all countries.

The starch amylose ratio of all wheat cultivars studied ranged from 18.18% to 28.77% (mean 23%) in both growing years. In one group, consisting of Hungarian cultivars (GK Holló, GK Jaszság, GK Margit, GK Rába, GK Szálka), the amylose ratio was lower than 20%. In old Hungarian wheat lines, derived from Bánkúti 1201, amylose ranges from 14.4% to 24.2% (Rakszegi *et al.* 2003). In addition, wheat grown in Hungary is noted for its relatively high frequency of the null waxy *Wx-B1b* allele (Marcoz-Ragot *et al.* 2000). This allele disables granule-bound starch synthase (GBSSI) activity, which in turn reduces the starch/amylose ratio. The reduced amylose content in wheat flour appears to have a positive impact on bread making quality by improving bread texture and shelf life (Lee *et al.* 2001). In agreement with this finding, Park *et al.* (2009) showed that good quality wheats contained more small B-starch granules.

We identified important correlations between the traits (Table 7). A statistically significant positive correlation ($P < 0.01$) was observed between the protein content and wet gluten, SDS test, falling number (FN), grain hardness, and duration of the vegetative period. Protein content, however, was negatively correlated with the sedimentation index (SI), starch content, α-AMS, grain weight per spike (GWS), and grain yield. Wet gluten was positively correlated with the SDS test, FN, volume weight, grain hardness, and duration of the vegetative period, and negatively correlated with gluten swelling, SI, starch, α-AMS, GWS, and grain yield. There was a positive correlation between the

Table 7. Pearson's correlation between traits in wheat

Traits	Baking quality traits								Milling quality traits			Traits conected with the yield		
	WG	GS	SDS	FN	SI	TS	AMY	αAMS	VW	HA	TKW	GWS	VP	GY
GP	0.90**	–0.20*	0.52**	0.32**	–0.45**	–0.51**	–0.14	–0.31**	0.23*	0.67**	0.05	–0.46**	0.32**	–0.38**
WG		–0.28**	0.44**	0.36**	–0.47**	–0.61**	–0.14	–0.27**	0.29**	0.65**	–0.03	–0.59**	0.46**	–0.42**
GS			0.48**	–0.09	0.19*	0.20*	0.05	–0.11	0.17	–0.19*	0.23*	0.16	–0.32**	0.17
SDS				0.33**	–0.14	–0.33**	–0.05	–0.29**	0.46**	0.48**	0.42**	–0.08	0.12	–0.13
FN					–0.32**	–0.31**	0.02	–0.41**	0.39**	0.47**	0.12	–0.09	0.39**	–0.07
SI						0.20*	–0.06	0.33**	–0.39**	–0.63**	–0.12	0.41**	–0.51**	0.27**
TS							0.32**	0.25**	–0.36**	–0.45**	0.08	0.38**	–0.34**	0.33**
AMY								0.11	–0.26**	–0.18*	–0.08	0.04	0.14	–0.09
αAMS									–0.53**	–0.43**	–0.17	0.35**	–0.12	0.27**
VW										0.50**	0.43**	–0.22*	0.04	–0.07
HA											0.22*	–0.37**	0.56**	–0.41**
TKW												0.36**	–0.24*	0.33**
GWS													–0.36**	0.63**
VP														–.044**

GP – grain protein, WG – wet gluten, GS – gluten swelling, SDS – sedimentation test, FN – falling number, SI – sedimentation index, VW – volume weight, HA – grain hardness, TS – total starch, AMY – amylose, αAMS – α-amylase, TKW – thousand kernel weight, GWS – grain weight per spike, VP – duration of vegetative period, GY – grain yield

