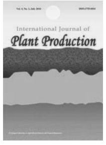

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Adaptive yield response of winter wheat cultivars across environments in Poland using combined AMMI and cluster analyses

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Abstract

The objective of the paper was to illustrate using and usefulness of a joint AMMI and cluster analyses to assess the grain yield adaptive response of Polish and foreign 31 winter wheat cultivars in a range of 20 environments (locations) and across 3 years (2005-2007) under integrated crop management, using data obtained in the post-registration variety testing trials (called PDO trials), to identify those entries with specific and wide adaptation. Two-stage combined analysis of variance for data in the three-way GLY classification was carried out according to a mixed model (cultivar and location as fixed factors and years as random factor). GL repeated (across years) interaction effects were modeled by (a) joint regression and (b) additive main effects and multiplicative interaction (AMMI). The thirty one cultivar adaptive responses, expressed by nominal yields based on significant AMMI-1 model, accounting for 27.8% of SS for GL interactions, were divided into six homogenous groups by Ward's method of cluster analysis. Group-mean cultivar adaptive responses indicated clearly the wide adaptation of cultivars in groups 1 and 2 including mostly German and United Kingdom entries and also two Polish ones. Cultivars from group 6, including three Polish cultivars and three foreign ones, were among at most four top-ranking entries at all locations excluding one environment (Wyczechy at Pomerania region). Cultivars from group 3, including seven Polish cultivars and one from United Kingdom and France, showed extremely specific adaptation characterized by nominal yield responses being positively related to GL interaction PC 1 scores of the locations. However, cultivars from group 5, including five Polish ones and a French one were poor adapted to the growing area. Presented the joint AMMI and cluster analyses were effective to distinguish adaptive responses of studied cultivars on the basis of data from PDO trials and could be seen as a better alternative, based more on probability-approached methodology, to common pattern analysis.

Keywords: Winter wheat; Grain yield; Post-registration cultivar trials (PDO trials); AMMI analysis; Cluster analysis; Nominal yield; Cultivar adaptive responses.

Introduction

Wheat is a major crop contributing to the nutrient supply of the world's population. Of the total wheat supply, an average of 53% is consumed as food in the developed countries, and close to 85% in the developing countries (Denčić et al., 2011). It has long been recognized that wheat yielding and other agronomic and quality traits vary considerably as a result of genotype, environment and their interaction (Allard and Bradshaw, 1964; Basford and Cooper, 1998; Trethowan and Crossa, 2007; Denčić et al., 2011).

The main objective of plant breeding in major crop species, including winter wheat, is to develop new cultivars showing one of two adaptation patterns called wide or specific (local) adaptation to the environments within a target production (growing) area (Sivapalan et al., 2000; Annicchiarico, 2002a; Annicchiarico, 2002b; Rane et al., 2007). The adaptation patterns of each tested cultivar can be described by their yield responses (called also cultivar adaptive responses (Annicchiarico et al., 2006b; Annicchiarico et al., 2011; Annicchiarico and Iannucci, 2008; Gauch et al., 2008) across a wide range of environments and also years in the production area. Predicting repeatable cultivar adaptive responses (responses across years) requires conducting multi-environment trials (METs) with a set of offered cultivars continued across representative test environments (locations) of the production area and years (Annicchiarico, 2002a; Annicchiarico, 2002b; Trethowan and Crossa, 2007; Annicchiarico et al., 2010). On the basis of yield data from these trials it is possible to estimate (predict) both the genotypic means yield (average across locations and years) and repeatable genotype x location, GL, interaction effects (Yan and Hunt, 1998; Trethowan et al., 2002, Annicchiarico, 2002b; Annicchiarico et al., 2006a; Annicchiarico et al., 2010). Sums of predicted genotypic mean yield and the GxL interaction effects for a given cultivar produce repeatable cultivar adaptive responses (Ghaderi et al., 1982; Yan et al., 2007; Rodriguez et al., 2008; Annicchiarico, 2002b).

