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Additive main effect and multiplicative interaction analysis of grain yield of wheat varieties in Lithuania

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Abstract: Stability of 13 winter wheat (*Triticum aestium* L.) varieties across 4 locations and 2 years with respect to grain yield were tested in Lithuania. The analysis of variance of the 13 varieties in 8 environments shows that genotype (G), location (L), crop-year (Y) and their interaction were significant (P < 0.01) for winter wheat grain yield. Highly significant G x L effects indicated the necessity for testing wheat varieties in Lithuania at multiple locations. The article describes a previously used method and shows that AMMI (additive main effects and multiplicative interaction) model was effective for studying winter wheat genotype-environment interaction (GEI). The first bilinear AMMI model terms accounted for 76.8%. The biplot shows that the varieties Zentos, Compliment, LIA 3948, Elfas and Marshal are best suited for cultivation in a wide range of environments, while the varieties Cubus, Aristos, Marshal and LP.790.1.98 are best suited for cultivation in favourable conditions. The variety Meunier is well-suited for cultivation in poor environments. GEI patterns revealed by AMMI plots indicate that winter wheat varieties are narrowly adapted. No genotype has superior performance in all environments. The variety Elfas was the best at combining yield stability and productivity. The varieties Aristos, LP 790.1.98 and Marshal were more stable but lower yielding than Elfas.

Key words: winter wheat, AMMI model, biplot, yield stability

INTRODUCTION

Genotype-environment interaction (GEI) in winter wheat (*Triticum aestivum* L.) varieties is the differential response of genotypes to changing environmental conditions. An ideal variety should have a high mean yield combined with a low degree of fluctuation, when grown over diverse environments. Two main contrasting concepts of stability are distinguished: “static” (Type 1) and “dynamic” (Type 2) (Lin et al., 1986; Becker & Leon, 1988). For static stability, the best genotype tends to maintain a constant yield across environments. Dynamic stability implies for a stable genotype a yield response in each environment that is always parallel to the mean response of the tested genotypes, i.e. zero GEI (Annicchiarico, 2002). Analysing of GEI for varieties can reduce errors in the breeding process as the selection in one condition cannot provide advantages in others. It is noteworthy that the high stability of yield can frequently be connected to its low level (or, conversely, low stability to high average yields), which complicates the breeding process. Increase and stability of productivity of a wheat variety, representing a pure line, depend on its individual buffering, i.e. on its ability to use favourable conditions of environments. Several methods have been proposed to analyse genotype x environment interactions and phenotypic stability. These methods can be divided into two major groups: univariate and multivariate stability statistics (Lin et al., 1986). Among multivariate methods, the additive main effect and the multiplicative interaction analysis (AMMI) are widely used for GEI investigation. This method has been shown to be effective because it captures a large portion of the GEI sum of square, it clearly separates main and interaction effects that present agricultural researchers with different kinds of opportunities, and the model often provides agronomically meaningful interpretation of the data (Ebdon & Gauch, 2002). The results of AMMI analysis are useful in supporting breeding program decisions such as specific adaptation and selection of environment (Gauch & Zobel, 1997). Usually, the results of AMMI analysis shown in common graphs are called biplot (Gabriel, 1971). The biplot shows both the genotypes and the environment value and relationships using singulars vectors technique (Eckart, & Young, 1936).

The present study was initiated to achieve the following objectives:

- To observe genotypic stability (with respect to grain yield) of 13 winter wheat varieties across 4 locations and 2 years in Lithuania.
- To select varieties combining a high level of grain yield with yield stability.
- To group the genotypes having similar response pattern over all environments.

