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ADAPTATION OF WINTER WHEAT CULTIVARS TO CROP MANAGEMENTS AND POLISH AGRICULTURAL ENVIRONMENTS

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ABSTRACT

Limited knowledge exists on complementary methodology for effective studying cultivar adaptive responses in two-factorial multi-environment trials planned in *split-block* design. The main objective of this paper, as the first - mostly methodological - part of the further studies, was to present and empirically illustrate the using, and to assess the usefulness of statistical methods for studying the adaptive yield response of winter wheat cultivars to agricultural environments and to two crop management intensities, on the basis of data from one-year multi-environment two-factorial trials arranged in a *split-block* design. The statistical methodology consists of the combined three-way analysis of variance according to the fixed-effects model for the cultivar × management x location (GxMxL) grain yield data from this series of trials, the AMMI analysis of the cultivar × location (G×L) interaction and the cluster analysis for the AMMI-modeled means of the cultivars at the test locations calculated across two crop management intensities. The suggested methodology was an effective tool for identifying various patterns of cultivar response to environments and to the intensity of crop managements. It permits effective identifying cultivars exhibiting wide or narrow adaptation. Wide adaptation exhibited by the Polish cultivar Bogatka and the German cultivar Jenga, losing in only very few environments the top two positions for yield to other groups of cultivars with specific adaptation or generally not adapted.

Keywords: ANOVA, AMMI analysis, cluster analysis, cultivar adaptive response, multi-environment post-registration two-factorial trials, winter wheat

INTRODUCTION

Wheat is the main crop species in the world, covers 53% of the food demands of the human population in the developed countries and 85% in the developing countries (Pena, 2007; Denčić et al., 2011). It is also the most important crop in Poland. Therefore, to increase efficiency of agriculture in Poland (and other countries), it has been attempted to improve wheat production through identification and implementation of yield-stable and adaptive cultivars. Quantitative wheat agronomic traits, such as grain yield are affected by the cultivar and the agricultural environment (Basford and Cooper, 1998; Sivapalan et al., 2000; Zhang et al., 2006; Sharma et al., 2009; Paderewski et al., 2011), the crop management and also interactions of these factors (Oscarsson et al., 1998; Ma et al., 2004; Souza et al., 2004, Anderson, 2010; Annicchiarico et al., 2010). Frequently occurred large genotype x environment and genotype x crop management interactions for yield are the cause of different genotypic adaptation to those conditions which are usually called different cultivar adaptive responses or cultivar adaptation patterns to environment and crop management (Gauch and Zobel, 1997; Gauch et al., 2008; Akcura et al., 2009; Annicchiarico et al., 2010, 2011a). Two cultivar adaptation patterns are distinguished, i.e. specific or local adaptation and wide adaptation (Gauch and Zobel, 1997; Annicchiarico, 2002; Akcura et al., 2009; Annicchiarico et al., 2011a, Paderewski et al., 2011).

To investigate cultivar adaptation patterns of important crop species, including wheat, multi-environment one- or two-factorial trials (METs) are carried out (Annicchiarico, 2002; Yan and Kang, 2003; Ma et al., 2004; Annicchiarico et al., 2010). They deliver data to compare cultivar responses in terms of yield and other plant traits to environments at one crop management (Basford and Cooper, 1998; Sivapalan et al., 2000; Annicchiarico, 2002; Fan et al., 2007; Sharma et al., 2009; Anderson, 2010; Annicchiarico et al., 2011a) or, simultaneously, to environments and crop managements (Cooper et al., 2001; Schmidt et al., 2001; Carr et al., 2003; Ma et al., 2004;

Souza et al., 2004; Anderson, 2010; Annicchiarico et al., 2010). In Poland, multi-environment two-factorial trials are conducted for economically important crop species, including winter and spring wheat, as a part of the Post-Registration Variety and Agrotechnology Testing System (the PDOiR system) coordinated and being carried out by the Research Centre for Cultivar Testing (COBORU) in Słupia Wielka (COBORU 2002, http://www.coboru.pl). In these trials for winter wheat cultivars included in the Polish National List (NLI) and in the Common Catalogue of Varieties of Agricultural Plants Species (CCA) were tested, one factor are the cultivars, the other the levels of crop management intensity (A1 – lower-input crop management, A2 – high-input crop management). At each location and year two-factorial PDOiR trial was arranged in the *split-block* design (Gomez and Gomez, 1984; Mintenko et al., 2002). Each year a set of tested cultivars substantially differs although some cultivars are assessed across a few years.

An effective study of the adaptive responses of cultivars to agricultural environment and to crop management intensity on the basis of yield data from the multi-location PDOiR trials in one year an advanced statistical methodology is required. It could include a three-way combined analysis of variance based on a linear fixed- or mixed-effects model for these data, separately from each year, establishing a three way classification cultivar x crop management x location, GxMxL (McIntosh 1983; Mintenko et al., 2002; Fan et al., 2007) and also on a multiplicative model like AMMI model (Cooper et al., 2001; Ma et al., 2004; Annicchiarico et al., 2010; Ilker et al., 2011). Only a few papers have presented rather comprehensive and complementary methodology which could be appropriate and effective in studying cultivar adaptive responses in two-factorial trials like PDOiR system (Ma et al., 2004; Anderson, 2010; Annicchiarico et al., 2010; Mądry et al., 2011). However, this methodology requires its adaptation to *split-block* design used in PDOiR system (McIntosh 1983; Mintenko et al., 2002) and efficient using AMMI analysis to interpretation of GxL interaction (Cooper et al., 2001; Ma et al., 2004).

The main objective of this paper, as the first - mostly methodological - part of the further studies, was to present and empirically illustrate the using, and to assess the usefulness of statistical methods for studying the adaptive response of grain yield in winter wheat cultivars to agricultural environments at locations and to two crop management intensities, on the basis of data from one-year (2008/2009 season) multi-environment two-factorial post-registration trials set up in a *split-block* design. The methodology includes a combined three-way analysis of variance (ANOVA) according to the fixed-effects model for the grain yield data from PDOiR trials, Tukey's procedure for multiple comparisons of means for the factor levels and their combinations, an AMMI analysis of the cultivar x location (GxL) interaction effects, and also the cluster analysis for the AMMI-modeled responses of the cultivars at the test locations on average across two crop management intensities A1 and A2.

