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YIELDING OF OLD AND MODERN POLISH WHEAT CULTIVARS UNDER DIFFERENT NITROGEN INPUTS AS ASSESSED BY COMBINED USING AMMI AND CLUSTER ANALYSES

ABSTRACT

The experimental material consisted of 15 winter wheat cultivars (14 Polish-bred cultivars and one British cultivar) representing the results of over 100 years of breeding. The cultivars were tested in two-factor field experiments (cultivars were one factor and nitrogen fertilization rates, the other factor) carried out in split-plot design across two consecutive years. This paper demonstrates a combined using AMMI and cluster analyses for effective and efficient estimate of grain-yield response to investigated environments (combinations of 2 years x 3 nitrogen fertilization rates). First, homogenous groups of cultivars were identified in terms of their genotypic profile of AMMI(*s*) estimates of GEI effects using Ward's method of cluster analysis. Then, these groups were divided into separate homogenous subgroups with respect to genotype means. The cultivars in each subgroup have a similar grain yield response to the environments and, then, similar adaptation pattern, although the genotype groups differed in adaptation to these environments.

Key words: AMMI analysis, cluster analysis, cultivar's adaptation patterns, wheat cultivars

INTRODUCTION

In the last few decades, the wheat cultivation systems, based on the use of new (intensive) cultivars with a high yield potential and high application rates of nitrogen, pesticides and irrigation, have made it possible to substantially increase grain yields both in the developed and developing countries. The commonly occurring Genotype by Environments (GE) interaction for crop plant yield and its dependence on environmental and genetic factors are a source of a fairly popular view that the modern and intensive wheat cultivars do not produce relatively high yields (above those of the old and extensive cultivars) in low-input cultivation systems equally well, especially at low nitrogen fertilization (El Bassam 1998, Carr *et al.* 2006, De Vita *et al.* 2007). However, results of various experimental studies

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do not fully confirm this thesis (Poutala *et al.* 1993; Austin 1999, Fufa *et al.* 2005, Carr *et al.* 2006, Carena *et al.* 2009). The cause of this phenomenon is mainly the improvement in the efficiency of nitrogen uptake and utilization by the plants of modern cultivars and the increased tolerance of unfavourable factors in the environment, i.e. environmental stress (Feil 1992, Ortiz-Monasterio *et al.* 1997, Foulkes *et al.* 1998, Le Gouis *et al.* 2000, Tollenar and Lee 2002, Brancourt-Hulmel *et al.* 2003, Kitchen *et al.* 2003, Guarda *et al.* 2004, Muurinen and Peltonen-Sainio 2006, Carena *et al.* 2009).

Therefore, it would seem necessary to examine, more widely and more convincingly, the types of grain-yield responses of old and new wheat cultivars to the rates of nitrogen fertilization (and the levels of other input factors). This applies to every species of grain crops, but especially to winter wheat as the most important grain crop in Poland and in the world.

The main aim of these studies, ever more frequently undertaken in various countries, is to search for such cultivars, among the old and modern ones, and to endeavour to breed new cultivars, that are specifically adapted to high input crop managements connected mainly with high nitrogen fertilization and intensive plant protection, or to lower input crop managements, or else are widely adapted to both types of these crop managements (Austin 1999, Ceccarelli 1989, 1994, 1996, Calderini and Slafer 1999, Le Gouis *et al.* 2000, Atlin *et al.* 2001, Brancourt-Hulmel *et al.* 2003, Guarda *et al.* 2004, Sinebo 2005, Carr *et al.* 2006, Mathews *et al.* 2006, Giunta *et al.* 2007, Murphy *et al.* 2007, Worku *et al.* 2007, Laperche *et al.* 2008). The central direction of this work aims at answering the question if some of the modern and intensive grain crop cultivars also yield relatively high at lower nitrogen fertilization rates in diverse environmental and weather conditions of the target cultivation areas – that is – if they are widely adapted to a broad range of nitrogen fertilization rates (Ortiz-Monasterio *et al.* 1997, Raun and Johnson 1999, Brancourt-Hulmel *et al.* 2003, Hasegawa 2003, Guarda *et al.* 2004, Ma *et al.* 2004).

It is highly desirable to carry out these studies in view of the three main agricultural systems used at present, i.e. intensive (conventional), organic, and integrated (Guarda *et al.* 2004, Laperche *et al.* 2006, 2008, Murphy *et al.* 2007). The specific cultivar-related needs of low-input, traditional agriculture are also important and recognized in areas with unfavourable farming conditions, which should also be made use of agriculturally for socio-economic and environmental reasons, not to mention the needs of cultivars adapted to marginal (low-input or extensive) farming systems (Ceccarelli 1989, 1994, 1996, El Bassam 1998, Atlin *et al.* 2001, Guarda *et al.* 2004, Laperche *et al.* 2006, Mathews *et al.* 2006). For each of the agricultural and farming systems mentioned such cultivars should be addressed that are best adapted (high-yielding) to these systems across agro-ecological conditions.

In an attempt to solve the agricultural problems mentioned above, a two-year experimental study was carried out at the Department of Agronomy of the Warsaw University of Life Sciences on the response of yield and other traits of 14 Polish winter wheat cultivars bred over a period of over 100 years, and of one new British cultivar, to three nitrogen fertilization rates over two years (growing seasons).

This paper demonstrates the application and usefulness of a combined Additive Main Effects and Multiplicativ Interaction (AMMI) and cluster analysis for describing grain-yield response of 15 cultivars to the specified environmental conditions (3 N doses × 2 years = 6 environments). The work involved estimation and interpretation of genotype and environmental effects, and GE interactions for grain yield on the basis of the data from these experiments. The work concentrated in particular on the analysis of the different yield responses of the studied cultivars to environmental conditions. In this way, the degree of yield stability of the cultivars under consideration and the types of their adaptation to diverse environmental conditions were determined. It was found that there were cultivar traits which significantly determined the degree of yield stability of the studied cultivars, which means that they turned out to be adaptive traits for the studied environmental conditions, that is, those traits of plants that determine their tolerance of the deficiency in the nitrogen available to plants in the soil. Attention was drawn to the possibility of assessing the repeatability (similarity) of the types of the responses of the cultivars to nitrogen fertilization rates over the two years of the study. A discussion was initiated on the scientific and practical importance of the results obtained in winter wheat breeding and cultivation.

MATERIALS AND METHODS

Plant material.

The experimental material consisted of 15 winter wheat cultivars, including 14 Polish-bred cultivars and one British cultivar (Table 1), representing the results of over 100 years of breeding.

Four old cultivars (denoted by O) were released before 1940, four intermediate age cultivars (I) were released between 1970 and 1989, and the last seven modern cultivars (M) were released in the 1990s or at the beginning of the 21st century.

Table 1

Names and years of registration of 15 winter wheat cultivars studied in a two-year series of cultivar vs. fertilization experiments

Cultivar	Registered	Cultivar	Registered
Dańkowska Selekcyjna (O)	ca. 1880	Kobra (M)	1992
Wysokolitewka Leszczyńskich O)	ca. 1920	Sakwa (M)	1996
Sobieszyńska 44 (O)	1920s	Kaja (M)	1997
Eka (O)	ca. 1930	Korweta (M)	1997
Begra (I)	1982	Zyta (M)	1999
Emika (I)	1985	Kris (M)	2000
Jawa (I)	1985	Tonacja (M)	2001
Almari (I)	1989		

(O) – old cultivar, (I) – cultivar of intermediate age, (M) – modern cultivar

Experimental station. The field experiments were carried out (Peskovski 2005) at the Experimental Station of the Warsaw University of Life Sciences in Chylice, Poland in two growing seasons – 2001/2002 and 2002/2003. The experimental station is situated at a latitude of between 52^{o}05’30” and 52^{o}06’06” north, and at a longitude of between 20^{o}33’00” and 20^{o}33’50” east. Black soil in the experiment is sufficient fertile to wheat growing.