MATERIALS AND METHODS

Thirteen winter wheat varieties Zentos, Aristos, Compliment, Cubus, Elfas, LP.562.4.99, LP.790.1.98, LIA 3937, LIA 3948, Marshal, Meunier, Residence and Vergas were tested at the State Variety Testing Stations (SVTS) in Plunge, Kaunas, Pasvalys and Utena, located on contrasting soils and climatic zones during the period 2003 to 2004. At each location, the 13 genotypes were planted in 18–20 m^2 test plots using a randomised complete block design with four replications. The seeding rate for all varieties was 450 seeds m^2. Soil acidity pH in Kaunas VTS was 7.1–7.3, Pasvalys 6.1–6.5, Plunge 5.7–6.1, Utena 5.9–6.9, mobile P_2O_5 208, 319, 267 and 73; K_2O 178, 374, 235 and 161 mg kg^{-1} soil, respectively. Percentage of organic matter was 2.0–2.4, 2.2–3.0, 1.8–2.1 and 1.9–2.2, respectively. Fertiliser application was 90 kg N ha^{-1} and 60 kg P_2O_5 ha^{-1}. The seeds were treated with Baitan Universal. Chemical weed control was conducted using the herbicide Secator. Fungicides were applied for disease control. Field design, records and investigations were done in compliance with the approved official testing methodology. An analysis of variance was done for the combined analyses of variance across the test environments of location and years. A combined ANOVA and AMMI analysis was processed using the program IRRISTAT. Last module for the program IRRISTAT was adapted from the program GEBEI developed by Dr. Jan Delasy from Queensland University, Australia (IRRISTAT 4.3 for Windows, 2002). In AMMI analysis, the model for phenotypic performance of genotype j tested in environment i can be expressed as

$$Y_{ger} = \mu + a_g + b_e + Sl_n\, g_{gn}\, d_{en} + r_{ge} + E_{ger}$$

where Y_{ger}= yield of genotype g in environment e for replicate r; μ = grand mean; a_g= mean deviation of the genotype g (genotype mean minus grand mean); and b_e = mean deviation of environmental mean; l_n = the singular value for IPCA axis n; g_{gn} = the genotype g eigenvector value for IPCA axis n; d_{en}= the environment e eigenvector value for IPCA axis n; r_{ge} = the residual; and E_{ger} = the error.

The genotype x environment interaction effects were calculated using the formula $(G \times E)_{ij} = \bar{y}_{ij} - \bar{y}_{i.} - \bar{y}_{.j} + \bar{y}_{..}$ (where $\bar{y}_{ij}$ is the mean of the i_{th} genotype on the j_{th} environment and $\bar{y}_{i.}$, $\bar{y}_{.j}$, and $\bar{y}_{..}$ are the mean of the i_{th} genotype, the mean of the j_{th} environment, and the overall mean, respectively (Vargas et al., 1999) .

RESULTS AND DISCUSSION

Analysis of variance. Grain yield largely depends on climatic conditions, in particular on the total precipitation in the experimental years. The analyses of variance are presented in Table 1. Genotype, location, genotype x location, crop-year, crop-year x genotype, crop-year x location and crop-year x location x genotype were significant (P < 0.01) for wheat grain yield. Such statistical interaction resulted from the changes in the relative ranking of the genotypes or changes in the magnitudes of differences between genotypes from one environment to another. The significant L x G effects (P < 0.01) demonstrated that genotypes responded differently to the variation in environmental conditions of location and indicated the necessity of testing wheat varieties at multiple locations. This shows the difficulties encountered by breeders in selecting new genotypes for release; these difficulties arise mainly from the masking effects of variable environments (Goncalves et al., 2003). Thus, it is important to study adaptation patterns, genotypes response and their stability in multi-location trials. The factors explained (%) show that winter wheat grain yield was most markedly affected by crop-years (38.7), locations (16.2) and their interaction (15.9) (Table 1).

The data from Table 2 show that better conditions for shaping high grain yields were in 2004 than in 2003. Across four locations, the best conditions were in Kaunas both in 2003 and 2004. The highest grain yield was observed for the variety Cubus (10.33 t ha^{-1}) in Kaunas in 2004 and the lowest for Meunier (3.28 t ha^{-1}) in Utena in 2003. Across location and years, however, only Vergas surpassed all other genotypes with a mean grain yield of 7.48 t ha^{-1}. The GEI analysis is important for breeders to design the dissemination strategy for new varieties. One part of varieties can be successfully grown only in regions characteristic of favourable growing conditions. Second part of varieties, which are broadly adapted for different environments, can perform well under variable conditions. It is noteworthy that yield stability is the most important socio-economic aim to minimise crop failure, especially in marginal environments.