MATERIALS AND METHODS

Experimental material

In this paper data for grain yield of twenty eight winter wheat cultivars (Table 1), tested in PDOiR trials across eight environments (trial locations) being COBORU Cultivar Testing Stations (Figure 1) in the 2008/2009 growing season, were used. The cultivars were selected to represent genetic variation for grain yield, grain quality traits and adaptability within modern winter wheat cultivars registered in the last few years in Poland and the European Union. Among the tested cultivars fifteen have been bred by the Polish breeding companies and the remaining thirteen by the Western European – mostly German - breeding companies. The eight trial locations represent effectively the main growing areas of winter wheat in Poland (Figure 1). The trials at each location were carried out at two levels of crop management intensity: A1 and A2, as shown in Table 2. Level A1 (lower, i.e. moderately intensive) does not include plant protection treatments, only the standard fertilization fitted to the soil conditions of a given station.

Figure 1. The trial locations (the COBORU Cultivar Testing Stations) of the PDOiR trials for winter wheat cultivars tested in 2008/2009 season in Poland

Other tillage and other management treatments were similar for both levels of crop management intensities. For both crop management intensities, grain density during sowing was the same, but ranged from 400 to 550 grains m^{-2} depending on the cultivar and soil fertility at a location.

In each location-year environment the trials were set up in two-factorial *split-block* design using two replicates

(Gomez and Gomez, 1984; Mejza, 1998, 1999; Mintenko et al., 2002). Within blocks, cultivars were randomly allocated to one group of sub-blocks, while two levels of crop management intensity were randomly allocated to another group of sub-blocks, arranged perpendicularly to the first ones. The size of plots for each cultivar-crop management combination was 16.5 m^2 (11 m × 1.5 m), but for harvesting in routine cultivar testing in PDOiR system the plot size was 15.0 m^2 (10 m × 1.5 m). However, in this research under the project granted by the Polish Ministry of Science and Higher Education plants were collected at full maturity stage from micro-plots of 1 m^2 area taken in the middle of each plot of 15m^2 area at all the test locations.

Statistical analysis

Data from the micro-plots for grain yield, obtained in the one-year post-registration trials planned in the *split-block* design, were subjected to the three-way combined ANOVA including cultivar, crop management intensity and location as fixed factors to assess significance of main effects of these factors and their interactions (McIntosh 1983; Gomez and Gomez, 1984). This combined ANOVA is a modified form of a similar ANOVA for two-factorial trials planned in the *split-plot* design presented by McIntosh (1983) and adapted to the *split-block* design of these trials (Gomez and Gomez, 1984; Mintenko et al., 2002). Cultivar means as well as means for some two-factor combinations were compared by the Tukey's test.

Table 1. Winter wheat cultivars tested across eight locations in post-registration multi-environment trials (PDOiR) in the growing season of 2008/2009

Cultivar	Year of release	Origin	
		Breeder	Country
Akteur	2007	Deutsche Saatveredelung AG,	Germany
Alcazar	2006	Secobra Recherches	France
Anthus	2006	KWS Lochow GmbH	Germany
Bogatka	2004	DANKO Hodowla Roślin sp. z o.o.	Poland
Boomer	2006	RAGT Seeds Ltd.	France
Figura	2007	DANKO Hodowla Roślin sp. z o.o.	Poland
Finezja	2002	DANKO Hodowla Roślin sp. z o.o.	Poland
Flair	2002	Saatzucht Hans Schweiger and Co. oHG	Germany
Garantus	2007	RAGT Seeds Ltd.	France
Jenga	2008	Nordsaat Saatzuchtgesellschaft mbH	Germany
Kohelia	2008	Hodowla Roślin Rolniczych - Nasiona Kobierzyc	Poland
Kris	2000	RAGT Seeds Ltd.	France
Legenda	2005	Poznańska Hodowla Roślin sp. z o.o.	Poland
Ludwig	2006	Saatzucht Donau Ges.m.b.H. and CoKG	Austria
Markiza	2007	Hodowla Roślin Strzelce sp. z. o.o. Grupa IHAR	Poland
Meteor	2007	SW Seed Hadmersleben GmbH	Germany
Mewa	2000	DANKO Hodowla Roślin sp. z o.o.	Poland
Mulan	2008	Nordsaat Saatzuchtgesellschaft mbH	Germany
Muszelka	2008	DANKO Hodowla Roślin sp. z o.o.	Poland
Nadobna	2003	Poznańska Hodowla Roślin sp. z o.o.	Poland
Naridana	2006	Poznańska Hodowla Roślin sp. z o.o.	Poland
Ostroga	2008	DANKO Hodowla Roślin sp. z o.o.	Poland
Rapsodia	2003	RAGT Seeds Ltd.	France
Satyna	2004	Hodowla Roślin Rolniczych - Nasiona Kobierzyc	Poland
Smuga	2004	DANKO Hodowla Roślin sp. z o.o.	Poland
Tonacja	2001	Hodowla Roślin Strzelce sp. z o.o. Grupa IHAR	Poland
Türkis	2006	SW Seed Hadmersleben GmbH	Germany
Wydma	2005	Hodowla Roślin Smolice sp. z o.o. Grupa IHAR	Poland

Cultivar adaptive responses of grain yield to environments were modeled by three techniques: ANOVA (for general mean and additive main effects of cultivars and locations), multiplicative interaction (AMMI) analysis for GxL interaction and cluster Ward's analysis for the AMMI-modeled grain yield means of cultivar x location classification (Crossa et al., 1991; Sivapalan et al., 2000; Annicchiarico, 2002; Ma et al., 2004, Annicchiarico et al., 2010).