Field experiments. In each year of the study, a two-factorial experiment was carried out with 15 winter wheat cultivars and three nitrogen fertilization rates (0, 80, and 170 kg N × ha^{-1}). The nitrogen doses were denoted by the symbols N0, N1, and N2. In both years, the experiments were designed in a split-plot design in 4 replications. On main plots (sub-blocks), the cultivars were distributed randomly in blocks, and on small plots, within sub-blocks, the nitrogen fertilization doses were distributed randomly. Twenty-one agronomic (yield-contributing) traits were under observation, including the data presented here for grain yield per plot, expressed in tonnes per hectare (t × ha^{-1}).

Modelling and concept for analysis. An analysis of variance of the experimental data for yield was carried out according to the ANOVA model appropriate for the split-plot design, separately in each year. No significant variation (F-test) was found in error I or error II variance in the two years of the study. Combined (averaged for years) mean squares for error I and II were calculated (McIntosh 1983).

An AMMI analysis and a cluster analysis were used to study grain-yield response of the cultivars under consideration to the conditions in 6 environments, defined as combinations of 2 years of experiments with 3 nitrogen fertilization rates (Voltas *et al.* 1999, Sivapalan *et al.* 2000, Brancourt-Hulmel and Lecomte 2003**,** Moreau *et al.* 2004, Sinebo 2005, De Vita *et al.* 2007, Worku *et al.* 2007). The environments thus considered were marked with symbols indicating the N dose and the harvest year, i.e. N0.2002, N0.2003, N1.2002, N1.2003, N2.2002, and N2.2003.

The AMMI analysis was carried out on the basis of a fixed two-factorial model for data (means from replications) in the classification: genotypes × environments, assuming that the genotypes and the environments are constant factors (Fufa *et al.* 2005, Grüneberg *et al.* 2005, Gauch 2006, Reynolds *et al.* 2007). To test the significance of the interaction principal components, the F_R test was used (Cornellius 1993, Cornellius *et al.* 1996). In this study, the main effects of the genotypes and environments, and the interaction principal components were considered significant at an actual significance level no greater than $\alpha=0.05$.

The AMMI(*s*) estimates of the Genotype by Environment interaction (GEI) effects were produced on the basis of *s* significant interaction principal components. They are more accurate than the ordinary estimates of GEI effects obtained with the method of least squares based on a fixed ANOVA model. This result from the removal from them the random experimental error which is entangled (compounded) with the ordinary estimates of GEI effects (Gauch 1988, 1990, 1992, 2006).

Homogeneous groups of cultivars were identified in terms of the genotypic profile of AMMI(*s*) estimates of GEI effects, i.e. the effects of the GE interactions of a given cultivar with the environments studied (Crossa *et al.* 1991, Gauch and Zobel 1996, Voltas *et al.* 1999, Sivapalan *et al.* 2000 Annicchiarico 2002). In grouping the cultivars, Ward's method of hierarchical cluster analysis was used, in which the measure of similarity was the square of Euclidean distance between AMMI(*s*) estimates of the GEI effects for the cultivars (Voltas *et al.* 1999, Sivapalan *et al.* 2000, de la Vega and Chapman 2006). It was accepted that the mean group patterns of cultivar responses were more reliable (accurate) for all the cultivars in a given group than the estimates of these patterns for each cultivar separately (Alagarswamy and Chandra 1998, Sivapalan *et al.* 2000, Annicchiarico 2002).

The cultivars in the homogenous groups in terms of the genotypic profile of GEI effects (homogenous in terms of the pattern of grain-yield response to the environments) were divided into separate homogenous subgroups according to genotypic means, using the procedure developed by Caliński and Corsten (1985). The subgroups thus obtained contain cultivars that are homogenous in terms of the pattern of yield response to environments, as well genotypic means of yield. Therefore, the cultivars in each of these subgroups have a similar, i.e. statistically not differentiated, type of response (response function) of grain yield to the environments studied, that is, their adaptability to these environments.

All the calculations in the analyses of variance were carried out by the GLM procedure in the SAS package (SAS Institute 2001), and the calculations in the AMMI analysis and cluster analysis were done using MATMODEL (Gauch and

Furnas 1991) and R package (R Development Core Team 2007).

RESULTS AND DISCUSSION

Estimation of mean squares for experimental errors in variance analysis according to AMMI model. On the basis of the data from the experiments, a separate analysis of variance was carried out each year according to the model for split-plot design. The mean squares for both types of experimental error were similar in both years of the study, i.e. in the two successive years they were, respectively, 0.323 and 0.306 for error I, and 0.179 and 0.220 for error II. The F test did not reveal significant variation in the variance of either error in the two years at the significance level of 0.05. That is why it was possible to calculate from the annual estimates mean square for error I, which was 0.314, and mean square for error II, which was 0.199. These mean squares for both errors, divided by the number of replications, which was 4, are used in the combined analysis of variance according to the fixed AMMI model (Table 2).

Table 2

Analysis of variance based on a fixed two-factorial AMMI model for grain yield of 15 winter wheat cultivars in 6 environments

Source of variation	Sum of squares		Degrees of freedom	Mean square	F_{emp}	P-value	
Genotypes (G)	60.34	48.9%[a]	14	4.31	54.83	0.000	**
Error I (*mean*)			84	0.0786			
Environments (E)	46.90	38.0%[a]	5	9.38	188.333	0.000	**
GE interaction	16.17	13.1%[a]	70	0.23	4.638	0.000	**
IPC1	16.17	70.3%[b]	70	0.23	4.638	0.000	**
IPC2	4.81	84.4%[b]	52	0.09	1.857	0.002	**
IPC3	2.52	92.6%[b]	36	0.07	1.407	0.077	NS
IPC4	1.20	97.2%[b]	22	0.05	1.098	0.353	NS
IPC5	0.46	100.0%[b]	10	0.05	0.923	0.514	NS
Error II (*mean*)			180	0.0498			

** significant at 0.01; * significant at 0.05, NS not significant at 0.05; a percentage share of the sum of squares for given effects (G, E, and GE) in the sum of squares for GE combinations b percentage share of the sum of squares of the first IPCs in the sum of squares for GEI effects

Variance analysis based on AMMI model

The results of grain-yield variance analysis, based on the fixed AMMI model for means from replications in the classification: cultivars x environments, are shown in Table 2. The main effects of the cultivars and the environments, and the GEI effects varied significantly. The sums of squares for the genotypic effects constituted 48.9%, and for the environmental effects 38.0%, of the total sum of squares for the combinations of the cultivars with the environments (GE combinations). The GEI effects had relatively less significance (13.1%) in determining the variation in grain yield. Therefore, the diversification in the adaptability pattern of the studied cultivars is determined more by the genotypic means than by the pattern of yield response of these cultivars to variable environmental conditions.

