Genotype by environment interaction for seed yield per plant in rapeseed using AMMI model

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Abstract – The objective of this study was to assess genotype by environment interaction for seed yield per plant in rapeseed cultivars grown in Northern Serbia by the AMMI (additive main effects and multiplicative interaction) model. The study comprised 19 rapeseed genotypes, analyzed in seven years through field trials arranged in a randomized complete block design, with three replicates. Seed yield per plant of the tested cultivars varied from 1.82 to 19.47 g throughout the seven seasons, with an average of 7.41 g. In the variance analysis, 72.49% of the total yield variation was explained by environment, 7.71% by differences between genotypes, and 19.09% by genotype by environment interaction. On the biplot, cultivars with high yield genetic potential had positive correlation with the seasons with optimal growing conditions, while the cultivars with lower yield potential were correlated to the years with unfavorable conditions. Seed yield per plant is highly influenced by environmental factors, which indicates the adaptability of specific genotypes to specific seasons.

Index terms: *Brassica napus*, adaptability, biplot, stability, yield component.

Interação genótipo x ambiente para a produção de sementes por planta em canola pelo modelo AMMI

Resumo – O objetivo deste trabalho foi avaliar a interação genótipo x ambiente para rendimento de grãos por planta em cultivares de canola cultivadas no norte da Sérvia, pelo modelo AMMI (modelo de efeitos principais aditivos e interação multiplicativa). O estudo foi composto por 19 genótipos de canola, analisados em sete anos por meio de ensaios de campo em delineamento de blocos ao acaso, com três repetições. O rendimento de grãos por planta das cultivares testadas variou de 1,82 a 19,47 g ao longo das sete estações, com média de 7,41 g. Na análise de variância, 72,49% da variação do rendimento total foi explicada pelo ambiente, 7,71% por diferenças entre os genótipos e 19,09% pela interação genótipo x ambiente. No biplot, as cultivares com alto potencial de rendimento genético tiveram correlação positiva com as estações do ano com condições favoráveis de crescimento, enquanto as cultivares com menor potencial de rendimento foram correlacionadas aos anos com condições desfavoráveis. A produção de grãos por planta é altamente influenciada por fatores ambientais, o que indica adaptabilidade de genótipos a estações de cultivo específicas.

Termos para indexação: *Brassica napus*, adaptabilidade, biplot, estabilidade, componentes de rendimento.

Introduction

Seeds from winter and summer rapeseed (*Brassica napus* L.) are used for oil extraction, which makes rapeseed the world's third most important source of vegetable oils. Currently, the production of this crop is mostly based on growing twice-improved (00 type) cultivars with no erucic acid and low levels of glucosinolates in seeds.

Although rapeseed is usually grown in Australia, Canada, China, India, and Western Europe it has been spreading to areas with moderate continental and continental climate, including Southeastern Europe (Marinković et al., 2007). Rapeseed in West Balkans is commonly grown in Northern Croatia and Serbia, where crop production is most intensive. Until the late 1990's, rapeseed was considered a marginal industrial crop; however, there has been a slight increase in the size of the areas in which it is grown. In the last seven years, the importance of rapeseed has significantly increased in this part of Europe, mainly due to the diverse use possibilities of its products (Popović et al., 2010).

Climate changes may result in strong impacts on agriculture, especially on crop growth and yield. Crops are largely determined by climate conditions during growing season; thus, even minor deviations from optimal conditions can seriously threaten yield. Therefore, knowledge on the effect of environmental factors on crop growth and development could reduce the possibilities of significant yield loss and improve the selection of specific cultivars for growing in the target regions.