AMMI analysis. The AMMI analysis of variance of winter wheat grain yield (t ha^{-1}) of the 13 genotypes tested in eight environments showed that 77.1% of the total sum of squares was attributable to environmental effects; only 7.1% to genotypic effects and 15.8% to G x E interactions effects (Table 3). The environments were diverse and caused the greatest variation in grain yield. The G x E sum of squares was 2.2 times larger than that for genotypes, which determined substantial differences in genotypic response across environments.

Table 1. Analyses of variance of grain yield for 13 winter wheat genotypes grown in four locations in 2003–2004.

Source	*DF*	*SS*	*MS*	Explained (%)
Total	415	1001.658		
Replications	3	0.519		
Crop - Year (Y)	1	387.776	387.776**	38.713
Locations (L)	3	162.805	54.268**	16.253
Genotypes (G)	12	65.700	5.475**	6.559
Y x L	3	159.447	53.149**	15.918
Y x G	12	42.621	3.552**	4.255
L x G	36	60.171	1.671**	6.007
Y x L x G	36	46.618	1.184**	4.654
Error	309	80.001	0.259	

** - significance at the 0.01 probability levels; *DF* – degrees of freedom, *SS* – sum of squares, *MS* – mean square

Table 2. Mean winter wheat grain yield performance (t ha^{-1}) for different locations in 2003–2004.

Location	Grain yield in 2003 (t ha^{-1})	Grain yield in 2004 (t ha^{-1})
Plunge	6.662**	6.553
Kaunas	7.035**	9.051**
Pasvalis	5.729	8.798**
Utena	5.089	7.836
Average (*LSD* .01 = 0.065)	6.128	8.059**
LSD .05	0.152	0.059
LSD .01	0.207	0.082

*, ** indicate the highest differences from the mean data significance at the 0.05 and 0.01 probability levels, respectively.

Table 3. Additive main effect and multiplicative interactions analysis of variance for winter wheat grain yield (t ha^{-1}) of the genotypes across environments.

Source	*DF*	*SS*	*MS*	Explained (%)
Total	103	230.285		
Environment (E)	7	177.507	25.358**	77.081
Genotypes (G)	12	16.425	1.386*	7.132
E x G	84	36.353	0.434**	15.786
IPCA 1	18	17.322	0.962**	47.651
IPCA 2	16	9.132	0.571**	29.120
IPCA 3	14	3.986	0.285*	10.964
IPCA 4	12	3.572	0.298**	9.827
E x G Residual	24	2.340		6.437

*,** - significance at the 0.05 and 0.01 probability levels, respectively

Table 4. Effects of the winter wheat varieties grain yield (t ha^{-1}) from the AMMI additive GE model.