*Determination of the number of significant interaction principal components in AMMI model***.** The sum of squares for the GEI effects was resolved into sums of squares for the interaction principal components, of which only the first two proved to be significant on the basis of the F_R test (Table 2). It was, therefore, accepted that the first two interaction principal components were sufficient to determine AMMI(*s*) estimators of GEI effects, which are unbiased and more precise than the ordinary estimators of the least squares (Gauch 2006).

The sum of squares for the GEI effects (calculated parameters of interaction effects) accumulates a much greater part of the sum of squares for the experimental error than the sums of squares for the main genotypic and environmental effects (Crossa *et al.* 1991, Gauch 1992, 2006, Gauch and Zobel 1996, 1997, Annicchiarico 2002). For that reason, the analysis of the similarity of the cultivars in terms of the pattern of yield response to the environments was based on AMMI(2) estimates of GEI effects (Gauch 2006).

Grouping of cultivars with similar patterns of yield response to environments

Ward's method of cluster analysis. The results of grouping the cultivars with similar genotypic profiles of AMMI(2) estimates of the GEI effects are shown in the form of a dendrogram (Fig. 1).

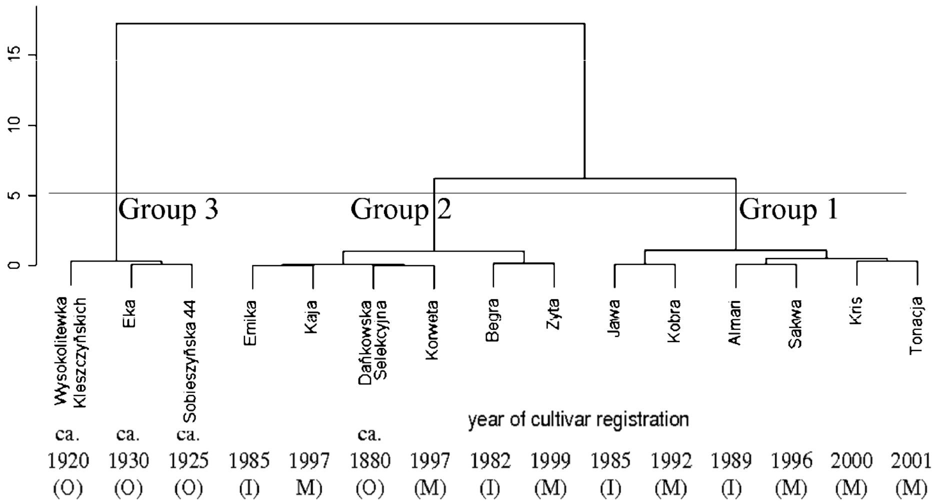


Fig. 1. A dendrogram produced by Ward's method of cluster analysis for genotypic profiles of AMMI(2) estimates of GEI effects, showing the grouping of winter wheat cultivars that have similar patterns of grain-yield response to environmental conditions; (O) – old cultivar, (I) – cultivar of intermediate age, (M) – modern cultivar

For each number of cultivar groups from 1 to 10, the intra-group and inter-group variation in AMMI(2) estimates of the GEI effects of the studied cultivars were determined (for the number of groups from 1 to 5 the results are shown in Table 3). The intra-group variation was measured with the sum of squares of the GEI effects for the cultivars in the groups in relation to the group means of the interaction effects. The inter-group variation was measured with the sum of squares for the group means of the GEI effects. This procedure follows the model of a one-way analysis of variance for data with a different number of units in groups (Voltas et al. 1999, SAS Institute 2001, de la Vega and Chapman 2006).

Table 3

Division of the total sum of squares for AMMI(2) estimates of GEI effects into the sums of square deviations between groups and within groups for different numbers of isolated groups of cultivars in Ward's method of cluster analysis

Number of cultivar groups	Sum of square deviations between groups	Portion of variation in GEI effects accounted for	Sum of square deviations within groups	Portion of variation in GEI effects accounted for
1			13.645	100.0%
2	8.616	63.1%	5.029	36.9%
3	11.744	86.1%	1.901	13.9%
4	12.328	90.3%	1.317	9.7%
5	12.879	94.4%	0.766	5.6%

On the basis of the percentage share of the sum of squares between groups in the total sum of squares for AMMI (2) estimates of GEI interactions (Table 3) for different numbers of cultivar groups, it was decided to divide the cultivars into 3 groups that were homogenous in terms of the GEI effects (Fig. 1). This constitutes a compromise between the divergent goals of cluster analysis, i.e. to obtain high similarity between the objects in a group and a small number of groups. The performed division of the cultivars into groups permits us to accept that the cultivars in each group have similar (not significantly different) patterns of grain-yield response to the environments. For the cultivars in each group, group means of AMMI(2) estimates of GEI effects in the environments studied were calculated.

Group G3 contained the three oldest cultivars bred in the 1920s, i.e. Wysokolitewka Kleszczyńskich, Eka, and Sobieszyńska 44. Six cultivars were in Group G2, including the very old cultivar Dańkowska Selekcyjna from the 19th century, and the cultivars from the years 1982-1999, i.e. Begra, Emika, Kaja, Korweta and Zyta. In Group G1, there were six cultivars from the years 1985-2001, i.e. Jawa, Almari, Kobra, Sakwa, Kris, and Tonacja (Fig. 1).

Graphs and estimates of the patterns of yield response of genotypes to environments. The AMMI(2) estimates of the GEI effects for cultivars and the group means of these effects in each of the three groups are shown in Fig. 2a-c. The horizontal axis of these graphs represents the environments in the order of non-decreasing mean yields, and the vertical axis represents the AMMI(2) estimates of the GEI effects (Sivapalan *et al.* 2000, Zhang *et al.* 2006a,b).

