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Ecological stability of broad bean (*Vicia faba* L.) in organic farming conditions

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The main direction in the breeding of legumes is the development of high-productive cultivars with stable yields. In order to assess the ecological stability of 17 broad bean accessions (Fb 1896, Fb 1903, Fb 1929, Fb 2481, Fb 2486, Fb 3270, BGE 002106, BGE 029055, BGE 032012, BGE 041470, BGE 043776, BGE 046721, FbH 13, FbH 14, FbH 15, FbH 16, BGP) with regard to key quantitative traits, a field experiment was conducted in the Institute of Forage Crops (Pleven) in 2016–2018. Plants were grown under organic farming conditions without the use of fertilizers or pesticides. Three types of stability parameters were calculated based on regression, variance, and nonparametric analysis. The results of the variance analysis showed a significant genotype × environment interaction for all quantitative traits except pod width. The factor 'environment' had the greatest impact on the phenotypic manifestation of the traits, followed by the factors 'genotype' and 'genotype × environment interaction'. In terms of plant height and 1st pod height, accessions FbH 16 and FbH 13 can be classified as high (79 cm, 35 cm) and ecologically stable (bi = 0.76, bi = 0.79). BGE 029055 was little variable and had high numbers of pods (15) and seeds (41) per plant. Accessions FbH 14, FbH 16, FbH 15, and BGP were distinguished by high seed weight per plant (from 28.36 to 34.93 g), but they exhibited instability (bi > 1) under unfavorable environmental conditions. In contrast, Fb 1903, BGE 043776, and Fb 3270 were very stable (bi < 1) but low-productive. Accessions Fb 1896, Fb 1929, Fb 2481, Fb 2486, BGE 002106, and BGE 029055 showed intermediate parameters, as they had the coefficient of linear regression close to 1, but they were also low-productive. BGE 041470 appeared to be of special interest for breeding. It had high values of 100 seed mass (101.38 g) and seed weight per plant (32.14 g), being relatively stable (bi = 1.10). GGE biplot analysis determined accessions BGE 046721, BGE 032012, FbH 15 and FbH 16 as a promising breeding material combining high and stable seed yield.

Key words: *Vicia faba* L.; stability parameter; productivity; traits; accessions; regression analysis; nonparametric analysis.

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Экологическая стабильность боба овощного (*Vicia faba* L.) в условиях органического хозяйства

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Важное направление в селекции бобовых – создание высокоурожайных сортов со стабильной продуктивностью. Для оценки экологической стабильности 17 образцов *Vicia faba* (Fb 1896, Fb 1903, Fb 1929, Fb 2481, Fb 2486, Fb 3270, BGE 002106, BGE 029055, BGE 032012, BGE 041470, BGE 043776, BGE 046721, FbH 13, FbH 14, FbH 15, FbH 16, BGP) по основным количественным признакам в Институте кормовых культур (г. Плевен, Болгария) в 2016–2018 гг. был проведен полевой эксперимент. Растения выращивали в условиях органического земледелия, без использования удобрений и пестицидов. На основе регрессионного, дисперсионного и непараметрического анализа были рассчитаны три типа параметров стабильности. Результаты дисперсионного анализа доказывают взаимодействие генотип × среда для всех количественных признаков, кроме ширины бобов. Фактор среды оказывает наибольшее влияние на фенотипическое проявление признаков, далее следуют факторы «генотип» и «генотип × среда». По признакам «высота растения» и «высота бобов» образцы FbH 16 и FbH 13 можно отнести к высоким (79 и 35 см соответственно) и экологически стабильным (bi = 0.76, bi = 0.79). BGE 029055 имеет низкую вариабельность, с высокими значениями количества бобов (15) и количества семян с растения (41). Образцы FbH 14, FbH 16, FbH 15 и BGP характеризуются высокой массой семян (от 28.36 до 34.93 г), но проявляют нестабильность (bi > 1) в неблагоприятных условиях среды. Fb 1903, BGE 043776 и Fb 3270, напротив, очень стабильны (bi < 1), однако низкопродуктивны. Промежуточные позиции занимают образцы Fb 1896, Fb 1929, Fb 2481, Fb 2486, BGE 002106 и BGE 029055, у которых коэффициент линейной регрессии приближается к единице, но они также являются низкопроизводительными. Интересен с позиций селекции образец BGE 041470, отличающийся высокими значениями массы 100 семян (101.38 г)

и массы семян с растения (32.14 г) и относительной стабильностью (bi = 1.10). Результаты анализа двойных диаграмм GGE позволяют расценивать образцы BGE 046721, BGE 032012, FbH 15 и FbH 16 как перспективный материал для селекции, сочетающий высокую и стабильную продуктивность семян.
Ключевые слова: *Vicia faba* L.; параметры стабильности; продуктивность; признаки; образцы; регрессионный анализ; непараметрический анализ.