Variety Name	Environments								Genotype Effects
	Plunge 2003 (A)	Kaunas 2003 (B)	Pasvalis 2003 (C)	Utena 2003 (D)	Plunge 2004 (E)	Kaunas 2004 (F)	Pasvalis 2004 (G)	Utena 2004 (H)	
Zentos	-0.088	0.085	0.731	0.854	0.240	-1.083	0.064	-0.804	0.208
Aristos	-0.799	-0.903	-0.039	-0.202	0.510	0.601	0.514	0.316	0.057
Compliment	-0.084	0.047	1.73**	-0.21	-0.605	-0.214	-0.305	-0.259	0.292
Cubus	-0.923	-0.706	-0.480	-0.020	-0.433	1.058	0.321	1.183*	0.220
Elfas	0.253	-0.290	0.254	0.101	0.103	-0.276	0.197	-0.340	0.364
LP.562.4.99	0.810	0.127	-0.434	-0.382	0.219	0.201	-0.416	-0.124	-0.312
LP.790.1.98	0.697	0.143	-0.425	-0.110	0.296	0.237	-0.600	-0.237	0.121
LIA 3937	-0.002	0.650	-0.391	0.631	-0.112	-0.681	0.002	-0.096	-0.200
LIA 3948	-0.320	0.256	0.160	1.137	-0.351	-0.730	0.493	-0.645	0.218
Marshal	0.133	0.340	-0.591	-0.544	0.383	0.204	0.134	-0.061	0.184
Meunier	0.824	-0.579	-1.34*	-0.743	-0.366	1.64**	-0.252	0.809	-1.07***
Residence	0.387	0.261	-0.295	-0.980	1.276*	-0.632	-0.019	0.002	-0.469*
Vergas	-0.888	0.569	1.113	0.470	-1.159	-0.328	-0.134	0.358	0.386*
Environ-ments Effects	-0.43*	-0.058	-1.4**	-2.0**	-0.5**	1.96**	1.70**	0.742	

*,**,*** - significance at the 0.05, 0.01and 0.001 probability levels, respectively

The first bilinear interaction term of the AMMI analysis of the G x E accounted for 47.6% of the G x E sum of squares, the second accounted for 29.1% and the third 11%, using 18, 16 and 14 degrees of freedom (*df*) respectively (Table 3). The first two bilinear terms accounted for 76.8% of the G x E sum of squares and used 34 of the total 84 df available in the interaction. They were significant at $P < 0.01$. The obtained data confirm adequacy to the AMMI model. This made it possible to construct the biplot and calculate genotypes and environments effects. (Gauch & Zobel, 1996; Yan & Hunt, 2001; Kaya et. al., 2002). The Interaction Principal Component Axes (IPCA) scores of a genotype in the AMMI analysis indicate the stability of a genotype across environments. The closer the IPCA scores are to zero, the more stable the genotypes are across their testing environments. Basically, these biplots belong to two types: AMMI 1 and AMMI 2 (Carbonell et al., 2004). In AMMI 1, the genotype and environment means are plotted on the abscissa, and the IPCA scores for the same genotypes and environments, on the ordinate. For interpretation of the AMMI 1 biplot, the magnitude and signal of the scores of the IPCA1 are observed; scores close to zero are characteristic of genotypes and environments, which contribute little to the interaction, that is, they are stable.

Table 4 shows effects of genotypes and site values from the additive genotype x environment model. The large differences of effects both on genotypes and on environments were observed. Environments G (1.70 t ha^{-1}) and F (1.96 t ha^{-1}) have the main high significant positive grain yield effects. Environments D (-2.0 t ha^{-1}), C (-1.4 t ha^{-1}) and E (-0.5 t ha^{-1}) have the main significant negative grain yield effects. Only the variety Vergas had a positive grain yield significant effect (0.386 t ha^{-1}) across all environments. The majority of the wheat varieties had a small not significant main positive effect. Only two varieties, Meunier and Residence, had main significant negative grain yield effects (-1.067 and -0.469 t ha^{-1}), respectively (Table 4).

In Figure, the IPCA 1 scores for both the genotypes (numbers) and environments (upper case) were plotted against the grain yield for the genotypes and the environments respectively. We can clearly see the association between genotypes and the environments plotting on the same graph. The IPCA scores of a genotype in the AMMI analysis are an indication of the adaptability over environments.

The graph space of Fig. 1 is divided into 4 quadrants from lower yielding environments in quadrants 1 and 4 to high yielding in quadrants 2 and 3. The biplot shows not only the average yield of a varietiy but also how it is achieved. The varieties Vergas, Elfas, Compliment, Zentos and LIA 3948 posed in quadrant 3 show that they have good adaptation to a wide range of environments. Varieties located near the plot origin were less responsive than the vertex varieties. Considering only the IPCA 1 scores it became clear that the variety Elfas was the most stable genotype, it was well adapted to high yielding sites or environments that are more favourable. The varieties Aristos, LP 790.1.98 and Marshal posed close to zero of IPCA 1 show that they have more stable but lower yields than Elfas. The varieties Cubus, Aristos, Marshal and LP.790.1.98 had a yield significantly over grand mean grain yield and had IPCA 1 score greater than the other varieties; therefore, it may be characterised by specific adaptation in favourable environments. The biplot also shows the yield of a variety at individual site. For example, the variety Cubus was best for high yielded sites H and F.