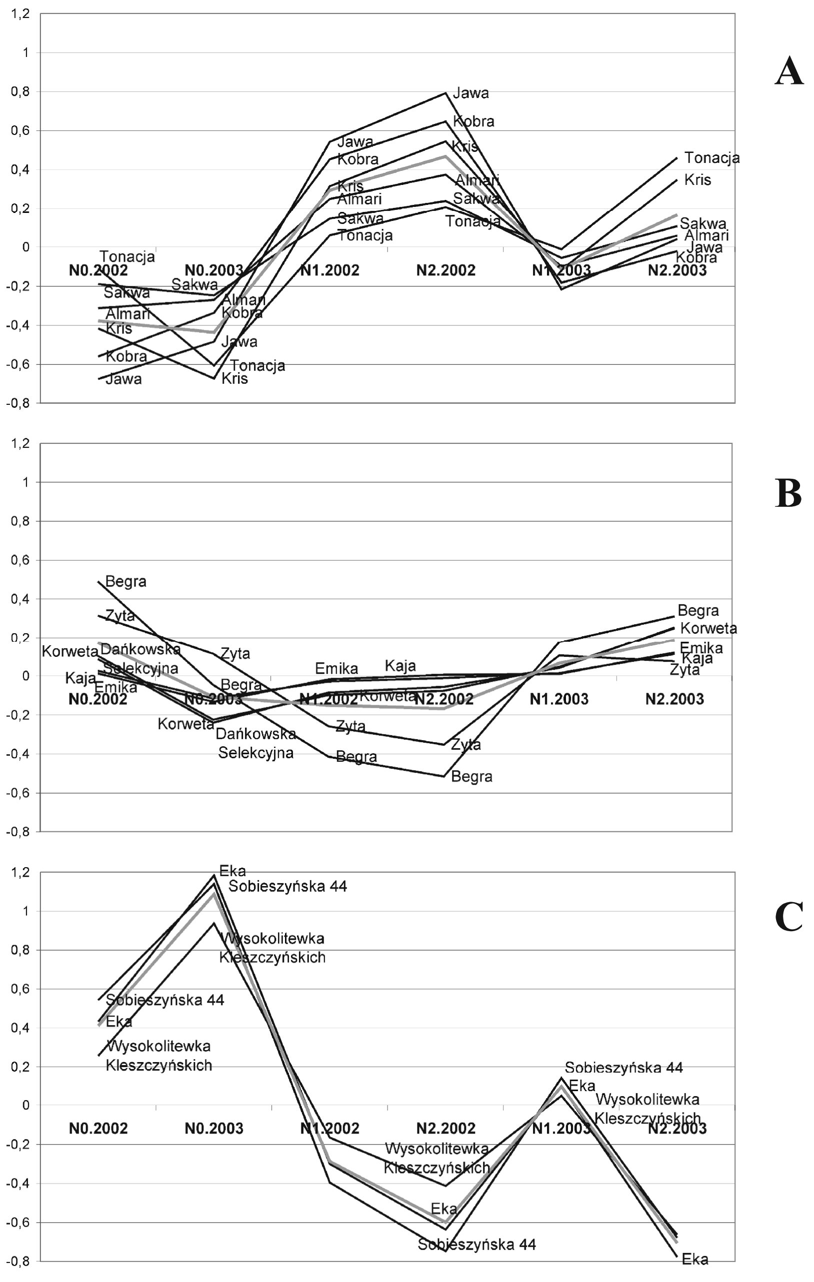


Fig. 2. AMMI(2) estimates of GEI effects for grain yield of winter wheat cultivars, illustrating the patterns of their yield response shape to environments, separately for three homogeneous groups G1, G2, and G3

Graphs 2a-c demonstrates high similarity of the patterns of the yield response shapes of the individual cultivars within each of the identified groups. This illustrates the effectiveness of the division of the cultivars into the three groups by means of a cluster analysis.

To make a substantive assessment of the obtained separate shapes of yield responses of the cultivars to the environmental conditions, use was made of the group means of yield response shapes of the cultivars to the environments, called group profiles of interaction effects, represented by the grey line (Graph 2a-c).

The pattern of the mean-yield response shape of each cultivar group to the studied environments can be assessed in terms of the genotypes' phenotypic stability in an agricultural sense, also called dynamic (Shukla 1972, Kang 1993, Piepho 1998, 1999).

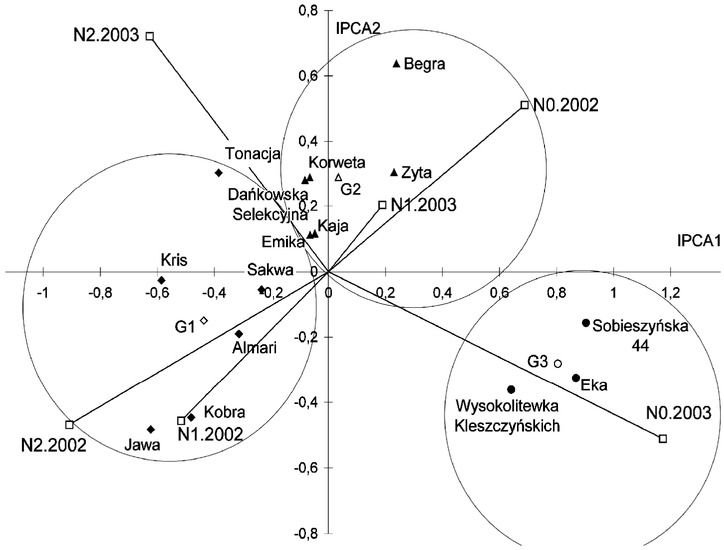
For the purpose of assessing yield stability of genotypes in the AMMI analysis, an AMMI(*s*) stability value (ASV) was used (Grausgruber *et al.* 2000, Adugna and Labuschange 2002, Rharrabti *et al.* 2003), which is graphically depicted on an AMMI(2) biplot (Graph 3) as the distance of the point of the genotype's parameters from the centre of the coordinate system. The values of ASV_i for the three groups of cultivars G1, G2, and G3 (for the group profile of interaction effects) were 0.46, 0.29, and 0.85, respectively. In Group G2 of stable cultivars were Dańkowska Selekcyjna from the 19th century and two old cultivars from the 1980s, i.e. Begra (1982) and Emika (1985). The cultivars in Groups G1 and G3 were not stable.

Graphical illustration of the similarity of GEI effects using an AMMI(2) biplot

AMMI(2) biplots present information on the nature of GE interactions in a different way than the graphs of the patterns of cultivar responses (Figs 2a-c). In this study, only two interaction principal components were significant (Table 2), and so the AMMI(2) biplot (Fig. 3) is a graphical illustration of the similarities of the cultivars (and their groups) and the environments in respect of the profile of the GEI effects, reproducing accurately, that is, without any loss of information, the estimates of the GEI effects determined with the AMMI method.

Degree of yield stability illustrated by AMMI(2) biplots. The distance of the point defined by the Genotypic parameters of Interaction Principial Component (GIPC) (GIPC1 and GIPC2 values for a given genotype) from the centre of the coordinate system is a measure of the variation in the interaction effects for the cultivars, that is, the degree of yield instability. The cultivars in Group G2 had a high yield stability, whereas the cultivars in Groups G1 and G3 produced unstable yields, which is also illustrated by Graphs 2a-c, or the ASV_i coefficient.

Interpretation of the parameters of the first principal component for GEI effects. On the AMMI(2) biplot (Graph 3) it can be seen that the higher the nitrogen fertilization rates, the lower the values of the environmental parameters of the first interaction principal component (EIPC1). The points for the environments with the highest nitrogen doses are located on the left-hand side of the plot, whereas the points for the zero-dose environments are on the right-hand side of the plot. Therefore, the environmental parameters of the first interaction principal component are associated with the nitrogen fertilization rates.



genotypic and environmental parameters scaled symmetrically

♦ Group G1 genotypes ◊ Group G1 mean

▲ Group G2 genotypes △ Group G2 mean

● Group G3 genotypes ○ Group G3 mean

□ environments

Fig. 3. Biplot of genotypic and environmental parameters of the first two interaction principal components in AMMI model for grain yield of winter wheat (circles include distinguished groups of genotypes)

What this relationship indicates is that the cultivars with positive GIPC1 parameters (the points on the right-hand side of Fig. 3) show a positive interaction effect with the environments without nitrogen fertilization (Betran *et al.* 2003). On the other hand, the genotypes with negative GIPC1 parameters (on the left-hand side of Fig. 3) show a positive interaction effect with the environments with the highest rate of nitrogen fertilization.

Relationship between cultivar traits and genotypic parameters of interaction principal components for yield

The correlation of the genotypic parameters of the first and second interaction principal components (GIPC1 and GIPC2) for grain yield with cultivar traits (genotypic means of traits for cultivars) can determine the importance of the GIPC1 and GIPC2 parameters in the context of the agronomic traits of the cultivars (Table 4). The coefficients of correlation between the genotypic means of cultivar traits and the GIPC1 and GIPC2 values for yield can be interpreted in terms of the degree of yield stability.