Cultivar and location main effects were estimated by ANOVA, whereas G×L interaction effects were predicted by the statistically significant axes of a double-centered principal components analysis performed on the matrix of G×L interaction effect estimates (Gauch, 1988, 1992; Gauch et al., 2008, Annicchiarico et al., 2011b). The AMMI(*T*)-modeled grain yield adaptive response of the *i*-th cultivar (i = 1,..,I) at the *j*-th location (j = 1,..,J), on average across crop management intensities, R_{ij}, is presented as (Annicchiarico, 2002; Annicchiarico et al., 2011b):

$$R_{ij} = \hat{g}_i + \sum_{t=1}^{T} \hat{u}_{ti}\hat{v}_{tj} \quad (1)$$

where: $\hat{g}_i$ is the cultivar main effect estimate, $\hat{u}_{ti}$ and $\hat{v}_{tj}$ are the scaled eigenvectors of the *i*-th cultivar and the *j*-th location, respectively, for the *t*-th of *T* significant G×L interaction principal components (PC axes were tested by the F_R test, because of its greater robustness to non-normality and heteroscedasticity of experimental errors compared with alternative tests - Piepho, 1995; Cornellius et al., 1996; Dias and Krzanowski, 2003).

Table 2. Characteristics of two crop management intensities, A1 and A2, included in the winter wheat multi-environment post-registration trial

Crop managements treatments	Crop management intensity	
	A1	A2
Nitrogen fertilization rate (kg N ha^{-1})	+ *	N rate for A1 +40 kg N ha^{-1}
Fungicide use: the first treatment (protection against stalk and leaves diseases)	-	+
Fungicide use: the second treatment (protection against leaves and spike diseases)	-	+
Growth regulator	-	+
Foliar compound fertilization	-	+

- denotes not used crop management treatments; + denotes used crop management treatments;
* nitrogen fertilization rate was fitted to productivity potential of agro-ecosystem at a trial location

The AMMI(*T*)-modeled cultivar × location grain yield responses R_{ij} were preferred to the ordinary least squares means not only because of their clearer display of adaptive responses (Crossa et al., 1991; Annicchiarico, 2002; Annicchiarico et al., 2011b), but also because of their greater theoretical (Gauch, 1992) and empirical (Annicchiarico et al., 2006) ability to predict cultivar responses. Ward's cluster analysis was used as based on the squared Euclidean distance between the AMMI(*T*)-modeled yield responses (1) of cultivar pairs at locations. For each group of cultivars with homogeneous (similar) yield responses to environments, the cultivar group-mean adaptive yield response was calculated (Crossa et al., 1991; Mądry et al., 2011).

The three-way combined analysis of variance for grain yield from the PDOiR trials under consideration here was performed using the GLM procedure in the program SAS (SAS Institute Inc. 2004). The AMMI analysis (Table 3) was performed in the language R (R Development Core Team, 2009) using the procedure 'La.svd', designed for singular value decomposition. The cluster analysis with Ward's method was performed using the procedure 'hclust' in R.

Table 3. Combined analysis of variance based on the fixed-effect model and AMMI analysis for winter wheat grain yield data from one-year two-factorial post-registration (PDOiR) multi-environment trials carried out in a *split-block* design

Sources of variation	Degrees of freedom Df	Sum of squares SS	Mean squares MS	F-ratio	P-value
Location (L)	7	10444575	1492082	306.99	<0.0001
Blocks in locations	8	394695	49337		
Management (M)	1	1877311	1877311	163.27	<0.0001
Management×Location (M×L)	7	375691	53670	4.67	0.023
Error I	8	91983	11498		
Cultivar (G)	27	503471	18647	4.15	<0.0001
Cultivar×Location (G×L):	189	1307860	6920	1.54	0.001
AMMI IPC1	33	316930	6920 a)	1.54 a)	0.001
AMMI IPC2	31	288571	6352 a)	1.41 a)	0.009
AMMI Remaindner	125	702358	5619	1.25 a)	0.076
Error II	216	970121	4491		
Management×Cultivar (GxM)	27	161590	5985	1.23	0.208
Management×Cultivar×Location (G×M×L)	189	894343	4732	0.97	0.574
Error III	216	1049823	4860		

a) Mean squares and F-ratio were computed according to the F_R test (Cornellius et al., 1996, Annicchiarico, 2002, Dias and Krzanowski, 2003)

RESULTS AND DISCUSSION

The F test based on the combined ANOVA (Table 3) indicated significantly different main effects of the winter wheat cultivars and crop management intensities for grain yield. However, the interaction effects of these factors were not significant. Thus, all the cultivars responded with a similar (not significantly different) increase in grain yield to the greater crop management intensity (A2), in relation to the lower level of crop management intensity (A1).

Ma et al. (2004) found also a similar (not significantly different) response of yield in spring wheat cultivars to nitrogen fertilization rate in the range of 50-200 kg N ha^{-1} across eastern Canada. Also, Carr et al. (2003) and Geleta et al. (2002) found no interaction of winter wheat cultivars and the sowing rate, that is, a different response of the cultivars' yield to this management factor, in the states of North Dakota and Nebraska (USA), respectively. An advanced interpretation of the management × cultivars interaction for yield in these studies will be discussed later in the work. The mean yield for each of the two crop management intensities, A1 and A2, calculated from data for the 28 tested cultivars and 8 locations (the means were calculated each from 448 micro-plot data) were equal 756 and 847 respectively. The difference between the grain yield means for the management intensities A1 and A2 was statistically significant (Table 3) and was close to 100 g m^{-2} (1 t ha^{-1}). It indicates that increasing the intensity of crop management in the trials (A2) resulted in an average increase in grain yield of about 12% in relation to the lower management intensity (A1).

The interaction between management × location was significant (Table 3), indicating a various response of the mean yield of the tested cultivars to an increase in the intensity of crop management across the test locations. This type of interaction for yield and its quality attributes has been also found in winter wheat (Cooper et al., 2001; Anderson, 2010; Annicchiarico et al., 2010). Figure 2 shows graphically means of yield for the combinations of management-location, which illustrate increasing yield-enhancing effects of increased crop management intensity at the test locations with an increase in their productivity, as measured by the environmental mean yield. Almost at all locations a significant increase in mean yield for the management intensity A2 as compared to A1 level was found. Only at two locations with the lowest mean yield, i.e. Głębokie and Marianowo, there was no significant difference in yield at the A1 and the A2 crop management intensities.