Introduction

Broad bean (*Vicia faba* L.) is an important legume crop that is primarily used as a protein source in human diet, as forage for animals and as an available source of nitrogen for the biosphere (Rubiales, 2010). Enlargement of broad bean growing is desirable, but it is hampered due to unstable yields (Link et al., 2010).

Yield is a complex quantitative characteristic that is usually controlled by several genes and affected by environmental conditions. The importance of genotype-environment interaction in national programs for cultivar evaluation and breeding programs has been found in most major crops (Kendal et al., 2016; Pouresmael et al., 2018). Researchers investigate and describe stable genotypes by use of different parametric and nonparametric methods or single-variate and multivariate statistical methods (Hamayoon et al., 2011; Imtiaz et al., 2013; Kendal, Sayar, 2016).

In recent years, breeders' interest in legume crops, and especially in broad beans, has increased. Great attention is paid to the study of the starting material, both for the development of new varieties and for the improvement of the existing ones (Kurkina, 2013). In order to identify the best donors and promising candidate cultivars, statistical analysis of as many quantitative traits as possible can be used (Kurkina, 2003; Buravtseva et al., 2009).

The main direction in the breeding of legumes is the development of high-productive cultivars with stable yields over the years (Kazydub, Shamanin, 2003). The terms "plasticity" and "stability" are used to characterize the potential of modification variability and genotypic variability of the individual traits (or their groups). Plasticity (the ability of traits to change), as well as stability under different environmental conditions, are considered to be the basic adaptive properties of living organisms. Ecological plasticity of a genotype (cultivar) is the ability to a sustainable formation of high (compared to other genotypes) yield over a wide range of meteorological and agro-technical conditions (Zhuchenko, 2012; Marakaeva, Kazydub, 2016). Stability is a particularly important characteristic of cultivars in organic production conditions (Konvalina et al., 2009; Georgieva, 2017).

The aim of this study was to evaluate the ecological stability of broad bean accessions regarding main quantitative traits in broad bean in organic farming conditions.

Material and methods

The experimental activity was conducted at the Institute of Forage Crops (Pleven, Bulgaria) during the period 2016–2018. The objects of the study were 17 broad bean (*Vicia faba* L.) accessions of different origins: Portugal (Fb 1896, Fb 1903, Fb 1929, Fb 2481, Fb 2486, Fb 3270), Spain (BGE 002106, BGE 029055, BGE 032012, BGE 041470, BGE 043776, BGE 046721) and Bulgaria (FbH 13, FbH 14, FbH 15, FbH 16, BGP).The randomized block method (Barov, 1982) was used, with a plot size of 4 m^2 and three replications. The sowing was done by hand, at a depth of 8 cm and with a rate of 30 seeds per m^2. Plants were grown under organic farming conditions without the use of fertilizers and pesticides. A biometric estimation was performed, including the following traits: plant height (cm), 1st pod height (cm), pods number per plant, pod lenght (cm), pod width (cm), seeds number per plant, seed weight per plant (g), 100 seeds mass (g).

The obtained data were processed by two-factor analysis of variance for each trait for determine of the influence of genotypes (accessions) (G), environments (E) and their interaction (G × E). The evaluation of the ecological stability of the studied accessions was performed using the following analyzes and parameters: *regression analysis* – according to (Eberhart, Russell, 1966) where the regression coefficient (bi) and the variance of the deviations from regression (Si^2) were calculated; according to (Tai, 1979) in which the parameters a_i (linear response to the environmental effects) and λ_i (deviation from the linear response) were determined; *variance analysis* – mean variance component (PP) according to (Plaisted, Peterson, 1979), ecovalence (W^2) according to (Wricke, 1965), stability variances (σ^2 and W_i) according to (Shukla, 1972) and (Annicchiarico, 1992) respectively; and *non-parametric analysis* – by the rank-parameter (Si_2) on the model of (Huehn, 1990a, b). Plaisted and Peterson's (1979) mean variance component (PP) was a measure of a cultivar's contribution to the G × E interaction and was determined from a total through "pair-wise" analysis. According to Annicchiarico's method (1992), a reliability index (W_i) was calculated which estimates the probability of a particular genotype (cultivar) to show a performance below the environmental average or below any standard used. GGE biplot model was done, which uses decomposition of the singular value of first two principal components (Yan, 2002). All experimental data were processed statistically with using the computer software GENES 2009.7.0 for Windows XP (Cruz, 2009).