Table 4

Coefficients of correlation between genotypic means of cultivar yield-contributing traits and genotypic means of cultivar grain yield and genotypic parameters of the first two interaction principal components for grain yield (GIPC1 and GIPC2)

Cultivar yield-contributing traits	Correlation with multi-environment mean of yield	Correlation w. GIPC1	Correlation w. GIPC2
Grain yield (t × ha^{-1})	1.00	-0.87	0.25
Number of ears per m^2	0.85	-0.78	0.22
Number of grains per ear	0.81	-0.77	0.04
Weight of 1000 grains	0.81	-0.61	0.36
Harvest index (HI)	0.96	-0.89	0.26
Biomass yield (t × ha^{-1})	0.89	-0.69	0.22
Straw yield (t × ha^{-1})	-0.16	0.34	-0.04
Nitrogen content in grain	-0.85	0.89	-0.07
Nitrogen content in straw	-0.67	0.48	-0.03
Total nitrogen uptake	0.94	-0.78	0.31
Nitrogen uptake in grain	0.98	-0.82	0.31
Nitrogen uptake in straw	-0.64	0.55	-0.15
Nitrogen uptake efficiency	0.84	-0.56	0.44
Nitrogen harvest index (NHI)	0.94	-0.80	0.27
Nitrogen utilization efficiency	0.95	-0.89	0.14
Nitrogen use efficiency	0.99	-0.80	0.30

Yield stability of cultivars in environments with different nitrogen fertilization rates can be associated with the genotypic mean of a given trait of the cultivars. The coefficients of correlation of the GIPC1 and GIPC2 parameters for grain yield with the multi-environment mean of a given agricultural trait of the cultivars describe the relationship between the average level of that trait and the degree of yield stability (Romagosa *et al.* 1993, Abamu and Alluri 1998, Chauhan *et al.* 1998, Vargas *et al.* 1999, Motzo *et al.* 2001, Yan and Hunt 2001, Lafitte and Courtois 2002, Sinebo 2005, Laurentin *et al.* 2007, Rodriguez *et al.* 2008). The stronger this correlation is, the stronger the relationship between the mean trait of the cultivars and the variation in the interaction effects of yield for the cultivars, that is, the degree of instability of their yield.

The GIPC1 parameters for grain yield were the most strongly correlated (Table 4) with the means of grain yield and its components (in particular, the number of ears per m^2, the number of grains per ear), the harvest index (HI), nitrogen harvest index (NHI) and the nitrogen uptake, utilization efficiency and content in grain. This indicates that among the studied cultivars those which were marked by moderate (close to mean values) levels of grain yield, the harvest index, and nitrogen uptake, utilization efficiency and content in grain, had relatively the highest yield stability within the studied range of nitrogen fertilization rates. The cultivars with unstable yields were those whose mean values of the listed traits were extreme, that is, relatively high or low (Rodriguez *et al.* 2008). The GIPC2 parameters for grain yield were weakly correlated with all of the studied traits of the cultivars; besides, their effect is smaller than the effect of GIPC1 (because of the obvious domination of the sum of squares for IPC1 over the sum of squares for IPC2, Table 2).

A very strong positive correlation (Table 4) was found between the genotypic means for yield and for its three components (the number of ears per m^2, the number of grains per ear, and the weight of 1000 grains), the harvest index and the nitrogen harvest index, nitrogen uptake, utilization and use efficiencies, and nitrogen uptake in grain, but a negative correlation with the nitrogen content in the grain. This indicates that the highest yielding cultivars on average for the studied range of nitrogen fertilization rates in the two years of the study were those cultivars which were characterized by high levels of nitrogen use efficiency, nitrogen uptake in grain, nitrogen utilization efficiency or NHI, a high biomass yield ($t \times ha^{-1}$), a large number of ears per m^2, a heavy weight of 1000 grains and a large number of grains per ear, but a low nitrogen content in the grain. The relatively low mean grain yield of the cultivars was associated with the relatively low values of those traits that were positively correlated with the mean yield of the cultivars.

Grouping of cultivars with similar yield responses to environments (cultivars of similar adaptability)

Although the cultivars in each of the three isolated groups have similar patterns of grain-yield responses to the environments (similar profiles of GEI effects for yield), they can nevertheless be significantly different in terms of the main effects, that is, the mean yield of the genotypes across the environments. Therefore, the isolated groups of cultivars homogenous in respect of the pattern of their responses can include genotypes with different yield responses (response function) to variable environmental conditions, that is, cultivars with different adaptability (adaptation) in these environments.

The cultivars in each of the three groups with homogeneous response patterns (profiles of GEI effects) were divided into subgroups that were homogenous in terms of the genotypic mean of yield. This division was performed with the use of non-hierarchical cluster analysis developed by Caliński and Corsten (1985).

The grouping method (Caliński and Corsten 1985) is described for a one-factorial ANOVA model with repetitions. The analysis of variance was carried out on the means from replications in subclasses (GE classification). For that reason, as the mean experimental error, required by the grouping method used for grouping cultivars with a similar multi-environment mean of yield, error I (mean) was adopted, because it is the error of estimating the mean yield of a cultivar in a subclass. Because the mean yield of each cultivar was based on six environmental means of the genotype yield in the environments (means from replications in the GE classification), the value of 6 was given as the number of repetitions. The grouping of the cultivars according to the genotypic means was carried out at a significance level of α=0.05 (Table 5).

The G1 and G2 groups were divided into two subgroups homogeneous in respect of the genotypic mean of yield of the cultivars, and the cultivars in Group G3 were divided into three homogeneous subgroups.

The subgroups of Group G1 were designated 1A and 1B (successive letters are assigned to subgroups of cultivars within a given group, according to the decreasing order of the mean yield of the cultivars in the subgroup). In an analogous way, the subgroups of the cultivars in Group G2 were designated 2A, 2B, and 2C, and the subgroups of the cultivars in Group G3 were denoted by the symbols 3A and 3B.

Table 5

Grain-yield means of the cultivar groups being homogenous in terms of their response to the environments

Group	Subgroup	Cultivars	Mean yield in subgroup
G1	1A	Tonacja, Sakwa, Kris, Kobra	5.47
	1B	Almari, Jawa	4.92
G2	2A	Kaja	5.39
	2B	Emika, Zyta, Korweta	5.00
	2C	Dańkowska Selekcyjna, Begra	4.37
G3	3A	Sobieszyńska 44	3.46
	3B	Wysokolitewka Kleszczyńskich, Eka	3.11

Mean grain-yield response of the homogeneous groups of the winter wheat cultivars to the environmental conditions are shown in Fig. 4. On the horizontal axis are marked the environments (in the order of non-decreasing environmental mean of yield, while the vertical axis represents the values of mean yields for each subgroup of cultivars in a given environment (Zhang *et al.* 2006 a,b).

The subgroups of the same group (e.g. 2A, 2B, and 2C) are different only with respect to mean genotype yield (and not in terms of GEI effects), so their yield response pattern differed by the same value in all the environments (response curves are shifted vertically, Fig. 4, 5). Therefore, in order to determine the highest-yielding subgroup of cultivars in a studied environment, it is only necessary to compare the responses by selecting for comparison only one subgroup from each group, namely the highest-yielding one (Subgroups 1A, 2A, and 3A). The cultivar Kaja (Group 2A) is a genotype that produces the highest yields at zero nitrogen fertilization, whereas at the fertilization rates of 80 and 170 kg N ha^{-1}, the highest yielding are the cultivars of Group 1A.