Development of hybrids and varieties with high and stable genetic potential for seed and oil yield are the main challenges in rapeseed breeding. Unfortunately, yield is a very complex trait due to gene action and interaction with the environment, i.e., different reactions of genotypes on changeable environmental conditions. The yield of a certain genotype in a specific environment consists of genotype main effects, environment main effects, and genotype by environment interaction. When field trials are carried out in different agroecological conditions, usually 80% of yield variation is caused by environment, while genotype and genotype by environment interaction cause 10% of variation each (Yan, 2001). In field crop trials, this interaction is often analyzed by the AMMI (additive main effects and multiplicative interaction) model. This model was originally developed for analysis in social sciences and physics (Mandel, 1961, 1969, 1971; Gollob, 1968), and later adjusted for research in plant sciences (Gauch, 1988, 1992; Cornelius, 1993). The AMMI analysis is a combination of analysis of variance (ANOVA) and principal component analysis (PCA) in which the sources of variability in genotype by environment interaction are partitioned by PCA. The AMMI is, therefore, also known as interaction PCA (Gauch & Zobel, 1990), and can have several models: AMMI0, which estimates the additive main effect of genotypes and environments, and does not include any principal component axis (IPCA); AMMI1, which combines the additive main effects from AMMI0 with the genotype by environment interaction effects estimated from the first principal component axis (IPCA 1); AMMI2, and so forth, until the full model with all IPCA axis (Gauch, 1985, 1988).

Seed yield per plant is one of the main yield components (Ozer et al., 1999), which is greatly influenced by genotype, environment and complex genotype by environment interactions (Sidlauskas & Bernotas, 2003). There are also highly significant and positive correlations of seed yield per plant with harvest index and seed weight (Ali et al., 2003). In crop production, yield stability is considered the most important socioeconomic category, especially in extreme environmental conditions (Piepho, 1988; Ceccareli, 1994). Therefore, it is fundamental to grow stable rapeseed cultivars with good seed and oil yields in diverse agroecological conditions (Moghaddam & Pourdad, 2011).

The objective of this study was to assess genotype by environment interaction for seed yield per plant in rapeseed grown in Northern Serbia by the AMMI model.

Materials and Methods

Plant material for field trials consisted of eight winter rapeseed cultivars and 11 inbred lines (UM-1, UM-2, UM-5, UM-6, UM-8, UM-9, UM-10, UM-11, UM-12, UM-13, UM-14). The inbred lines were selected from the rapeseed breeding program of the Institute of Field and Vegetable Crops, Novi Sad, Serbia, and were developed by self-pollination of selected individuals from the gene pool of seven cultivars: Sremica, Banacanka, Falcon, Honk, Samurai, Jet Neuf, and B-009. The cultivars tested in trials were: Sremica, 00 type cultivar from Serbia, with high stalk, large seeds and 40 to 43% oil content; Banacanka, 00 type cultivar from Serbia, with medium-high stalk, large seeds and 42% oil content; Samurai, 00 type cultivar from France, with short stalk, medium-sized seeds and 40 to 43% oil content; Falcon, 00 type cultivar from Germany, with high stalk, medium-sized seeds and 37 to 43% oil content; Jet Neuf, cultivar from France with 1,35% erucic acid, medium-high stalk, small seeds and 38 to 42% oil content; Oktavija, Hungarian cultivar with high level of glucosinolates and erucic acid in seeds, high stalk, large seeds and 43% oil content; Jana, Hungarian cultivar with high level of glucosinolates and erucic acid in seeds, high stalk, medium-sized seeds and 42% oil content; B-009, 00 type cultivar from France, with medium-high stalk, large seeds and 39 to 45% oil content. The varieties were chosen for their role in rapeseed breeding programs in Southeastern Europe, and because they differed in several qualitative and quantitative traits (Marjanović-Jeromela et al., 2009). The importance to test new experimental lines and to compare them with cultivars used as their parental components was also taken into account.

The study was carried out during seven growing seasons, from 1995/1996 to 2002/2003, except for the 2000/2001 season, at the experimental fields of the Institute of Field and Vegetable Crops, Novi Sad, Serbia. The field trials in all years were arranged in a randomized complete block design, with three replicates. Seeds were sown by hand in four rows, 4.0 m long, with between-row spacing of 25 cm. Thinning at HB 3 stage (Harper & Berkenkamp, 1975) provided within-row spacing of 5 cm. Other agricultural practices were optimal for local agroecological conditions (Todorović et al., 2003) in all investigated seasons. The harvest was done manually, when most plants reached the second technical level of maturity (Harper & Berkenkamp, 1975), and seed yield per plant (g) was measured.

Precipitation (mm) and average temperature (°C) were measured during intensive spring growth and seed formation (Table 1). Since climate conditions in winter are important for winter rapeseed growth, the total precipitation of the winter months (December, January and February) was also calculated as a possible indicator of the amounts of accumulated water in the soil, and the average temperatures.