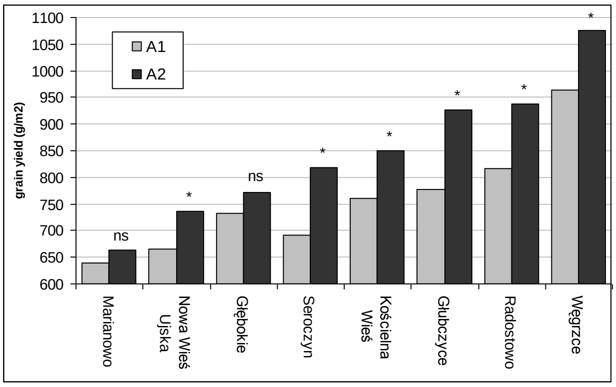


Figure 2. Response of grain yield of winter wheat to two crop management intensities A1 and A2, as averaged across 28 cultivars, across 8 test locations ordered for increasing environmental mean ($LSD_{\alpha=0.05}$=46.7 for comparisons of means at A1 and A2 respective to each of the test locations)

Detailed comparisons of cultivar means (calculated across 8 locations and 2 intensities of crop management) are shown graphically in Figure 3. These means ranged from 750 to 850 g m^{-2} (the range between the mean yields was about 100 g m^{-2}),it means that the range is from 7.5 to 8.5 t per hectare. Using Tukey's procedure within the tested cultivars three homogeneous groups were identified (Figure 3) including cultivars that exhibited relatively high (black bars), moderate (grey bars) and lower yield (white bars).

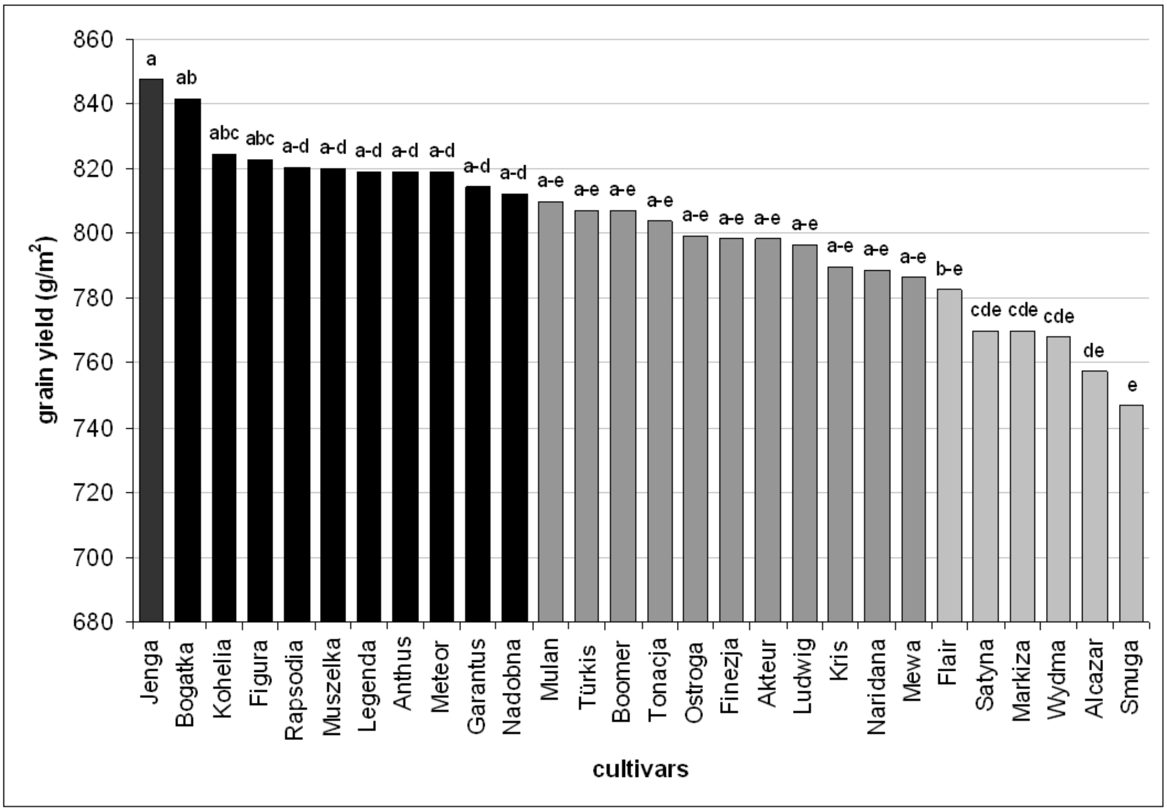


Figure 3. Comparison of winter wheat cultivar means for grain yield calculated across 2 crop management intensities and 8 test locations, and homogenous groups of means established using Tukey's procedure (Tukey's $HSD_{\alpha=0.05}$=63.1)

The value of Tukey's $HSD_{\alpha=0.05}$ for cultivar means was relatively high and represented about 60% of the range between these means due to the relatively small number of microplot observations from which the cultivar means were calculated (there were 32 of them), despite the smaller mean square of error II than of error I, which also affected the LSD value for the cultivar yield means. Therefore, the homogeneous groups are difficult to distinguish and then one cultivar is usually classified into several homogeneous groups, with the exception of the two cultivars with the highest (Jenga) and lowest (Smuga) mean yield. The cultivar Jenga had a significantly higher mean yield compared with the cultivars marked in white in Figure 3, while the cultivar Smuga had a significantly lower mean yield compared with the cultivars marked in black. A special case of the inseparability of the homogeneous groups are the cultivars marked in grey, which belonged simultaneously to all the homogeneous groups (denoted by letters from a to e), therefore, statistically, they did not differ significantly from the other cultivars. Figure 4 shows the response of grain yield of the tested cultivars, as averaged across eight locations, to the level of crop management intensity. The cultivars are presented in a non-increasing order of cultivar means for yield, as in Figure 3.