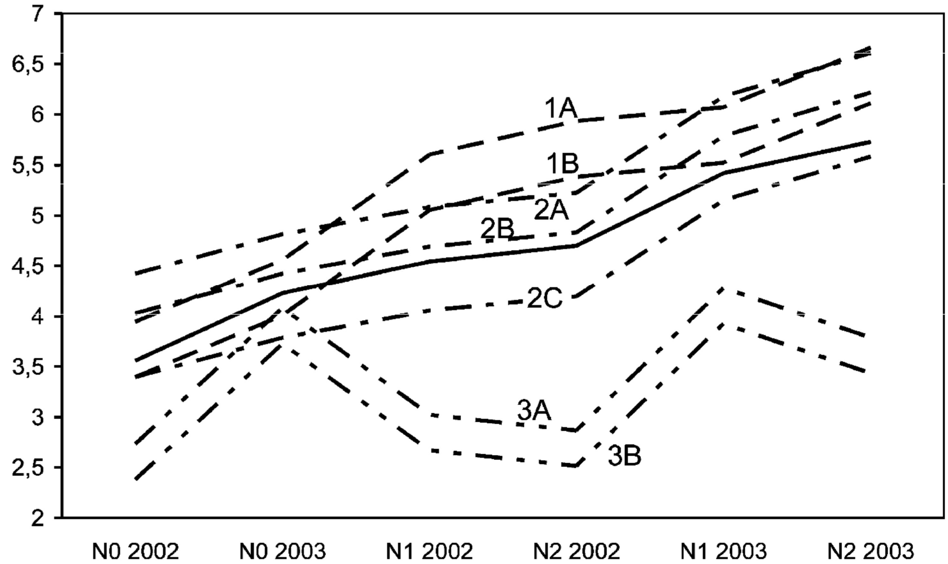


Fig. 4. Mean grain-yield response of seven groups of winter wheat cultivars to environmental conditions defined as combinations of N doses and years. Continious line – mean response of cultivars to environmental conditions

The cultivars in subgroups 1A, 2A, and 2B were distinguished by wide adaptation because they produced yields above the environmental mean in all the environments (Fig. 4). The highest degree of wide adaptation was shown by the cultivars of intermediate age and the modern cultivars isolated in Subgroup 1A (Kobra from 1992, Sakwa from 1996, Kris from 2000 and Tonacja from 2001) and Subgroup 2A (Kaja from 1997), because the yields they produced were above the environmental mean in all the environments, and because those yields were much greater than the environmental means across all the genotypes studied. The intermediate-age cultivars, gathered in Subgroup 2B (Emika from 1985, Korweta from 1997 and Zyta from 1999) had a smaller degree of wide adaptation than the cultivars in Subgroups 1A and 2A, because the yield advantage of the cultivars from Subgroup 2B over the environmental means was significantly smaller than the yield advantage of the cultivars from Subgroup 2A, and smaller than that of the cultivars in Subgroup 1A. The intermediate-age cultivars from Subgroup 1B (Jawa from 1985 and Almari from 1989) were adapted to the environments fertilized with nitrogen at the rates of 80 and 170 kg N × ha^{-1}.

The cultivars Kaja (2A), Emika, Zyta and Korweta (2B) were stable (response pattern consistent with the mean response pattern of all the cultivars studied), whereas the cultivars of Groups 1A and 1B were better adapted to the environmental conditions at the fertilization rates of 80 and 170 kg N × ha^{-1} (environments with a higher yield potential, Fig. 4).

The old cultivar Dańkowska Selekcyjna from 1880, and the intermediate-age cultivar Begra from 1982 (Subgroup 2C), although they produced stable yields, those yields were below the environmental means in all the environments. For that reason, these two cultivars did not satisfy the requirement of wide adaptation, i.e. they were not well adapted to any of the environments studied, defined by the different amounts of nitrogen available to plants in the soil, and weather conditions. The old cultivars in Group 3A (Sobieszyńska 44 from the 1920s) and Group 3B (Wysokolitewka Leszczyńskich from 1920, and Eka from 1930) produced the lowest yields, much lower than the environmental mean, both under the conditions of low and very high nitrogen availability in the soil in each year of the study. These cultivars are the worst adapted to highly variable conditions of nitrogen availability to plants in the soil.

As shown in Fig. 4, the yield response functions of the studied cultivars of winter wheat to significantly varied environmental conditions, arising from significantly variable amounts of nitrogen available to plants in the soil and different weather conditions, indicate an agreement between the year of cultivar release and its degree of wide adaptation. In general, the younger the cultivar, the greater its degree of wide adaptation, that is, it produces yields that are higher than the environmental mean in most or all of the environments studied.

Graph of mean-genotype group nominal yields

If for practical reasons a lower accuracy of the approximated estimates of GEI effects is sufficient (lower than that obtained using the AMMI model with all the significant interaction principal components), and consequently a lower yield accuracy of the genotypes in the environments studied, a model with only one interaction principal component (AMMI(1) truncated model) may be considered (Gauch and Zobel 1997, Annicchiarico *et al.* 2006, 2008). For the case under consideration here, the AMMI(1) model accounts for 70.3% of the variation (the sum of squares) of the GEI effects, which is 83.2% of the GEI effects described by the AMMI(2) model (Table 2). The AMMI(1) model describes 96.9% of the variation in the main effects of cultivars and GE interaction effects as also affecting the order of cultivars' yields in the environments. Then, in this study the AMMI(1) model could approximate (predict) well the mean yield of the cultivars in the environments. Therefore, the AMMI(1) model could be regarded as an alternative tool (as compared with the AMMI(2) model) for predicting the GEI effects (patterns of yield response shape of the studied cultivars to the environments) and also the environmental yield response pattern of these cultivars. To test this hypothesis, a nominal yield graph was constructed (Fig. 5). This graph presents the AMMI(1)-modeled environmental yield responses as mean-genotype group nominal yields being a function of the environment PC 1 score according to Gauch and Zobel (1997) and Annicchiarico *et al.* (2006, 2008). It improves the prediction of genotype responses theoretically (Gauch 1992) and empirically (Annicchiarico *et al.* 2006). Nominal yields, which sum up the estimated genotype mean value and the product of the genotype by the environment scaled scores on PC 1 (excluding the environment main effect, irrelevant for genotype ranking), allow for linearizing the adaptive responses. Adaptative responses of cultivar groups identified and shown by mean-genotype group nominal yields (Fig. 5) are quite consitent with those identified by common mean-grain yield response graph (Fig. 4). Therefore, nominal yield was really both an alternative and more efficient tool as compared to common mean-grain yield response graph being based on full AMMI model for predicting diverse adaptation patterns in a set of studied winter wheat cultivars.