Cultivars having wide adaptation are defined as these that in representative METs produced yields substantially above the environmental means and then were among a few top-ranking ones at a majority of locations across the production area which is characterized by substantial variation in environmental conditions (Braun et al., 1996; Annicchiarico, 2002b; Rodriguez et al., 2008). Such cultivars produce relatively high and stable yields within the area (Annicchiarico, 2002b; Singh et al., 2007; Yan et al., 2007; Yang et al, 2009). Cultivars having specific adaptation are defined as these that produced yields substantially above the environmental means and then were among a few top-ranking ones in a range of a sub-region (macroenvironment) within the target region, usually of limited environmental variation (Gauch and Zobel, 1997; Annicchiarico, 2002b; Lillemo et al., 2005; De la Vega and Chapman, 2006) or in at least one environment within the target area (Annicchiarico and Iannucci, 2008; Annicchiarico et al., 2010). Usually, cultivars with wide adaptation have fairly high yield potential and stress tolerance, whereas specifically-adapted ones have top levels of either yield potential or stress tolerance (Annicchiarico, 2002b; Singh et al., 2007; Trethowan and Crossa, 2007; Ulukan, 2008). Although widely adapted cultivars are usually preferred, the merits of those with local adaptation are also recognized (Annicchiarico, 2002a; Annicchiarico, 2002b; Zhang et al., 2006; Singh et al., 2007).

Predicting repeatable cultivar adaptive responses of newly released cultivars of important crops is assessed in Poland within the post-registration variety testing trials (called PDO trials) which are METs repeated across environments and years. They deliver essential information for effective cultivar recommendations for megaenvironments (locally adapted cultivars) or for large sub-regions including also whole country (widely adapted cultivars). Many different statistical methods have been used to estimate or predict cultivar adaptive responses using data from METs, both more graphical (Yan et al., 2007; Yang et al., 2009; Kozak, 2010a; Kozak, 2010b) and advanced (Gauch, 1992; Gauch, 2006; Gauch and Zobel, 1997; Annicchiarico, 2002b; Gauch et al., 2008). Among them those advanced techniques based on AMMI model have been effective (Samonte et al., 2005; Annicchiarico et al., 2006b; Annicchiarico et al., 2010; Annicchiarico et al., 2011; Gauch et al., 2008), especially nominal yield based on AMMI-1 modeled GL data allowing more accurate predicting cultivar adaptive responses than usual mean data for GL classification because of their greater theoretical (Gauch, 1992; Gauch and Zobel, 1996) and empirical (Annicchiarico et al., 2006a) ability to predict the future responses of cultivars.

However, in a case of a large number of assessed cultivars, the tool of nominal yield used in its classic form can be less effective due to many lines on the nominal yield graph and difficulties to clearly distinguish them (Haussmann et al., 2000; Kozak, 2010b). A solution of this problem could be grouping AMMI-modeled cultivar adaptive responses into homogenous groups using cluster analysis. The objective of this study is to illustrate using and usefulness of a joint AMMI and cluster analyses to assess the genotype grain yield adaptive responses of Polish and foreign recent winter wheat cultivars across major wheat growing area in Poland under integrated crop management, using data obtained in the PDO trials.

Materials and Methods

Experimental material

In this study data were used for grain yield of thirty one Polish and foreign recent winter wheat cultivars tested across twenty locations (called Experimental Stations for Cultivar Testing) and repeated over three growing years 2005-2007. The cultivars were assessed in the post-registration variety testing trials (PDO trials) conducted within the nation-wide PDO trials system developed by the Research Centre for Cultivar Testing (COBORU) in Słupia Wielka, near Poznań, Poland (http://www.coboru.pl/English/aindex.htm). The test locations had been selected in such a way to cover (represent) major Polish wheat growing area. In each trial an integrated crop management with N-rates of 40 kg ha^{-1} less as compared to yield expectations and standard PK fertilizations for a given location and pesticide use limited to a seed treatment, without use of growth regulators to prevent lodging. The seeding rate was in a range of 400 to 450 grains/m^2 at locations, depending on the cultivar, while at locations with less quality soils seeding rate was increased by 50 or

100 grains/m^2. All experiments at macroenvironments were designed as a randomized complete block with two replicates, with plot sized 15 m^2 (10 × 1.5 m).

The cultivars and breeding companies which bred them and years of their release (1996-2004) are given in Table 1. Among the tested 31 cultivars 22 ones have been bred by Polish breeding companies and remaining 9 ones have been bred by German, French and United Kingdom companies. The locations of the Experimental Stations for Cultivar Testing (SDOOs), whose names and geographical position are reported in Figure 1, were well-scattered across the main Polish common wheat growing area and then they represent this area.