Results

Analysis of variance

The results of the two-factor analysis of variance of the traits (Table 1) confirmed the differences in the environmental conditions during the experimental period. With regard to the trait of pod width, the variances of factors were insignificant, on the basis of which it can be considered that genotype differences between the accessions were not essential. For all other traits, the influence of the factors was statistically significant, and the environment had the greatest share. The effect of genotype was stronger pronounced than that of GE interaction for the 1st pod height, pod length and 100 seeds mass. In terms of plant height, the GE interaction was more pronounced. Consequently, for improving this trait, further research will be needed. The statistical significance of the factors genotype, environment and their interactions for almost all traits was an objective prerequisite for determining the stability parameters.

Table 1. Mean squares in analysis of variance of broad bean accessions regarding main quantitative traits

Source of variation	DF	Plant height	1st pod height	Pods number	Seeds number	Pod lenght	Pod width	100 seeds mass	Seed weight
Environment	2	12851.1*	690.94*	286.32*	2926.02*	113.83*	1.20	35356.36*	9731.29*
Genotype	16	177.13*	147.74*	34.32*	289.38*	17.72*	0.24	2292.23*	310.92*
G×E	32	182.05*	72.12*	23.55*	263.85*	3.18***	0.08	709.42*	239.80*
Env/Gen	34	927.29*	108.52*	39.012*	420.45*	9.69*	0.14	2747.48*	848.94*
Env/Gen 1	2	605.38*	92.03*	23.24*	58.24*	1.30	0.13	5874.38*	608.41*
Env/Gen 2	2	1122.58*	156.85*	32.18*	273.06*	2.65*	0.05	452.619*	343.72*
Env/Gen 3	2	732.47*	205.65*	23.94*	136.60*	6.28**	0.10	3476.60*	446.80*
Env/Gen 4	2	1051.84*	283.73*	23.23*	149.73*	1.78	0.01	3253.31*	436.17*
Env/Gen 5	2	903.05*	109.54*	17.44*	70.98*	9.37***	0.16	4837.00*	831.81*
Env/Gen 6	2	3035.11*	516.04*	12.72*	419.25*	2.57*	0.04	597.64*	59.35*
Env/Gen 7	2	903.00**	3.64**	20.17*	600.13*	17.01*	0.19	225.16*	455.60*
Env/Gen 8	2	951.12***	9.35***	29.57*	610.76*	2.38	0.11	295.67*	563.18*
Env/Gen 9	2	1326.65*	81.75*	17.65*	376.83*	15.97*	0.18	2068.95*	694.54*
Env/Gen 10	2	1073.02*	83.75*	19.26*	266.96*	17.48*	0.05	1285.91*	794.75*
Env/Gen 11	2	1380.87*	70.74*	7.68**	36.51*	1.40	0.43	1209.42*	93.13*
Env/Gen 12	2	700.98*	44.45*	5.21**	3.46**	7.83**	0.21	3452.99*	383.41*
Env/Gen 13	2	469.91*	47.73*	6.51**	306.33*	14.00*	0.22	3273.78*	1014.93*
Env/Gen 14	2	660.35*	11.43**	345.16*	2023.68*	17.02*	0.08	3474.64*	2971.63*
Env/Gen 15	2	142.95*	2.34*	20.34*	710.91*	14.30*	0.17	2949.75*	1652.84*
Env/Gen 16	2	477.29*	14.25*	24.62*	658.21*	16.51*	0.01	5105.18*	1505.32*
Env/Gen 17	2	227.38*	111.63*	34.21*	446.05*	16.83*	0.33	4874.15*	1576.42*
Total	50	1							

Note: Genotypes: 1, Fb1896; 2, Fb1903; 3, Fb 1929; 4, Fb 2481; 5, Fb 2486; 6, Fb 3270; 7, BGE 002106; 8, BGE 029055; 9, BGE 032012; 10, BGE 041470; 11, BGE 043776; 12, BGE 046721; 13, FbH 13; 14, FbH 14; 15, FbH 15; 16, FbH 16; 17, BGP.
* Significant at $p < 0.1$; ** $p < 0.05$; *** $p < 0.01$.