A two-way fixed effect model was fitted to determine the magnitude of the main effects of variation and their interaction on seed yield per plant. Least-squares means were simultaneously produced for the AMMI model. Genotype main effect (G), environment main effect (E) and genotype by environment (GxE) interaction were analyzed by the AMMI model (Gauch & Zobel, 1990), represented by:

$$\gamma_{ge} = \mu + \alpha_g + \beta_e + \sum_{n=1}^{N} \lambda_n \gamma_{gn} \delta_{en} + Q_{ge},$$

in which: γ_{ge} is the yield mean of genotype g in environment e; μ is the grand mean; α_g are the genotypic mean deviations (means minus grand mean); β_e are the environmental mean deviations; N is the number of PCA axis retained in the adjusted model; λ_n is the singular value for PCA axis n; γ_{gn} is the genotype eigenvector for PCA axis n; δ_{en} is the environment eigenvector for PCA axis n; Q_{ge} are the residuals, including AMMI noise and pooled experimental error. Expected distribution of Q_{ge} is normal. At Sigilar, partitioning value of 0.5 was used for specified parameter α.

The PCA analysis level of significance was tested with the F test according to Gollob (1968). In the biplot, which is the easiest way to represent the AMMI1 model, genotype by environment interactions are placed on the vertical axis (IPCA 1), while genotype and environment averages are placed on the horizontal axis. Applied analysis procedures, as well as the interpretation of results, were based on the protocol by Gauch & Zobel (1990). For the AMMI analysis, the program Excel Biplot Macros was used (Lipkovich & Smith, 2002).

Results and Discussion

Climate conditions in spring and winter varied during the seven growing seasons in which the genotypes were tested (Table 1). The amount of winter precipitation was usually over 100 mm, except in the 2001/2002 season, when winter was exceptionally dry. The amount of rainfall during spring was moderate and mostly equally distributed, with the exception of May, in the 1996/1997 season, when the weather was extremely dry, and June, in the 1997/1998 season, when excessive amounts of rainfall were recorded.

Seed yield per plant of tested cultivars varied from 1.82 to 19.47 g throughout the seasons, with an average of 7.41 g (Table 2). The UM-8 line had the highest average yield, and the lines UM-12 and UM-13 had the lowest. The average yield per season also varied from 4.19 g, in the 1997/1998 season, to 13.65 g in the 1998/1999 season. All tested cultivars had the highest average yield in the 1998/1999 season, which could be explained by early spring growth due to high average

Table 1. Precipitation (P) and average temperature (T) conditions in spring (March to June) and winter, during the seven growing seasons in which the experiment was carried out.

Month	1995/1996		1996/1997		1997/1998		1998/1999		1999/2000		2001/2002		2002/2003	
	P (mm)	T (°C)	P (mm)	T (°C)	P (mm)	T (°C)	P (mm)	T (°C)	P (mm)	T (°C)	P (mm)	T (°C)	P (mm)	T (°C)
March	29.8	2.2	32.2	5.5	22.6	4.0	11.1	8.0	31.7	6.8	10.1	8.6	8.9	5.6
April	25.2	11.6	75.2	7.5	39.8	13.2	61.2	12.7	24.6	14.7	30.4	11.1	21.9	11.3
May	90.0	18.1	17.4	17.7	64.1	16.1	76.2	16.9	40.4	18.5	84.7	19.1	30.7	20.6
June	79.1	20.6	62.0	20.7	103.7	21.5	91.0	20.1	31.5	22.0	27.5	22.0	61.5	24.2
Winter	145.0	-0.6	156.6	0.7	150.1	3.8	117.9	2.1	162.3	1.1	61.3	1.4	112.3	-1.9

temperatures in March and April (8.0 and 12.7ºC, respectively). Average temperatures in May and June, with high amount of rainfalls, offered optimal conditions for the development of vegetative mass and a longer grain-filling period. Therefore, environmental factors, especially temperature and precipitation, had the most significant influence on seed yield per plant (Tables 1 and 2). Low levels of moisture in the critical stages of rapeseed development, such as intensive early spring growth, flowering, grain formation and filling, are the main causative agents of significant seed yield reduction (Champolivier & Merrien, 1996). This was observed in the second growing season, when extremely dry conditions in May resulted in severe yield reduction. According to Chauhan et al. (2007), dry conditions during this period can cause forced maturity in the pod-filling stage, resulting in yield reduction. In the 2001/2002 season, very low levels of winter moisture, combined with the lack of rainfall in March, had negative effects on early spring growth and, consequently, caused significant decrease in seed yield.