Table 1. Winter wheat cultivars tested in post-registration trials (PDO trials) carried out at locations across years 2005-2007.

Cultivar	Year of release	Breeding company		Cultivar	Year of release	Breeding company	
KOBRA PLUS	1992	HRR Nasiona Kobierzyc	PL	FLAIR	2002	Saatzucht Hans Schweiger & Co.oHG	DE
TONACJA	2001	HR Strzelce	PL	ARISTOS	2003	Fr. Strube Saatzucht KG	DE
FINEZJA	2002	HR Danko	PL	KOBIERA	2003	Nasiona Kobierzyc	PL
BOGATKA	2004	HR Danko	PL	NADOBNA	2003	PHR Tulce	PL
SAKWA	1996	HR Strzelce	PL	RAPSODIA	2003	RAGT Seeds Ltd.	UK
KAJA	1997	PHR Tulce	PL	RUBENS	2003	Limagrain Verneuil Holding	FR
MEWA	1998	HR Danko	PL	RYWALKA	2003	HR Strzelce	PL
SYMFONIA	1999	HR Smolice	PL	TREND	2003	KWS Lochow GmbH	DE
ZYTA	1999	HR Strzelce	PL	DOROTA	2004	RAGT Seeds Ltd.	UK
SORAJA	2000	HR Strzelce	PL	FREGATA	2004	HR Strzelce	PL
KRIS	2000	RAGT Seeds Ltd.	UK	SATYNA	2004	Nasiona Kobierzyc	PL
NUTKA	2001	HR Strzelce	PL	OLIVIN	2004	R2n SAS	FR
SŁAWA	2001	PHR Tulce	PL	SMUGA	2004	HR Danko	PL
SUKCES	2001	HR Strzelce	PL	ZAWISZA	2004	HR Smolice	PL
TURNIA	2001	Małopolska Hodowla Roślin	PL	MUZA	2004	Małopolska Hodowla Roślin	PL
PEGASSOS	2001	Fr. Strube Saatzucht	DE				

PL-Poland, DE-Germany, FR-France, UK-United Kingdom.

Figure 1. Locations of the Experimental Stations for Cultivar Testing in Poland within the network of COBORU stations where post-registration trials (PDO trials) for winter wheat were carried out across 2005-2007.

Statistical analysis

Plot data of grain yield were subjected to: (a) an analysis of variance (ANOVA) for each macroenvironment being location-year combination, assuming cultivar as a fixed factor and block as a random factor (Annicchiarico et al., 2010); (b) a combined ANOVA for genotype-location-year cell means designed in a complete three-way classification, holding cultivar and location as fixed factors and year as a random factor (Annicchiarico, 2002b; Annicchiarico et al., 2010). Testing each effects in the mixed ANOVA model for the combined analysis was done using F test assuming error variance in macroenvironments to be homogenous (McIntosh, 1983; Annicchiarico, 2002b).

Genotype-location repeated (across years) interaction (GL interaction) effects in the combined 3-way ANOVA were modeled by two major techniques for analysis of cultivar adaptation, namely: (a) joint regression, where GL interaction effects are modeled by genotype regression as a function of environment mean yield (Finlay and Wilkinson, 1963) and (b) additive main effects and multiplicative interaction (AMMI), where modeled GL interaction effects are accounted for by one (AMMI-1), two (AMMI-2) or more statistically significant axes of a double-centered principal component analysis performed on the GL interaction matrix (Gauch, 1992; Annicchiarico, 2002b). Testing GL interaction principal component (PC) axes were carried out by the F_R test (Cornellius, 1993; Piepho, 1995). GLY interaction was used as the error term for testing PC axes (Annicchiarico et al., 2010). For testing heterogeneity of regressions deviations from regression was used as the error term (Finlay and Wilkinson, 1963; Annicchiarico et al., 2010).

Cultivar adaptive responses can be graphically displayed as nominal yields for each cultivar being a function of the location PC 1 score. Nominal yields are cultivar expected responses based on AMMI-1 modeled GL interaction effects (called also AMMI-1 modeled cultivar responses) from which the location main effect, that has no influence on cultivar ranking, has been eliminated in order to linearize the adaptive responses (Gauch, 1992; Gauch and Zobel, 1997; Annicchiarico, 2002b). Additionally, an important advantage of the AMMI modeling cultivar adaptive responses, beyond their more predictive ability, is that allows for reducing the number of cultivars that were top-ranking in at least one location in comparison with observed data, thereby simplifying cultivar evaluation and recommendation (Annicchiarico et al., 2006b).