Evaluation of stability

The influence of environmental conditions on the trait formation was expressed by the values of the stability parameters calculated by the different methods (Table 2 and Table 3). Regarding the plant height, when comparing the accessions, it was found that the FbH 13 and FbH 16 (79 cm) had the greatest height, followed by Fb 3270 and BGE 043776 (78 cm) (Fig. 1). For the experimental conditions, BGP and FbH 15 were the most stable. They were characterized by very low values of bi (bi = 0.24; bi = 0.31), as in FbH 15, the value of Si^2 was considerably lower (Si^2 = 43.97).

The accessions Fb1896, Fb 1929, BGE 046721 and FbH 14 were distinguished by mean stability for bi (bi = 0.86–0.95) and low variance. From the highest plant accessions, particular attention should be paid to FbH 16 and FbH 13, which were definitely stable (bi = 0.76; bi = 0.79) and weakly affected by the environmental conditions, unlike Fb 3270 and BGE 043776, whose plants were also high but they exhibited strong variability. According to the values of the regression coefficient, BGE 002106, BGE 029055, Fb 2481 and Fb 2486 were stable, with height below the average for the group of tested accessions, and BGE 032012 and BGE 041470 exhibited plasticity with respect to this trait due to its high value (bi = 1.18–1.32).

The trait of 1st pod height had high values in FbH 16, Fb 2481 and FbH 13, followed by Fb 1929 and BGE 046721. According to stability data, FbH 16 exhibited high stability (bi = 0.06; σ^2 = 4.17; W_i = 103.31), while Fb 2481 and Fb 1929 (considering the coefficient of linear regression bi as well as the parameter PP) were characterized by very well-expressed responsiveness (bi > 1; PP = 33.65–36.85). Similarly was the behavior of Fb 1896, Fb 1903, Fb 2486, Fb 3270, BGE 032012, BGE 041470 and BGE 043776, but they set their 1st pods at a relatively lower height. Plants of FbH 13 formed their first pods highly and, according to most stability parameters, showed very low variability.

The largest number (15) of pods per plant was obtained from accessions BGE 029055 and FbH 14 (see Fig. 1). The following positions were occupied by Fb 2486, BGE 043776, BGP (12 pods per plant). According to the stability data of the considered trait (see Table 2), all parameters defined FbH 14 as unstable. It is notable that accessions that formed a larger number of pods (11–15) were highly variable and responsive to improvement in growing conditions. An exception was

Table 2. Parameters of phenotypic stability in broad bean accessions regarding main quantitative traits