**significant at the 0.01 level, *significant at the 0.05 level

Table 8. The proposed best cultivars with more stable traits

Cultivar	Traits
Komfort (AUT)	high wet gluten, grain yield and grain weight per spike, low starch
Saturnus (AUT)	high SDS test, volume weight, grain hardness and thousand-kernel weight
GK Rába (HUN)	high gluten swelling and grain yield, low amylose
GK Csongrád (HUN)	high protein and wet gluten
Silvius (AUT)	high volume weight and sedimentation index
GK Bagoly (HUN)	high protein, low starch
GK Forrás (HUN)	high wet gluten, low starch

falling number and volume weight, grain hardness and duration of the vegetative period, and a negative correlation with SI, starch, and α-AMS activity. Starch content was positively correlated with amylose, α-AMS, grain weight per spike and yield, while negatively correlated with the volume weight, grain hardness, and duration of the vegetative period. Thousand-kernel weight was positively correlated with grain weight per spike as well as with grain yield. Likewise, grain weight per spike was positively correlated with the yield, yet negatively correlated with the duration of the vegetative period. The duration of the vegetative period was in negative correlation with the grain yield. Several correlations identified in our study have been documented by others (Lyon & Shelton 1999; Every *et al.* 2002; Konopka *et al.* 2004).

Several authors have confirmed the influence of the genotype (G), environment (E), and genotype × environment interaction (G × E) on wheat baking quality (Yan & Hunt 2001; DuPont & Altenbach 2003; Kim *et al.* 2003; Williams *et al.* 2008) as well as on the physical-chemical properties of starch (Tester & Karkalas 2001). The traits associated with protein content were more influenced by E and G × E than those associated with the protein quality, dough rheology, and starch characteristics, where G effects were of much greater importance (Massaux *et al.* 2008; Williams *et al.* 2008).

The results of the work done by Yan and Hunt (2001) indicate that the plant height and maturity were the major genotypic causes of G × E interaction, whereas cold winter and hot summer temperatures were the major environmental causes of G × E interaction. Positive interactions were found between earlier maturation versus warmer winters or hotter summers, and between reduced plant height versus warmer winters or cooler summers.

Some cultivars were stable in one trait and unstable in another, suggesting that the genetic factors involved in the genotype × environment interaction differed between traits. No cultivar has yet been identified that possesses stability in all quality traits (Grausgruber *et al.* 2000).

Gross *et al.* (2003) reported a number of strong and stable QTLs for the grain protein content and yield, as well as for one of its components, namely thousand-kernel weight (TKW). No strong negative pleiotropic effect has been detected for the grain protein content or yield. These results suggest that it may be possible to improve these economically important traits in the same breeding scheme. QTLs for TKW could thus be used efficiently in yield breeding due to the existence of co-location between QTLs controlling the two traits.

Difficulty arises in selecting the best cultivars with precision, due to the different requirements of millers, bakers, and farmers for the traits which are inversely related (Table 7). Although we attempted to select cultivars for the growth with the best bread making quality and ability to withstand the adverse climatic condition in the year 2005, no wheat cultivar demonstrated a stable mean among all the traits evaluated. However, more foreign wheat cultivars with stable quality traits were identified. Based on the traits we examined, foreign cultivars such as the Komfort (AUT), Saturnus (AUT), GK Rába (HUN), GK Csongrád (HUN), Silvius (AUT), GK Bagoly (HUN), and GK Forrás (HUN) were superior (Table 8). In addition to a good baking quality, these cultivars possessed quality traits that were stable, comparable, and ultimately better than the Slovak cultivars Armelis and Ilona.

Our results show that, in the Slovak locality of Borovce the best stable traits were identified in the cultivars originating from countries in close proximity, mainly Austria and Hungary. The Austrian cultivars, when compared to the Slovak cultivars, had significantly stable lower starch while the Hungarian cultivars lower starch and amylose (Table 6), which have indirect positive effects on the baking quality. However, the cultivars from these countries also possessed stable traits, that also have a direct positive effect (Tables 3–5 and 8). Seven selected cultivars were also able to maintain the best quality traits under unfavourable environmental conditions.

In addition, because our observations are based only on two growing years and one locality as well as on a limited number of cultivars from different countries, no generalised conclusions can be made at this time.

CONCLUSIONS

Summer rainfall in 2005 had a positive effect on the grain yield but a negative effect on most bread-making traits. With the individual traits, we observed differences in the significance of the growing year, cultivar, and country of origin. Significant differences also emerged in comparison with the Slovak cultivars. By studying the performance of foreign winter wheat cultivars for the bread quality traits and grain yields over a period of two years, we identified some specific Austrian and Hungarian superior cultivars as the most adapted for the growth in Slovakia. Each of them possessed more quality traits that were stable, comparable, and ultimately better than the control Slovak cultivars.

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