The cultivar adaptive responses expressed by nominal yields of the thirty one entries were divided into groups by Ward's method of cluster analysis, in which the measure of the distances between the cultivars was the squared Euclidean distance for the cultivar-specific AMMI-1 modeled GL means, e.g., nominal yields (Annicchiarico, 2002b). These cultivar groups are homogeneous in terms of the cultivar adaptive responses. Due to instead of cultivars their group-mean cultivar adaptive responses (average-group nominal yields) obtained by clustering are presented graphically on the plot in this study, which certainly overcomes the problem of too many responses within one plot (Haussmann et al., 2000; Annicchiarico et al., 2006b; Annicchiarico and Iannucci, 2008; Kozak, 2010b).

The statistical package R (R Development Core Team, 2010) was used for all analyses except joint regression and AMMI analysis, which were performed by CropStat (formerly IrriStat), released by the International Rice Research Institute (IRRI, 2007) and recommended by Annicchiarico (2002b).

Results and Discussion

The combined analysis of variance

The ANOVA (Table 2) has found all effects studied for grain yield to be significant in the target growing area. Among them the most important for assessment of cultivar adaptive responses are main effects of cultivars, genotype x location (GL) interaction effects and genotype x location x years (GLY) interaction effects (Allard and Bradshaw, 1964; Annicchiarico, 2002b; Annicchiarico et al., 2011). The GL interaction effects are repeatable in time and then may be exploited by recommendation of cultivars for specific adaptation to some environments contrasting for GL interaction effects (Annicchiarico et al., 2006a; Annicchiarico et al., 2010). The significant effects of GLY interactions are, in turn, relate to lack of repeatability across years of GL interaction effects (Annicchiarico, 2002b; Roozeboom et al., 2008). The study clearly shows that in these trials there were both different shapes of mean multi-year grain yield response of the studied winter wheat cultivars to spatially varied eco-geographical conditions across Poland and genotypic means. Due to these one may expected that some cultivars would show specific adaptation, also other ones may be widely adapted within the range of the Polish major wheat growing area.

Table 2. The combined analysis of variance for winter wheat grain yield obtained in a post-registration trials (PDO trials) under integrated crop management including GL interaction partitioned by: (a) joint regression and (b) AMMI analyses.

Source	DF	Sum of Squares (SS)	Mean Squares (MS)	F_{Ratio}
Cultivar (G)	30	11647.8	388.3	8.25**
Location (L)	19	188708.7	9932.0	5.61**
Year (Y)	2	70115.0	35057.5	9225.66**
Cultivar × Location (GL)	570	15860.7	27.8	1.35**
(a) Heterogeneity of regressions	30	1367.6 (8.6)^{a}	45.6	1.70**
Deviations from regression	540	14493.1 (91.4)^{a}	26.8	1.30**
(b) PC 1	48	4414.6 (27.8)^{a}	92.0	4.46**
Residua	522	11446.1 (72.2)^{a}	21.9	1.06^{ns}
Cultivar × Year	60	2823.4	47.1	12.39**
Location × Year	38	67236.3	1769.4	465.63**
Cultivar × Location × Year	1140	23504.5	20.6	5.42**
Poolled mean error	2179		3.8	

^{a} numbers in brackets are percentage of SS for GL interaction effects explained by regression, interaction principal component PC1 and respective residuals.

^{ns} not significant.

** Significant at $P<0.01$.

The selected, as an optimal, AMMI model included one PC axis (AMMI-1) and was preferable to joint regression on the basis of its greater GL interaction SS accounted for (27.8% vs. 8.6%) and the highly significant deviations from regression term and no significant variation residuals term (Table 2). Similar results showing superiority of AMMI to joint regression models in realized accuracy predicting GE interaction effects were documented by researchers in many studies (Annicchiarico et al., 2006a; Annicchiarico et al., 2006b; Annicchiarico et al., 2010; Annicchiarico et al., 2011; Solomon et al., 2008).

Grouping cultivars and group-mean nominal yields analysis

Six homogenous groups of cultivars with similar nominal yields were distinguished when dendrogram was truncated at these six-group level, retaining 89% of dissimilarity (dendrogram not shown).