Accessions	bi	Si^2	a_i	λ_i	σ^2	PP	W^2	W_i
	Eberhart, Russell, 1966		Tai, 1979		Shukla, 1972	Plaisted, Peterson, 1979	Wricke, 1965	Annicchiarico, 1992
				Plant height				
Fb 1896	0.86**	24.51**	0.8669	39.6022	14.69	38.9799	101.3134	96.6814
Fb 1903	1.06	184.23**	1.0578	294.1470	936.34	79.4805	558.7322	91.1648
Fb 1929	0.93	52.96**	0.9291	84.9413	39.15	44.8390	167.4867	91.5588
Fb 2481	1.09	100.43**	1.0916	160.6005	142.12	57.8982	314.9792	91.9984
Fb 2486	1.09	3.10**	1.0899	5.4691	71.45	32.0026	22.5111	86.7744
Fb 3270	1.94**	116.75**	1.9450	186.5475	–8.33	180.6308	1701.1350	88.8600
BGE 002106	1.08	14.99**	1.0789	24.4243	38.59	34.9145	55.3980	84.1335
BGE 029055	1.10*	14.60**	1.1085	23.7940	351.60	35.5501	62.5767	90.7561
BGE 032012	1.32**	0.74	1.3240	1.7015	47.84	44.3418	161.8715	93.4103
BGE 041470	1.18**	8.91**	1.1838	14.7143	54.03	36.9819	78.7482	90.5619
BGE 043776	1.35**	0.27	1.3512	0.9337	245.44	46.6715	188.1837	102.2922
BGE 046721	0.95	12.36**	0.9498	20.2371	205.40	33.7193	41.9000	97.6550
FbH 13	0.76**	20.34**	0.7619	32.9499	46.44	43.0864	147.6932	104.3693
FbH 14	0.90*	31.41**	0.9003	50.6029	23.40	39.7729	110.2691	95.6382
FbH 15	0.31**	43.97**	0.3181	70.6230	19.58	104.0226	835.9135	88.7764
FbH 16	0.79**	0.03	0.7946	0.0476	118.85	35.6631	63.8529	105.7174
BGP	0.24**	119.96**	0.2491	191.7374	0.33	137.4324	1213.2480	90.0438
				1st pod height				
Fb 1896	1.29	15.77**	1.2928	25.6599	24.01	16.5806	55.2583	86.9871
Fb 1903	1.92**	4.24**	1.9224	7.2371	186.74	19.0091	82.6858	89.5109
Fb 1929	1.50*	75.50**	1.5045	120.8449	203.76	33.6578	248.1301	97.6634
Fb 2481	2.24**	52.64**	2.2437	84.3306	25.86	36.8590	284.2840	100.6840
Fb 2486	1.58**	4.93**	1.5823	8.3652	32.82	15.5190	43.2677	72.4388
Fb 3270	3.25**	57.62**	3.2526	92.0538	7.25	63.4964	585.1307	83.5793
BGE 002106	0.23**	0.69	0.2262	1.5986	70.32	16.2578	51.6120	81.6485
BGE 029055	0.26**	4.01**	0.2658	6.8280	110.24	24.3403	142.8964	63.9726
BGE 032012	1.22	13.71**	1.2223	22.3807	47.56	15.7731	46.1379	95.1409
BGE 041470	1.26	12.67**	1.2577	20.7200	6.71	15.6185	44.3912	76.0487
BGE 043776	1.32	0.33	1.3196	0.0067	0.67	12.4233	8.3049	91.5196
BGE 046721	0.78	12.80**	0.7802	20.9221	3.97	15.5222	43.3041	105.1743
FbH 13	1.08	0.32	1.0838	0.0164	161.84	11.7412	0.6005	115.3304
FbH 14	0.18**	6.39**	0.1811	10.6762	13.94	18.2874	74.5346	101.0185
FbH 15	0.23	0.23	0.2309	0.1270	36.65	15.9604	48.2529	98.1128
FbH 16	0.06**	0.81	0.5578	1.6707	4.17	29.4062	200.1110	103.3181
BGP	0.07**	72.05**	0.2763	115.2605	66.35	42.6060	349.1913	79.2728
				Pods number				
Fb 1896	1.13	0.74	1.1336	1.7139	11.73	3.9314	3.8258	99.3485
Fb 1903	0.58	17.32**	0.5807	28.1234	28.86	8.8026	58.8420	70.7805
Fb 1929	1.19	0.21	1.1884	0.1928	28.67	3.7303	1.5543	67.0757
Fb 2481	1.14	0.50	1.1430	1.3265	1.64	3.8745	3.1832	82.9719
Fb 2486	0.99	0.35	0.9874	1.0895	228.57	3.7748	2.0565	109.5617
Fb 3270	0.07**	1.51*	0.7752	2.7405	14.35	13.4150	110.9343	72.4880
BGE 002106	0.98	2.30**	0.9812	4.2002	21.31	4.2938	7.9188	84.8447
BGE 029055	1.27	1.19*	1.2739	2.4223	0.55	4.2193	7.0777	131.0650

Table 2 (continued)