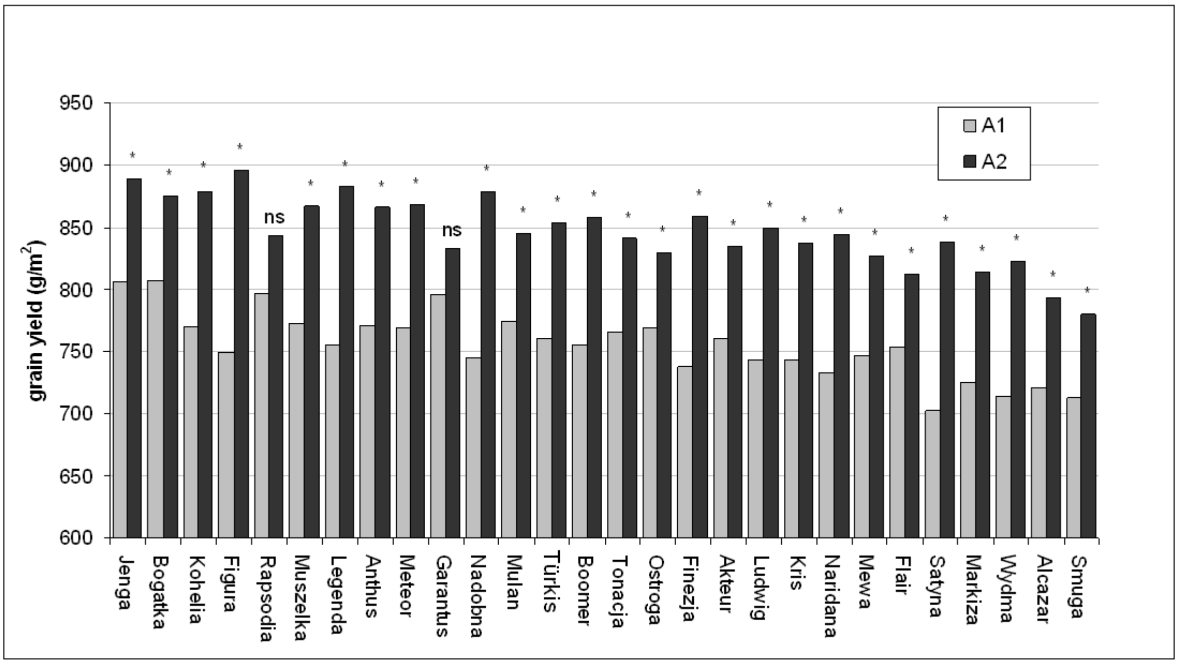


Figure 4. Response of grain yield of the tested winter wheat cultivars to two crop management intensities A1 and A2 as averaged across 8 locations ($LSD_{\alpha=0.05}$=48.3 for comparisons of means at A1 and A2 respective to each of the tested cultivar)

Figure 4, in detail, illustrates the non-significant interaction of management × cultivar concluded in the combined ANOVA (Table 3). It indicates that all the 28 cultivars were characterized by a significantly and similarly high mean grain yield (calculated across the locations) under the more intensive crop management, A2, in relation to A1 (statistically significant differences are marked with an asterisk, *); only for the cultivars Rapsodia and Garantus these differences were rather not significant (marked with the symbol 'ns') although they were similar to those for previous 26 cultivars. Then, the Figure 4 shows similar mean (across the locations) response of the tested winter wheat cultivars for grain yield to the crop management intensities. Because of the non-significant three-way interaction management × cultivar × location ($p\leq0.574$) and the two-way interaction management × location ($p\leq0.023$), it could be concluded that a similar, positive response of grain yield of each of the tested winter wheat cultivars to increased intensity of management became apparent at each test location (Annicchiarico, 2002; Carr et al., 2003; Fan et al., 2007).

The interaction of cultivar × location was significant (Table 3), and it indicates variation in genotypic yield response at the tested agricultural environments (locations), on average across the two crop management intensities. The non-significant three-way interaction cultivar × management × location, G×M×L (Table 3) indicates that the yield responses of each cultivar to the environments were similar (repeatable) when using each of the two crop management intensities. The non-significant G×M×L interaction justifies the correctness (without loss of information) of restricting ourselves to analysis, interpretation and presentation of the varied cultivar adaptive yield response to environments as based only on mean yields across two crop managements (here on the AMMI(*T*)-modeled mean yield responses). The G×L interaction for yield and its quality in winter wheat and other crop species is a commonly found phenomenon at different latitudes (Ayoub et al., 1994; Oscarsson et al., 1998; Cooper et al., 2001; Schmidt et al., 2001; Annicchiarico, 2002; Ma et al., 2004; Souza et al., 2004; Drzazga et al., 2009; Sharma et al., 2009; Anderson, 2010; Annicchiarico et al., 2010).

Since the sum of squares for the G×L interaction effects is almost 3 times greater than the sum of squares for the main effects of the cultivars (G) (Table 3) evaluating cultivar adaptive yield responses only on the basis of cultivar yield means is not sufficient (Annicchiarico, 2002; Yan and Kang, 2003). The F_R test in AMMI analysis of G×L interaction effects (Cornellius et al., 1996; Annicchiarico, 2002; Dias and Krzanowski, 2003) demonstrated the significance of the first two interaction principal components, which accounted for 46.3% of the sum of squares for the G×L interaction effects (Table 3). Thus, the AMMI(*T*)-modeled yield response of the *i*-th cultivar at the *j*-th location, on average across the two crop management intensities, R_{ij} (1) was estimated including the two significant G×L interaction PCs (Gauch, 1988, 1992; Annicchiarico et al., 2011b). Then, it will be called AMMI(*2*)-modeled cultivar adaptive response. Using Ward's cluster analysis method for the AMMI(*2*)-modeled adaptive responses of cultivar pairs at the locations, nine homogeneous groups (clusters) of cultivars were distinguished (Table 4), which accounted for 86.5% of the total sum of squares for the AMMI(*2*)-modeled cultivar yield responses. Each group contains cultivars exhibiting similar (homogeneous) the AMMI(*2*)-modeled cultivar adaptive yield response across eight environments in Poland. Adaptive response patterns of these cultivar groups were repeatable across the both studied crop managements. It is so due to non-significant G×M×L interaction.