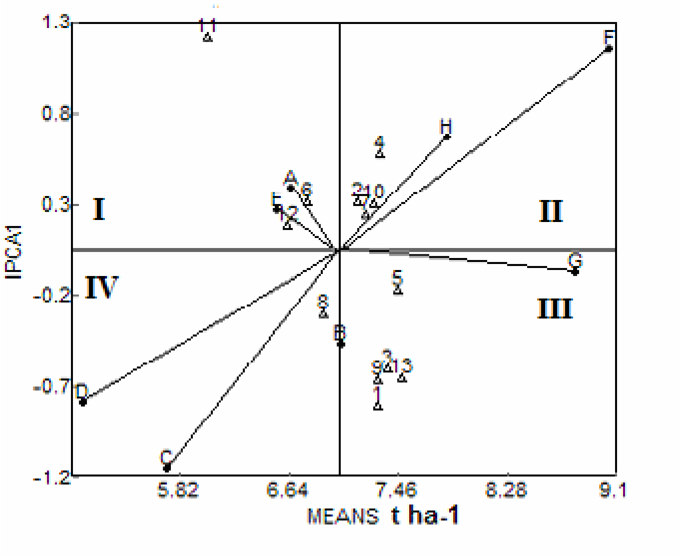

Fig. 1. AMMI 1 model biplot for grain yield (t ha^{-1}) of the 13 wheat varieties in 8 environments. 1- Zentos, 2- Aristos, 3- Compliment, 4- Cubus, 5- Elfas, 6- LP.562.4.99, 7- LP.790.1.98, 8- LIA 3937, 9- LIA- 3948, 10- Marshal, 11- Meunier, 12- Residence, 13- Vergas.

With respect to the test sites, F was most discriminating as indicated by the longest distance between its marker and the origin. Site H was not the most discriminating, but varieties differences at H sites should be highly consistent with those averaged over sites, because it had near zero scores than F site. The length of a genotype vectors reflects the amount of interaction for that variety. Thus according to Fig. 1, most GEI is due to the fact that the variety Meunier has grain yield below average and large IPCA 1 scores value in the trial. As a result, this variety is most suitable for poor environments.

The new varieties of wheat have to be adapted to a broad range of environmental conditions in Lithuania in order to ensure their yield stability and economic profitability. Farmers are more interested in the varieties that produce consistent yields under their growing conditions, and breeders want to meet these needs. An alternative model to AMMI for studying and interpreting interaction includes partial least squares regression (Aastveit, 1986) and factorial regression (Denis, 1988). Comparative studies have found that AMMI, partial least squares regression, and factorial regression models are all useful and may identify similar variety and environmental variables in explaining the interaction (Vargas et al., 1999). GEI patterns revealed by AMMI plots indicate that winter wheat varieties are narrowly adapted. No genotype has superior performance in all environments (Table 4).

CONCLUSIONS

1. The analysis of variance of the 13 varieties in 8 environments shows that genotype (G), location (L), crop-year (Y) and their interaction were significant ($P < 0.01$) for winter wheat grain yield. The AMMI model was very effective for studying GEI interaction. The first bilinear AMMI model terms accounted for 76.8%.
2. No genotype has superior performance in all environments. The biplot shows that the varieties Zentos, Compliment, LIA 3948, Elfas and Marshal are best-suited for cultivation in wide range of environments, while the varieties Cubus, Aristos, Marshal and LP.790.1.98 are best-suited for cultivation in favourable conditions. The variety Meunier is well-suited for cultivation in poor environments.

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