Group-mean repeatable adaptive responses of the six cultivar homogenous groups are reported in Figure 2 as lines presenting mean nominal grain yield across cultivars in a group. Due to the obtained clusters of the cultivar nominal yields include rather similar entries, the group-mean nominal yields reflect accurately adaptive response of all cultivars in each group. The dot line represents a constant function of means for nominal yields of all the tested cultivars at environments on the PC 1 location scores. Then, the Figure 2 makes easier to identify cultivar groups with specific and wide adaptation and those not adapted to varied environmental conditions across the target region.

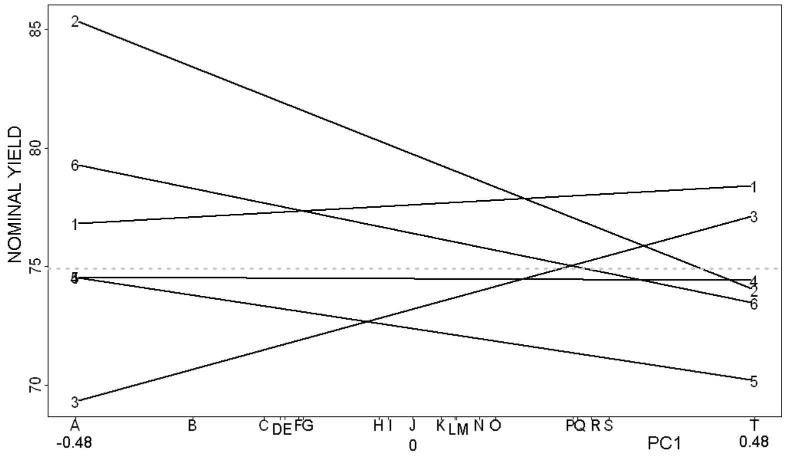

Figure 2. Group-mean nominal grain yields showing repeatable adaptive responses for seven homogenous groups of winter wheat cultivars (the dot line represents a constant function of means for nominal yields of all the tested cultivars at environments on the PC 1 location scores).

Groups of cultivars: 1-ARISTOS^{DE}, FLAIR^{DE}, KRIS^{UK}, NUTKA^{PL}, PEGASSOS^{DE}; 2-BOGATKA^{PL}, RAPSODIA^{UK}, TREND^{DE}; 3-DOROTA^{UK}, FREGATA^{PL}, KOBIERA^{PL}, OLIVIN^{FR}, SAKWA^{PL}, SUKCES^{PL}, SYMFONIA^{PL}, TURNIA^{PL}, ZAWISZA^{PL}; 4-FINEZJA^{PL}, KAJA^{PL}, MEWA^{PL}, SORAJA^{PL}, TONACJA^{PL}, 5-KOBRA PLUS^{PL}, MUZA^{PL}, RUBENS^{FR}, RYWALKA^{PL}, SLAWA^{PL}, ZYTA^{PL}; 6-NADOBNA^{PL}, SATYNA^{PL}, SMUGA^{PL}.

Locations: A-Kościelna Wieś; B-Czesławice; C-Zybiszów; D-Głubczyce; E-Zadąbrowie; F-Krościna Mała; G-Masłowice; H-Tomaszów Bol; I-Marianowo; J-Seroczyn; K-Pawłowice; L-Węgrzce; M-Rychliki; N-Tarnów; O-Głębokie; P-Cicibór; Q-Radostowo; R-Nowa Wieś Ujska; S-Słupia; T-Wyczechy.

Interpretation of adaptive response patterns

The similarity of environments for cultivar adaptive response as indicated by the environment ordination on the first GL interaction PC (Figure 2) has not confirmed their geographical distribution. It shows that climate across Poland is not major discriminating factor of differentiation patterns in winter wheat cultivars for grain yield at various environments. It would be justified to suppose that soil properties and biotic factors could be more important in affecting how cultivars are ranked for yield in a range of environments (Lillemo et al., 2005; Rane at al., 2007; Roozeboom et al., 2008; Trethowan and Crossa, 2007).