The three sources of variation were highly significant. In the analysis of variance, the sum of squares for environment main effect represented 72.49% of the total, and this factor had the highest effect on seed yield per plant (Table 3). The differences between genotypes explained 7.71% of the total yield variation, while the effects of GxE interaction explained 19.09%. Values for the three principal components were also highly significant. The three principal components of GxE interaction accounted jointly for 86.26% of the whole effect it had on the variation of seed yield. The first principal component (IPCA 1) accounted for 54.22% of the variation caused by interaction, while IPCA 2 and IPCA 3 accounted for 17.80 and 14.24%, respectively. Since the tested rapeseed cultivars were from different European breeding centers, the difference in their phenotypic values of seed yield per plant is probably a consequence of different breeding strategies. The obtained cultivars have the best adaptability to the environmental conditions for which they were bred, which explains why 72% of the variation in seed yield data was due to the main effects of years.

Table 2. Average yield per plant (g), for genotypes and years, and principal component analysis values of tested rapeseed (*Brassica napus*) cultivars.

Genotype	1995/1996	1996/1997	1997/1998	1998/1999	1999/2000	2001/2002	2002/2003	Mean	IPCA 1	IPCA 2	IPCA 3
Sremica	10.43	4.30	8.70	19.47	6.27	4.77	5.93	8.55	2.21	0.60	0.07
Banacanka	7.53	4.85	5.41	14.50	6.72	5.20	6.81	7.29	0.64	0.72	0.02
Samurai	7.98	2.83	4.55	14.06	8.36	5.12	7.34	7.18	0.49	0.03	0.02
Falcon	11.44	3.12	4.07	17.16	9.98	5.27	9.22	8.61	0.92	-0.88	-0.35
Jet Neuf	7.28	3.97	5.98	16.59	10.52	5.83	6.56	8.11	0.72	0.03	1.15
Oktavija	7.75	4.60	5.17	15.11	9.72	4.20	8.71	7.89	0.32	-0.15	0.27
Jana	9.06	5.06	5.29	14.59	5.25	4.78	8.42	7.50	0.75	0.59	-0.92
B-009	8.13	3.20	4.32	18.32	11.04	5.84	11.26	8.87	0.43	-1.50	0.33
UM-1	6.54	5.32	3.15	14.77	10.04	4.40	8.61	7.55	-0.06	-0.32	0.60
UM-2	7.91	3.68	3.25	11.49	7.54	4.29	8.51	6.67	-0.12	0.21	-0.67
UM-5	3.35	5.41	2.50	11.74	9.63	6.87	11.12	7.23	-1.34	-0.24	0.39
UM-6	5.88	4.49	2.67	13.21	10.75	6.00	9.75	7.54	-0.66	-0.48	0.48
UM-8	9.15	4.67	5.30	16.45	8.33	6.97	14.07	9.28	0.02	-0.91	-1.13
UM-9	9.08	3.66	3.64	10.04	9.80	5.64	10.59	7.49	-0.76	0.02	-0.99
UM-10	6.05	5.36	4.78	12.91	9.69	6.01	6.88	7.38	-0.17	0.68	0.79
UM-11	5.81	5.13	4.21	10.54	7.90	3.82	10.18	6.80	-0.74	0.36	-0.54
UM-12	2.78	3.03	1.82	10.08	8.72	2.89	9.36	5.52	-1.05	-0.40	0.25
UM-13	4.32	4.51	1.93	9.82	7.78	3.48	6.80	5.52	-0.68	0.55	0.28
UM-14	4.87	4.59	2.82	8.49	7.39	6.00	7.02	5.88	-0.92	1.09	-0.05
Mean	7.12	4.30	4.19	13.65	8.71	5.12	8.80	7.41	-	-	-
IPCA 1	1.34	-0.93	0.90	2.31	-1.24	-0.75	-1.63	-	-	-	-
IPCA 2	0.18	1.42	1.24	-1.22	-0.77	0.51	-1.36	-	-	-	-
IPCA 3	-1.46	0.31	0.03	0.84	1.46	0.18	-1.36	-	-	-	-

IPCA, principal component of interaction.