Table 4. Groups of winter wheat cultivars with a similar AMMI(*2*)-modeled cultivar adaptive yield response across eight environments in Poland, distinguished with Ward's cluster analysis method

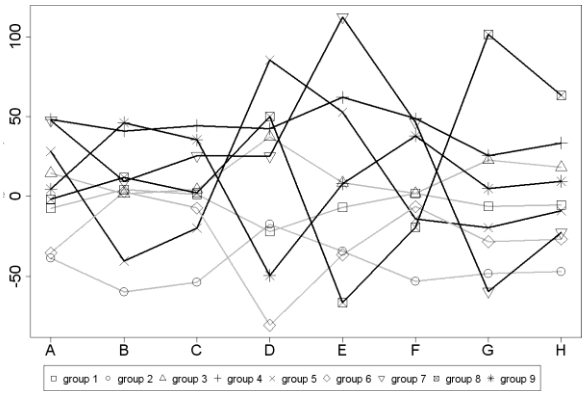
Group 1	Group 2	Group 3	Group 4	Group 5	Group 6	Group 7	Group 8	Group 9
Akteur	Alkazar	Anthus	Bogatka	Boomer	Flair	Kohelia	Legenda	Rapsodia
Finezja	Smuga	Figura	Jenga	Nadobna	Markiza		Meteor	Türkis
Garantus	Wydma	Mulan			Satyna			
Kris		Muszelka						
Ludwig		Tonacja						
Mewa								
Naridana								
Ostroga								

The AMMI(*2*)-modeled cultivar group-mean adaptive yield responses across eight environments in Poland for each of the nine distinguished groups of the cultivars is shown in Figure 5. The lines in Figure 5 reflect group-mean the adaptive responses of the cultivars yield, obtained for a cultivar group at a location as means of AMMI(*2*)-modeled cultivar yield response described by (1). Such cultivar adaptive responses determined by substraction of environmental mean from the AMMI(*T*)-modeled cultivar yield at a location is often applied in work on the assessment of the adaptive response of cultivar traits in order to obtain a smaller range of variation in the scale of the means transformed in this way and to better visually illustrate the differences in the cultivars at each environment, while these cultivar differences do not change after such a transformation (Cooper et al., 2001; Annicchiarico, 2002; Zhang et al., 2006).

Figure 5 is the basis for assessment of the relative adaptability of cultivars at the test environments, since it permits to identify those groups of cultivars (with a similar adaptive response), which were among the highest yielding cultivars only at one environment or a group of environments (cultivars with narrow adaptation) or in all or almost all these environments (cultivars with wide adaptation). When performing the AMMI analysis of data in the classification G×L, researchers often restrict themselves to the AMMI(*1*) model, even if statistical test or other method (for example the cross-validation method) has demonstrated the significance of a larger number of G×L interaction principal components. Such a model can be called sub-optimal (Annicchiarico et al., 2011a).

As a result of choosing such a model, we obtain an easy to interpret, even for a large number of cultivars, the graph of the nominal yield (Gauch, 1992; Gauch and Zobel, 1997; Annicchiarico, 2002; Gauch et al., 2008). In the example presented here, the first G×L interaction principal component accounted (IPC1) for only 24.2% of the sum of squares for the G×L interaction effects, then it was justified to include the second principal component (IPC2) recognized as significant based on the F_R test (Table 3). Considering the AMMI(*2*)-modeled cultivar group-mean adaptive yield response in Figure 5, one may conclude that in the 2008/2009 growing season wide adaptation exhibited cultivars of Group 4 containing Bogatka bred by DANKO Hodowla Roślin sp. z o.o and Jenga bred by Nordsaat Saatzuchtgesellschaft mbH. Their yields were both the highest or at the second place at all the locations, and in the third place in Seroczyn. Group 8 containing cultivars Legenda bred by Poznańska Hodowla Roślin sp. z o.o. and Meteor bred by SW Seed Hadmersleben GmbH), showed narrow adaptation to environments at two locations with the highest mean yield, i.e. Radostowo and Węgrzce which are characterized by high soil fertility of their agro-ecosystems. These cultivars yielded relatively high also in Seroczyn and very poorly in Kościelna Wieś. At the other locations they yielded close to the environmental mean (close to zero in Figure 5).

(a)



(b)

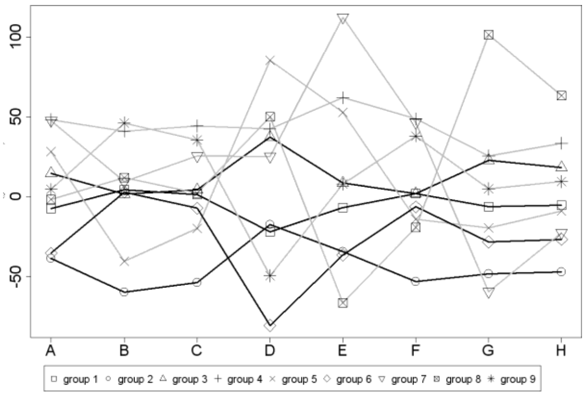


Figure 5. The AMMI(*2*)-modeled cultivar group-mean adaptive yield response patterns across eight environments in Poland for each of the nine distinguished groups of winter wheat cultivars; a) bold and light lines describe mean yield response of cultivar groups showing both specific and wide adaptation or relatively non-adapted to these environments, respectively b) the two response patterns of the cultivar groups are presented using opposite kind of lines. Cultivar groups are presented in Table 5. The location names are: A-Marianowo; B-Nowa Wieś Ujska; C-Głębokie; D-Seroczyn; E-Kościelna Wieś; F-Głubczyce; G-Radostowo; H-Węgrzce