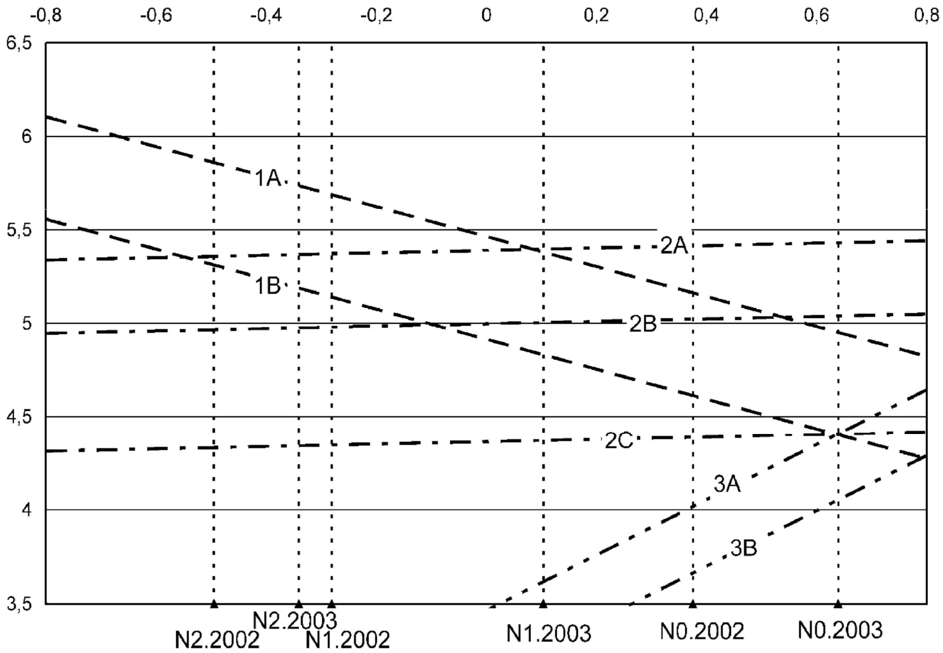


Fig. 5. Mean nominal grain yield of seven groups of winter wheat cultivars predicting AMMI(1)-modeled patterns of genotype yield response to the diverse environments

REFERENCES

Adugna W., Labuschagne M.T. 2002. Genotype-environment interactions and phenotypic stability analyses of linseed in Ethiopia. Plant Breeding 121:66-71

Alagarswamy G., Chandra S. 1998. Pattern analysis of international sorghum multi-environment trials for

grain-yield adaptation. Theor. Appl. Genet. 96:397-405
Annicchiarico P. 2002. Genotype-environment interactions: challenges and opportunities for plant breeding and cultivar recommendations. FAO Plant Production and Protection Paper No. 174. Food and Agriculture Organization, Rome
Annicchiarico P., Bellah F., Chiari T. 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., Iannucci A. 2008. Breeding strategy for faba bean in Southern Europe based on cultivar responses across climatically contrasting environments. Crop Sci. 48:983–991
Atlin G.N., Cooper M., Bjørnstad Å. 2001. A comparison of formal and participatory breeding approaches using selection theory. Euphytica 122:463-475
Austin R.B. 1999. Yield of wheat in the United Kingdom: recent advances and prospects. Crop Sci. 39:1604-610
Betran F.J., Beck D., Bänziger M., Edmeades G.O. 2003. Genetic analysis of inbred lines and hybrid grain yield under stress and non-stress environments in tropical maize. Crop Sci. 43:807–817
Brancourt-Hulmel M., Lecomte C. 2003. Effect of environmental variates on genotype x environment interaction of winter wheat: a comparison of biadditive factorial regression to AMMI. Crop Sci. 43: 608-617
Calderini D.F., Slafer G.A. 1999. Has yield stability changed with genetic improvement of wheat yield? Euphytica 107:51-59
Caliński T, Corsten L.C.A. 1985. Clustering Means in ANOVA by Simultaneous Testing. Biometrics 41: 39-48
Carena M.J., Yang J., Caffarel J.C., Mergoum M., Hallauer A.R. 2009. Do different production environments justify separate maize breeding programs? Euphytica (in press)
Carr P.M., Kandel H.J., Porter P.M., Horsley R.D., Zwinger S.F. 2006. Wheat cultivar performance on certified organic fields in Minnesota and North Dakota. Crop Sci. 46:1963-1971
Ceccarelli S. 1989. Wide adaptation: How wide? Euphytica 40:197-205
Ceccarelli S. 1994. Specific adaptation and breeding for marginal conditions. Euphytica 77:205-219
Ceccarelli S. 1996. Adaptation to low/high input cultivation. Euphytica 92:203-214
Chauhan Y.S., Wallace D.H., Johansen C., Singh L. 1998. Genotype-by-environment interaction effect on yield and its physiological bases in short-duration pigeonpea. Field Crops Research 59:141-150
Cornelius P.L. 1993. Statistical tests and retention of terms in the additive main effects and multiplicative interaction model for cultivar trials. Crop Sci. 33:1186-1193
Cornelius P.L., Crossa J., Seyedsadr M. 1996 Statistical tests and estimators of multiplicative models for genotype-by-environment interaction. W Kang M.S., Gauch H.G. (Eds.), Genotype by Environment Interaction. CRC Press, Boca Raton. 199-234
Crossa J., Fox P.N., Pfeiffer W.H., Rajaram S., Gauch H.G. 1991. AMMI adjustment for statistical analysis of an international wheat yield trial. Theor. Appl. Genet. 81:27-37
El Bassam N. 1998. A concept of selection for 'low input' wheat varieties. Euphytica 100:95-100
Feil B. 1992. Breeding progress in small grain cereals —A comparison of old and modern cultivars. Plant Breeding 108:1-11
Foulkes M.J., Sylvester-Bradley R., Scott R.K., 1998. Evidence for differences between winter wheat cultivars in acquisition of soil mineral nitrogen and uptake and utilisation of applied fertilizer nitrogen. J. Agric. Sci. Camb. 130: 29-44
Fufa H., Baenziger P.S., Beecher B.S., Graybosch R.A., Eskridge K.M., Nelson L.A. 2005. Genetic improvement trends in agronomic performances and end-use quality characteristics among hard red winter wheat cultivars in Nebraska. Euphytica 144:187-198
Gauch H.G. 1988. Model selection and validation for yield trials with interaction. Biometrics 44:705-715
Gauch H.G. 1990. Full and reduced models for yield trials. Theor. Appl. Genet. 80:153-160
Gauch H.G. 1992. Statistical analysis of regional yield trials. AMMI analysis of factorial designs. Elsevier Science, New York
Gauch H.G. 2006. Statistical analysis of yield trials by AMMI and GGE. Crop Sci. 46:1488-1500
Gauch H.G., Furnas R.E. 1991. Statistical analysis of yield trials with MATMODEL. Agron. J. 83:916–920
Gauch H.G., Zobel R.W. 1996. AMMI analysis of yield trials, 85-122. W: M.S. Kang, H.G. Gauch (Ed.) Genotype by environment interaction. CRC Press, Boca Raton
Gauch H.G., Zobel R.W. 1997. Identifying mega-environments and targeting genotypes. Crop Sci. 37:311-326
Giunta F., Motzo R. Pruneddu G. 2007. Trends since 1900 in the yield potential of Italian-bred durum wheat cultivars. Europ. J. Agron. 27:12–24
Grausgruber H., Oberforster M., Werteker M., Ruckenbauer P., Vollmann J. 2000. Stability of quality traits in