Measuring GxE interaction is very important to determine an optimum breeding strategy for releasing cultivars with an adequate adaptation to target environments (Fox et al., 1997). Among the tested cultivars, the variety Sremica had the highest IPCA 1 value of 2.21, while the highest value of IPCA 1 was 2.31 in the 1998/1999 season (Figure 1). The 1999/2000 and 2002/2003 seasons had similar agroecological conditions, indicated by their close placement on the biplot. They also had the strongest effect on yield performance of the lines UM-5, UM-6, and UM-12. The conditions in the 1998/1999 season had negative correlation with the lines UM-14, UM-11, and UM-13, and significantly reduced their yield. In the same season, agroecological conditions had positive effect on yield of the varieties Falcon and B-009. These genotypes were selected in regions with higher amounts of precipitation and uniformly distributed rainfalls during intensive growth and plant development (April and May), without large temperature oscillations, as in the spring of 1999.

Table 3. Analysis of variance of main effects and interactions for rapeseed (*Brassica napus*) cultivars seed yield per plant.

Source of variation	Df	Sum of squares	Mean squares	F	Variability explained (%)
Replication	2	36.58	18.29	5.18	0.68
Genotype	18	412.03	22.89	6.49^{**}	7.71
Year	6	3,869.37	644.89	182.922^{**}	72.49
GxE	108	1,019.42	9.44	2.68^{**}	19.09
IPCA 1	23	552.72	24.03	6.81^{**}	54.22
IPCA 2	21	181.42	8.64	2.45^{**}	17.80
IPCA 3	19	145.21	7.64	2.17^{**}	14.24

**Significant at 1% probability. GxE, genotype by environment interaction; IPCA, principal component of interaction.

The differences and genotype distributions in the biplot are a consequence of genotype variations in different conditions (long and cold winter in the 1996/1997 season, and calm winter and moderate spring in the 1998/1999 season) (Figure 1, Table 1). This indicates that rainfalls in the grain-filling period, cold winters, and early spring temperatures have a large impact on yield variation.

The clustering of some of the tested cultivars according to their IPCA 1 values and average yield on biplot (Figure 1) also explains their similarities in yield per plant variations (Shafii et al., 1992; Marjanović-Jeromela, 2005). In general, environments with scores near zero have little interaction across genotypes and provide low discrimination among genotypes (Anandan et al., 2009); however, in this