Group 7 with Kohelia bred by the Hodowla Roślin Rolniczych - Nasiona Kobierzyc yielded the highest at Kościelna Wieś, while at Głubczyce and Marianowo it was not far behind the highest yielding group there (Group 4, in both cases). On the other hand, at both locations with the highest yield (fertile agro-ecosystems), it yielded very poorly. It indicates that Kohelia was not relatively adapted to the fertile agro-ecosystems in the studied season. Narrow adaptation to the agro-ecosystem at Nowa Wieś Ujska (the first place in yielding) and Głębokie and Głubczyce was shown by Group 9 including Rapsodia bred by the RAGT Seeds Ltd. and Türkis bred by SW Seed Hadmersleben GmbH. Two cultivars in Group 5, i.e. Boomer bred by SW Seed Hadmersleben GmbH. and Nadobna bred by Poznańska Hodowla Roślin sp. z o.o. were narrowly adapted to the environments in Seroczyn. Stable yields, but only just close to environmental means, were produced by the cultivars from Group 1 (Akteur, Finezja, Garantus, Kris, Ludwig, Mewa, Naridana, Ostroga); not much higher were the yields of Group 3 cultivars (Anthus, Figura, Mulan, Muszelka, Tonacja). Stable, but relatively very low, yields were produced by the cultivars from Group 2 (Alcazar, Smuga, Wydma), thus demonstrating the lack of relative adaptation to the environments in the major winter wheat growing areas in Poland. Lack of adaptation to the environments in Poland was also shown by the not very stable cultivars of Group 6 (Flair, Markiza, Satyna).

CONCLUSIONS

The adapted and assessed comprehensive statistical methodology including a combined three-way analysis of variance for data from one-year, multi-location two-factorial PDOiR trials set up in split-block design, an AMMI analysis for the cultivar×location interaction and a cluster analysis for AMMI-modeled cultivar adaptive responses at the locations, proved to be a complementary and effective tool for evaluating winter wheat cultivar adaptive responses for grain yield across environments (at locations) and crop management intensities. In those cases it is advisable to choose an AMMI model retaining more than one significant G×L interaction principal component, the AMMI($T>1$)-modeled group-mean cultivar adaptive yield responses across environments for each of distinguished groups by clustering cultivars facilitate an efficient identifying and interpretation of the varied adaptability patterns of the tested cultivars. In the weather conditions of the 2008/2009 season, the newest released winter wheat cultivars, included in the Polish National List (NLI) and in the Common Catalogue (CCA), yielded similarly on average across the test locations being representative of the agro-ecosystems in Poland and two crop management intensities; the range of the cultivar grain yield means was from 740 to 840 g m^{-2}, i.e. 7.4 to 8.4 t ha^{-1}. Positive, yield-enhancing effects of the increased intensity of crop management of winter wheat cultivars across the agro-ecosystems of the representative test stations decreased with decreasing productivity of these environments, as measured by the mean yield. In the 2008/2009 growing season, the modern Polish and Western European winter wheat cultivars responded differently for grain yield across agro-ecosystems in Poland, while their adaptive responses were not dependent on the crop management intensity. These cultivars responded similarly, i.e. with a similar significant increase in yield, to the increase in the intensity of crop management, irrespective of the environments. Wide adaptation exhibited by Polish cultivar Bogatka and the German cultivar Jenga, losing in only very few environments the top two positions for yield to other groups of cultivars with narrow adaptation.

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LITERATURE CITED

Akcura M., Y. Kaya, S. Taner, 2009. Evaluation of durum wheat genotypes using parametric and nonparametric stability statistics. Turk. J. Field Crops 14(2): 111– 122.

Anderson W.K., 2010. Closing the gap between actual and potential yield of rain-fed wheat. The impacts of environment, management and cultivar. Field Crops Res. 116:14–22

Annicchiarico P., 2002. Genotype x environment interactions - Challenges and opportunities for plant breeding and cultivar recommendations, FAO Plant Productions and Protection Paper No 174, FAO, Rome, 115pp

Annicchiarico P., F. Bellah, T. Chiari, 2006. Repeatable genotype×location interaction and its exploitation by conventional and GIS-based cultivar recommendation for durum wheat in Algeria. Eur .J. Agron. 24:70–81

Annicchiarico P., E. Chiapparino, M. Perenzin, 2010. Response of common wheat varieties to organic and conventional production systems across Italian locations, and implications for selection. Field Crops Res. 116:230-238

Annicchiarico P., L. Pecetti, A. Abdelguerfi, A. Bouizgaren, A.M. Carroni, T. Hayek, M. M'Hammadi Bouzina, M. Mezni, 2011a. Adaptation of landrace and variety germplasm and selection strategies for lucerne in the Mediterranean basin. Field Crops Res. 120:283-291

Annicchiarico P., L. Pecetti, H. Bouzerzour, R. Kallida, A. Khedim, C. Porqueddu, N.M. Simões, F. Volaire, F. Lelièvre, 2011b. Adaptation of contrasting cocksfoot plant types to agricultural environments across the Mediterranean basin. Environ. Exp. Bot. 74:82– 89

Ayoub M., S. Guertin, J. Fregeau-Reid, D.L. Smith, 1994. Nitrogen fertilizer effect on breadmaking quality of hard red spring wheat in eastern Canada**.** Crop Sc. 34:1346-1352

Basford K.E., Cooper M. 1998. Genotype x environment interactions and some considerations of their implications for wheat breeding in Australia. Austr. J. Agric. Res. 49:153-174

Bradu D., K.R. Gabriel, 1978. The biplot as a diagnostic tool for model of two-way tables. Technometrics 1978 47–63

Carr P.M., R.D. Horsley, W.W. Poland, 2003. Tillage and seeding rate effects on wheat cultivars: I. grain production. Crop Sci. 43:202–209.