Comparisons performed on the group-mean value of nominal yield responses (Figure 2) indicated clearly the wide adaptation of cultivars in groups 1 and 2 including mostly German and United Kingdom entries and also two Polish ones NUTKA and BOGATKA. Cultivars from group 2, showing the highest genotypic mean yield across environments, won at 15 of 20 environments and they were among the second top-ranking ones at four remaining locations and the fours ones only in one environment. Cultivars from group 1 were among the at most three top-ranking ones at all environments, although their mean yield was the second among all six cultivar groups. Also cultivars from group 6 including three Polish cultivars, e.g. NADOBNA, SATYNA and SMUGA, were among at most four top-ranking ones at all locations excluding one environment (Wyczechy at Pomerania region in Northern part of Poland), which extremely discriminated cultivars as compared to most environments, where these cultivars were not adapted. Cultivars from the groups 1, 2 and 6 outperformed environmental yield means in all environments excluding Wyczechy. Given characterization of the performing cultivars from groups 1, 2 and 6 suggests clearly that these sets of entries showed wide adaptation across Polish winter wheat growing area. Among the three groups of cultivars those in group 6 manifested lowest degree of wide adaptation (Singh et al., 2007; Trethowan and Crossa, 2007; Rodriguez et al., 2008).

In spite of such an interpretation of adaptive responses of the three cultivar groups in wide adaptation categories, however, group-mean nominal yields of these cultivars manifested also their specific adaptation. Cultivars from group 2 performing usually at the top, responded very poorly in Wyczechy. Similarly, cultivars from the group 6, showed also relatively poor adaptation at Wyczechy. But alternation of yield ranking of the cultivar group 1 in the environments was in contrast to the cultivar groups 2 and 6. They were relatively less adapted to most environments but best adapted to Wyczechy.

Cultivars from group 4, including nine five Polish cultivars, e.g. FINEZJA, KAJA, MEWA, SORAJA and TONACJA were very stable in yielding across the target region and their genotypic means approached to environmental means. These cultivars could be also taken into account in their recommendation to Polish eco-geographical conditions in a wide range. Cultivars from group 3, including seven Polish ones (FREGATA, KOBIERA, SAKWA, SUKCES, SYMFONIA, TURNIA and ZAWISZA) and also DOROTA from United Kingdom and OLIVIN from France, showed extremely specific adaptation. Their nominal yields were positively related to GL interaction PC 1 scores of the locations. Then, these cultivars were relatively at least and at most adapted to contrast environments, respectively at Kościelna Wieś and Wyczechy, showing relatively almost the greatest yield at Wyczechy. However, cultivars from group 5, including five Polish cultivars and a French one, e.g. KOBRA PLUS, MUZA, RUBENS, RYWALKA, SLAWA and ZYTA, were generally poor adapted to the growing area showing relatively poor yield below environmental means across all environments.

Usefulness of the statistical methodology used

The joint AMMI and cluster analyses used for PDO trials data allowed a reliable grouping of winter wheat cultivars manifesting similar nominal grain yields in a range of environments and then adaptive response across Polish growing area. In this study six such separate homogeneous groups of cultivars were distinguished. Cultivars from different groups showed substantially various adaptive response patterns. The considered here procedure made it easier to classify cultivars in terms of adaptive responses, and distinguished groups of cultivars with wide or specific adaptation. This information is essential to provide improved cultivar recommendation and other extension cultivar services to farmers. Presented the joint AMMI and cluster analyses as a methodological approach to distinguish most effectively adaptive responses of studied cultivars on the basis of PDO trials yield data could be seen as a more efficient alternative to pattern analysis (Basford and Cooper, 1998; Zhang et al., 2006). The joint AMMI and cluster analyses integrate more statistical procedures based on probability-approached methodology as compared to pattern analysis which is a data analysis method based on descriptive and graphical tools not involving statistical tests (Zhang et al., 2006).

Conclusions

1. The study clearly shows that in PDO trials there were substantially various adaptive responses across Polish major winter wheat growing area of the studied cultivars. Due to these some cultivars showed specific adaptation and other ones, mostly bred in Germany and United Kingdom, were widely adapted in a range of the growing area,
2. The joint AMMI and cluster analyses used for PDO trials allowed to predict accurately and classify effectively cultivar adaptive responses as based on nominal yields (expressed by AMMI-1 model); this makes easier to identify cultivars with specific and wide adaptation and those not adapted to varied environments across the growing area as compared to presenting nominal yields for each tested cultivar,
3. This new procedure integrates both descriptive and probability-based methodological approach to cultivar adaptive response evaluating and, then, can be seen as a more efficient alternative to pattern analysis or GGE analysis because of its ability to make more critical decisions on cultivar selection or recommendation which should be based on statistical tests.

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