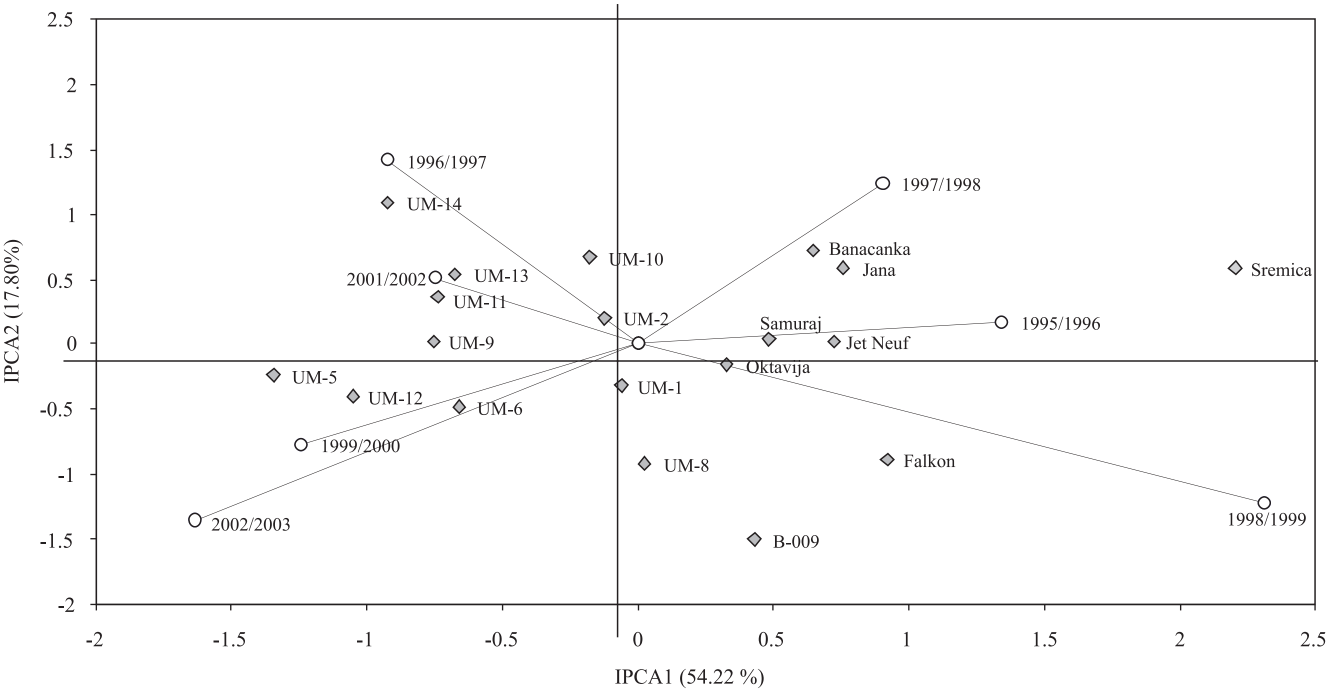

Figure 1. Biplot for genotype by environment interaction of rapeseed (*Brassica napus*) cultivars in seven cultivation years, showing the effects of primary and secondary components (IPCA 1 and IPCA 2, respectively).

study, this pattern was not observed in any of the seasons.

Genotype stability is considered a reaction to changing environmental conditions, which depend on unpredictable variation components (Kang, 2002). In this study, climatic conditions were the source of this variation component. The stability of tested cultivars can be evaluated according to biplot for seed yield per plant (Figure 2). Experimental lines from Serbia interacted differently with climate conditions in the observed seasons. The lines UM-5, UM-6, and UM-12 interacted positively with the 1999/2000 and 2002/2003 seasons, but negatively with the 1995/1996 and 1997/1998 seasons (Figures 1 and 2). The lines UM-11, UM-13, and UM-14 interacted positively with the 1996/1997 and 2001/2002 seasons, but negatively with the 1998/1999 season. The analysis showed that some genotypes have high adaptation; however, most of them have specific adaptability (Yan & Hunt, 1998; Atanasova et al., 2009). The line UM-8 had very stable and high average seed yield per plant, with the IPCA 1 value closest to zero. Similar IPCA 1 values were found in the lines UM-1, UM-2, and UM-10. This kind of genotype is considered highly desirable in rapeseed breeding.

Genotypes on the highest point in certain sections of the graph have the best results in environments located in the same section (Figure 2) (Yan, 2001, Gvozdanović-Varga, et al. 2004, Hristov et al., 2010). A large group of genotypes (Banacanka, Samurai, Oktavija, Jana, UM-1, UM-2, UM-5, UM-6, UM-9, UM-10, and UM-11), with average seed yield per plant close to the general mean of 7.41 g, are distinguished on the biplot. Due to the differences in their reactions to changing environmental conditions, reflected in their IPCA 1 values, the genotypes were distributed in different sections of the biplot. Oktavija, UM-1, UM-2, and UM-10 had the highest stability. A second group of cultivars (Sremica, Falcon, B-009, and UM-8) had the highest averages of yield per plant, but with different adaptations (Figures 1 and 2): Sremica showed specific adaptation to the conditions of the 1997/1998 season, Falcon and B-009 to the 1998/1999 season, and UM-8 showed general adaptation.