COBORU, 2002. Cereals. Methodology of cultivar testing. COBORU, Słupia Wielka (In Polish)

Cooper M., D.R. Woodruff, I.G. Phillips, K.E. Basford, A.R. Gilmour, 2001. Genotype-by-management interactions for grain yield and grain protein concentration of wheat. Field Crops Res. 69:47-67

Cornelius P.L., J. Crossa, M. Seyedsadr, 1996 Statistical tests and estimators of multiplicative models for genotype-by-environment interaction. In: Kang M.S., H.G. Gauch (Eds.), Genotype by Environment Interaction. CRC Press, Boca Raton, 199-234

Crossa J., P.N. Fox, W.H. Pfeiffer, S. Rajaram, H.G. Gauch 1991. AMMI adjustment for statistical analysis of an international wheat yield trial. Theor. Appl. Genet. 81:27–37

Denčić S., N. Mladenov, B. Kobiljski, 2011. Effects of genotype and environment on breadmaking quality in wheat. Int. J. Plant Prod. 5:71-82

Dias C., W. Krzanowski, 2003. Model selection and cross validation in additive main effect and multiplicative interaction models. Crop Sci. 43:865-873

Drzazga T., J. Paderewski, W. Mądry, P. Kajewski, 2009. The winter wheat yield response to environments in post-registration trials. Biuletyn IHAR 253:71-82 (In Polish)

Fan X.M., M.S. Kang, H. Chen, Y. Zhang, J. Tan, C. Xu, 2007. Yield stability of maize hybrids evaluated in multi-environment trials in Yunnan, China. Agron. J. 99:220-228

Gauch H.G. 1988. Model selection and validation for yield trials with interaction. Biometrics 44:705-715

Gauch H.G. 1992. Statistical analysis of regional yield trials. AMMI analysis of factorial designs. Elsevier Science, New York, NY.

Gauch H.G., H.P. Piepho, P. Annicchiarico, 2008. Statistical analysis of yield trials by AMMI and GGE: Further considerations. Crop Sci. 48:866–889

Gauch H.G., R.W. Zobel, 1997. Identifying mega-environments and targeting genotypes. Crop Sci. 37:311-326

Geleta B., M. Atak, P.S. Baenziger, L.A. Nelson, D.D. Baltenesperger, K.M. Eskridge, M.J. Shipman, D.R. Shelton 2002. Seeding rate and genotype effect on agronomic performance and end-use quality of winter wheat. Crop Sci. 42:827–832

Gomez K.A., A.A. Gomez, 1984. Statistical procedures for agricultural research. 2nd ed. John Wiley & Sons, Toronto, Canada

Ilker E., H. Geren, R. Unsal, I. Sevim, F. Aykut Tonk, M. Tosun, 2011. AMMI-biplot analysis of yield performances of bread wheat cultivars grown at different locations. Turk. J. Field Crops, 16(1): 64-68

Ma B.L., W. Yan, L.M. Dwyer, J. Fregeau-Reid, H.D. Voldeng, Y. Dion, H. Nass, 2004. Graphic analysis of genotype, environment, nitrogen fertilizer, and their interactions on spring wheat yield. Agron. J. 96:169–180

Mądry W., E.S. Gacek, J. Paderewski, D. Gozdowski, T. Drzazga 2011. Adaptive yield response of winter wheat cultivars across environments in Poland using combined AMMI and cluster analyses. Int. J. Plant Prod. 5:299-310

McIntosh M.S. 1983. Analysis of combined experiments. Crop Sci. 75:153-156.

Mejza I. 1998. Characterization of certain split-block designs with a control. Biometrical J. 40:627–639

Mejza I. 1999. Planning of multi-environment two-factorial trials planned in a split-plot design and data analysis. Roczniki Akademii Rolniczej w Poznaniu, vol 301 (In Polish)

Mintenko A.S., S.R. Smith, D.J. Cattani 2002. Turfgrass evaluation of native grasses for the Northern Great Plains Region. Crop Sci. 42:2018–2024

Oscarsson M., R. Anderrsson, P. Aman, A. Jonsson 1998. Effects of cultivar, nitrogen fertilization rate and environment on yield and grain quality of barley. J. Sci. Food Agric. 78: 359-366

Paderewski J, H.G. Gauch, W. Mądry, Drzazga T., Rodrigues P.C. 2011. Yield response of winter wheat to agro-ecological conditions using additive main effects and multiplicative interaction and cluster analysis. Crop Sci. 51:969–980

Pena R.J. 2007. Current and future trends of wheat quality needs. In: Buck H. T., Nisi J. E., Salomon N. (Eds.). Wheat production in stressed environments. Springer, pp: 411-424

Piepho H.P. 1995. Robustness of statistical tests for multiplicative terms in the additive main effects and multiplicative interaction model for cultivar trials. Theor. Appl. Genet. 90:438-443

R Development Core Team. 2009. R: A language and environment for statistical computing. Available at http://www.Rproject.org (verified 3 Dec. 2010). R Foundation for Statistical Computing, Vienna, Austria

SAS Institute. 2004. SAS system for Windows. v. 8.2. SAS Inst., Cary, NC

Schmidt J.P., J.A. Lamb, M.A. Schmitt, G.W. Randall, J.H. Orf, H.T. Gollany, 2001. Soybean varietal response to liquid swine manure application. Agron. J. 93:358–363

Sharma R.C., A.I. Morgounov, H.J. Braun, B. Akin, M. Keser, D. Bedoshvili, A. Bagci, C. Martius, M. van Ginkel, 2009. Identifying high yielding stable winter wheat genotypes for irrigated environments in Central and West Asia. Euphytica 171,53-64

Sivapalan S., L. O'Brien, G. Ortiz-Ferrera, G.J. Hollamby, I. Barclay, P.J. Martin, 2000. An adaptation analysis of Australian and CIMMYT/ICARDA wheat germplasm in Australian production environments. Aust. J. Agric. Res. 51: 903-915

Souza E.J., J.M. Martin, M.J. Guttieri, K.M. O'Brien, D.K. Habernicht, S.P. Lanning, R. McLean, G.R. Carlson, L.E. Talbert, 2004. Influence of genotype, environment, and nitrogen management on spring wheat quality. Crop Sci. 44:425-432

Yan W., M.S. Kang, 2003. GGE Biplot Analysis: A Graphical Tool for Breeders, Geneticists, and Agronomists. CRC Press. Boca Raton, FL

Zhang Y., Z. He, A. Zhang, M. van Ginkel, G. Ye, 2006. Pattern analysis on grain yield of Chinese and CIMMYT spring wheat cultivars grown in China and CIMMYT. Euphytica 147:409-420