Austrian-grown winter wheats. Field Crops Res. 66: 257–267.
Grüneberg W.J., Manrique K., Zhang D., Hermann M. 2005 Genotype x environment interactions for a diverse set of sweetpotato clones evaluated across varying ecogeographic conditions in Peru. Crop Sci. 45: 2160-2171
Guarda G., Padovan S., Delogu G. 2004. Grain yield, nitrogen-use efficiency and baking quality of old and modern Italian bread-wheat cultivars grown at different nitrogen levels. Eur. J. Agron. 21:181-192
Hasegawa H. 2003. High-yielding rice cultivars perform best even at reduced nitrogen fertilizer rate. Crop Sci. 43:921-26
Kang M.S. 1993. Simultaneous selection for yield and stability: Consequences for growers. Agron. J. 85:754-757
Kitchen J.L., Mcdonald G.K., Shepherd K.W., Lorimer M.F., Graham R.D. 2003. Comparing wheat grown in South Australian organic and conventional farming systems. 1. Growth and grain yield. Aust. J. Agric. Res. 54:889-901
Lafitte H.R., Courtois B. 2002. Interpreting cultivar x environment interactions for yield in upland rice: assigning value to drought-adaptive traits. Crop Sci. 42:1409-1420
Laperche A., Brancourt-Hulmel M., Heumez E., Gardet O., Le Gouis J. 2006. Estimation of genetic parameters of a DH wheat population grown at different N stress levels characterized by probe genotypes. Theoret. Appl. Genet. 112: 797-807
Laperche A., Le Gouis J., Hanocq E., Brancourt-Hulmel M. 2008. Modelling nitrogen stress with probe genotypes to assess genetic parameters and genetic determinism of winter wheat tolerance to nitrogen constraint. Euphytica 161: 259-271
Laurentin H., Montilla D., Garcia V. 2007. Interpreting genotype×environment interaction in sesame (*Sesamum indicum* L.). Journal of Agricultural Science 145:263-271
Le Gouis J., Béghin D., Heumez E., Pluchard P. 2000. Genetic differences for nitrogen uptake and nitrogen utilisation efficiencies in winter wheat. Eur. J. Agron. 12:163-173
Ma B.L., Yan W., Dwyer L.M., Frégeau-Reid J., Voldeng H.D., Dion Y., Nass H. 2004. Graphic analysis of genotype, environment, nitrogen fertilizer, and their interactions on spring wheat yield. Agron. J. 96:169-180
Mathews K.L., Chapman S.C., Trethowan R., Singh R.P., Crossa J., Pfeiffer W., Van Ginkel M., Delacy I. 2006. Global adaptation of spring bread and durum wheat lines near-isogenic for major reduced height genes. Crop Sci. 46:603-613.
Mcintosh M.S. 1983. Analysis of combined experiments. Agron. J. 75:153–155
Moreau L., Charcosset A., Gallais A. 2004. Use of trial clustering to study QTL × environment effects for grain yield and related traits in maize. Theor. Apel. Genet. 110: 92–105
Motzo R., Giunta F., Deidda M. 2001. Factors affecting the genotype × environment interaction in spring triticale grown in a Mediterranean environment. Euphytica 121:317-324
Murphy K.M., Campbell K.G., Lyon S.R., Jones S.S. 2007. Evidence of varietal adaptation to organic farming systems. Field Crops Research 102:172177
Muurinen S., Peltonen-Sainio P. 2006. Radiation-use efficiency of modern and old spring cereal cultivars and its response to nitrogen in northern growing conditions. Field Crops Research 96:363-373
Ortiz-Monasterio J.I., Sayre K.D., Rajaram S., Mcmahon M. 1997. Genetic progress in wheat yield and nitrogen use efficiency under four nitrogen rates. Crop Sci. 37:898-904
Peskovski G. 2005. Postęp hodowlany a pobieranie I wykorzystanie azotu przez odmiany pszenicy ozimej (*Triticum aestivum ssp. vulgare*) w Polsce. Praca doktorska Wydział Rolnictwa i Biologii SGGW [In Polish]
Piepho H.P. 1998. Methods for comparing the yield stability of cropping systems-a review. J. Agron. Crop Sci. 180: 193-213
Piepho H.P. 1999. Stability analysis using the SAS system. Agron. J.,.91: 154-160
Poutala R.T., Korva J., Varis E. 1993. Spring wheat cultivar performance in ecological and conventional cropping systems. J. Sustain. Agric. 3:63-83
R Development Core Team 2007. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. ISBN 3-900051-07-0, URL http://www.R-project.org
Raun W.R., Johnson G.V. 1999. Improving nitrogen use efficiency for cereal production. Agron. J. 91:357-363
Reynolds M.P., Condon A.G., Vargas M., Calderini D. 2007. Effects of source/sink traits on yield, biomass and radiation use efficiency of random sister lines from three wheat crosses in a high yield environment. Journal of Agricultural Science, Cambridge 145:3-16.
Rharrabti Y., Garcia Del Moral L.F., Villegas D., Royo C. 2003. Durum wheat quality in Mediterranean environments III. Stability and comparative methods in analyzing G x E interaction. Field Crops Research

80:141-146

Rodriguez M., Rau D., Papa R., Attene G. 2008. Genotype by environment interactions in barley (*Hordeum vulgare* L.): different responses of landraces, recombinant inbred lines and varieties to Mediterranean environment. Euphytica 163:231-247

Romagosa I., Fox P.N., García Del Moral L.F., Ramos J.M., García Del Moral B., Roca De Togores F., Molina-Cano J.L. 1993. Integration of statistical and physiological analyses of adaptation of near-isogenic barley lines Theoret. Appl. Genet. 86:822-826

SAS Institute. 2001. SAS system for Windows. v. 8.2. SAS Inst., Cary, NC

Shukla G.K. 1972. Some statistical aspects of partitioning genotype– environmental components of variability. Heredity 29: 237-245

Sinebo W. 2005. Trade off between yield increase and yield stability in three decades of barley breeding in a tropical highland environment. Field Crops Research 92:35-52

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

Tollenaar M., Lee E.A. 2002. Yield potential yield, yield stability and stress tolerance in maize. Field Crops Research 75:161-170

Vargas M., Crossa J., Van Eeuwijk F.A., Ramirez M.E., Sayre K. 1999. Using partial least squares regression, factorial regression and AMMI models for interpreting genotype x environment interaction. Crop Sci. 39:955-967

Vega de la A.J., Chapman S.C. 2006. Defining sunflower selection strategies for a highly heterogeneous target population of environments. Crop Sci. 46:136-144

Vita de P., Li Destri O., Nigro F., Platani C., Riefolo C., Di Fonzo N., Cattivelli L. 2007. Breeding progress in morpho-physiological, agronomical and qualitative traits of durum wheat cultivars released in Italy during the 20th century. Europ. J. Agronomy 26:39-53

Voltas J., Romagosa I., Lafarga A., Armesto A.P., Sombrero A., Araus J.L. 1999. Genotype by environment interaction for grain yield and carbon isotope discrimination of barley in Mediterranean Spain. Australian Journal of Agricultural Research 50:1263-1271

Worku M., Bänziger M., Schulte Auf'M Erley G., Friesen D., Diallo A.O. Horst W.J. 2007. Nitrogen uptake and utilization in contrasting nitrogen efficient tropical maize hybrids. Crop Sci. 47:519–528

Yan W., Hunt L.A. 2001. Interpretation of genotype x environment interaction for winter wheat yield in Ontario. Crop Sci. 41:19-25

Zhang Y., He Z., Zhang A., Van Ginkel M., Pena R.J., Ye G. 2006a. Pattern analysis on protein properties of Chinese and CIMMYT spring wheat cultivars sown in China and CIMMYT. Australian Journal of Agricultural Research 57:811–822

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