Some of older varieties had high stability, which is not surprising considering the fact that they were developed for cultivation in a wide area of different agroecological conditions in Europe. Cultivars with high genetic yield potential had positive correlation with the seasons in which climate conditions were

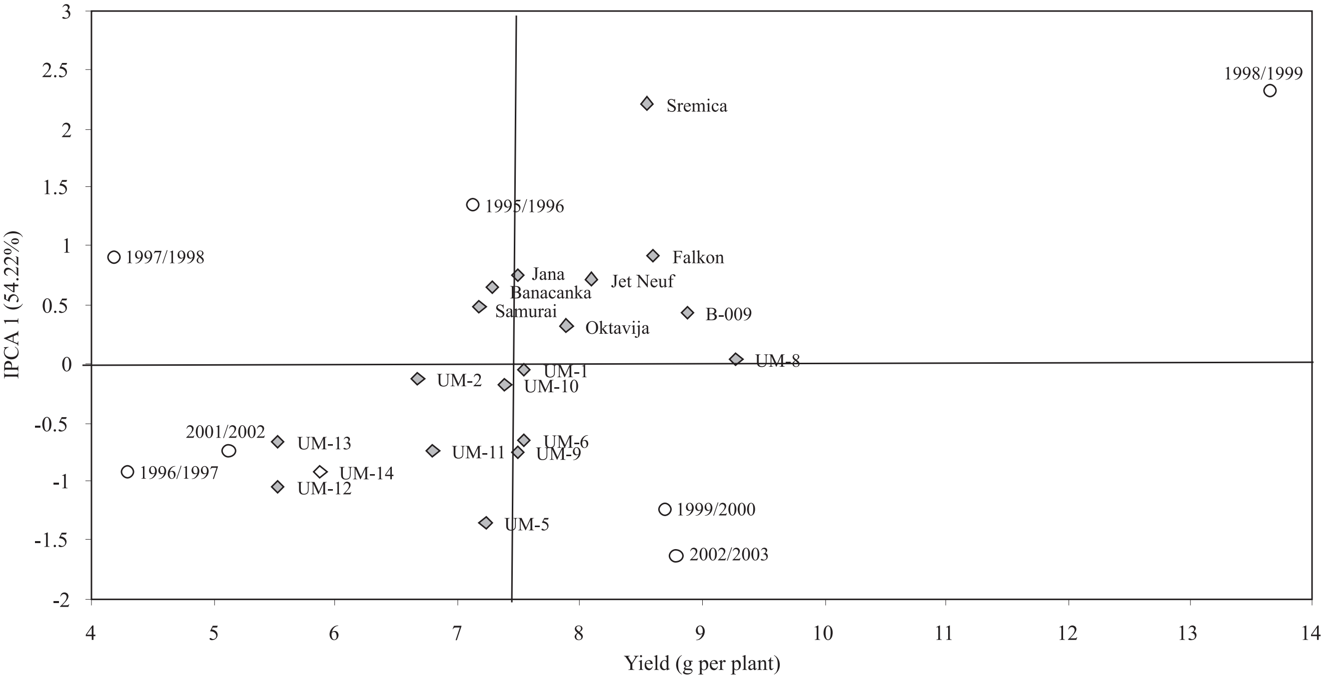

Figure 2. Biplot for the primary component of interaction (IPCA 1) and average rapeseed (*Brassica napus*) seed yield (g) per plant. Vertical line at the centre of biplot is the general grand mean.

optimal for rapeseed growing, while cultivars with lower yield potential were correlated to the years with unfavorable conditions, as in Vargas et al. (1999).

A graphically represented AMMI analysis enables selection of stable and high-yielding cultivars for this region, as well as cultivars with specific adaptability. The AMMI analysis is adequate in characterizing GxE interaction for seed yield per plant in rapeseed. Sudarić et al. (2006) reached the same conclusion in their study on soybean under similar agroecological conditions in Southeastern Europe.

Climate data collected in this study are useful in the analysis of GxE interaction, especially for these specific regions, since climate conditions can range drastically from year to year. The obtained data is also useful for the development of rapeseed breeding programs, not just in the main growing areas of Northern Serbia and Croatia, but also in other countries of Southeast Europe, such as Bosnia, Herzegovina, and Former Yugoslav Republic of Macedonia.

Conclusions

1. Environmental factors and genotype by environment interaction have the highest influence on the formation of seed yield per plant in rapeseed.
2. The line UM-8 is recommended for further inclusion in the breeding program due to its stability and high seed yield, whereas the lines UM-1, UM-2, and UM-10 are recommended because of their stability.

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