Accessions	bi	Si^2	a_i	λ_i	σ^2	PP	W^2	W_i
	Eberhart, Russell, 1966		Tai, 1979		Shukla, 1972	Plaisted, Peterson, 1979	Wricke, 1965	Annicchiarico, 1992
BGE 032012	1.02	0.31	1.0226	0.0429	41.00	3.6013	0.0978	85.2169
BGE 041470	1.07	0.25	1.0662	0.1360	28.64	3.6284	0.4031	72.4842
BGE 043776	0.40	2.99**	0.3974	5.2887	23.82	5.5536	22.1467	106.2217
BGE 046721	0.38	1.49	0.3816	2.8798	1.79	5.2091	18.2556	74.5156
FbH 13	0.53	0.87	0.5271	1.9108	19.93	4.5757	11.1025	88.4313
FbH 14	4.27**	25.27**	4.2791	40.1479	21.47	42.2413	436.5020	83.2290
FbH 15	0.77	6.54**	0.7715	10.9442	28.78	5.5718	22.3528	82.5891
FbH 16	0.95	5.89**	0.9521	9.9328	0.15	5.2550	18.7748	86.7098
BGP	1.09	9.17**	1.0891	15.1406	17.43	6.1396	28.7652	99.9964
				Seeds number				
Fb 1896	0.33**	26.11**	0.3284	42.1215	42.46	64.4062	234.4991	78.2605
Fb 1903	0.65**	133.84**	0.6458	213.8359	113.48	83.1058	445.6945	60.3994
Fb 1929	0.89	0.33	0.8908	–0.0018	175.39	44.0063	4.1004	70.1788
Fb 2481	0.93	0.14	0.9318	0.3142	212.15	43.8375	2.1940	68.6338
Fb 2486	0.23**	41.06**	0.2269	65.9392	737.04	72.8423	329.7770	93.4250
Fb 3270	0.31**	83.03**	0.3082	132.5242	248.78	228.0640	2082.8700	66.4390
BGE 002106	1.77**	42.03**	1.7659	67.4807	13.19	72.7638	328.8903	85.7961
BGE 029055	1.86**	9.86**	1.8603	16.2036	59.02	68.8939	285.1836	121.1575
BGE 032012	1.43**	16.88**	1.4282	27.4285	182.01	53.8015	114.7286	92.6802
BGE 041470	1.17	19.89**	1.1726	32.2421	93.13	49.9243	70.9385	94.6878
BGE 043776	0.03**	23.89**	0.0336	38.5313	83.77	82.6130	440.1294	66.6970
BGE 046721	0.13**	0.08	0.1282	0.6190	708.10	66.9059	262.7313	92.4008
FbH 13	0.92	106.55**	0.9210	170.3375	317.61	72.2229	322.7817	74.6468
FbH 14	2.86**	415.14**	2.8531	661.9547	327.45	258.6003	2427.7500	67.6624
FbH 15	1.67**	155.14**	1.6662	247.7587	42.03	98.4585	619.0894	87.1802
FbH 16	1.95**	1.42*	1.9520	2.7444	123.01	71.7127	317.0196	62.5495
BGP	1.57**	14.03**	1.5706	22.8795	218.19	57.3785	155.1271	126.6104
				Pod length				
Fb 1896	0.44	0.31	0.4310	0.0130	81.62	0.5798	4.3228	86.9333
Fb 1903	0.59	0.12	0.5872	0.3292	467.37	0.4522	2.8821	93.9952
Fb 1929	0.82	0.84	0.8200	1.8710	81.77	0.5470	3.9528	89.4074
Fb 2481	0.47	0.13	0.4660	0.3045	566.13	0.5830	4.3589	82.3804
Fb 2486	1.05	1.01	1.0495	2.1340	722.30	0.5556	4.0493	92.5431
Fb 3270	0.12	1.32*	0.1138	2.5855	212.64	1.5511	15.2931	62.7822
BGE 002106	1.59	0.21	1.5903	0.1739	38.76	0.6356	4.9527	94.2557
BGE 029055	0.56	0.12	0.5511	0.3297	641.46	0.4889	3.2962	80.6047
BGE 032012	1.52	0.02	1.5261	0.4861	10.04	0.6034	4.5894	104.2784
BGE 041470	1.55	0.67	1.5498	1.5747	261.03	0.8148	6.9767	129.3576
BGE 043776	0.43	0.23	0.4260	0.1475	112.51	0.6089	4.6519	77.4786
BGE 046721	0.84	1.74*	0.8391	3.2989	18.40	0.7774	6.5539	127.0036
FbH 13	1.02	4.36**	1.0200	7.4793	88.38	1.4441	14.0837	82.2417
FbH 14	1.54	0.47	1.5422	1.2566	75.16	0.7519	6.2667	89.6194
FbH 15	1.37	0.81	1.3744	1.8112	84.77	0.6636	5.2693	90.2566
FbH 16	1.57	0.31	1.5738	0.0197	8.28	0.5873	4.4073	99.0947
BGP	1.54	0.36	1.5402	1.0922	19.64	0.7221	5.9298	91.1550

Table 2 (end)

Accessions	bi	Si^2	a_i	λ_i	σ^2	PP	W^2	W_i
	Eberhart, Russell, 1966		Tai, 1979		Shukla, 1972	Plaisted, Peterson, 1979	Wricke, 1965	Annicchiarico, 1992
				100 seeds mass				
Fb 1896	1.68**	3.02**	1.6800	5.2232	0.09	289.0503	1932.9440	112.0244
Fb 1903	0.47**	4.59**	0.4627	7.8220	6.34	225.5393	1215.6430	108.1333
Fb 1929	1.29**	0.33	1.2930	–0.0869	7.36	149.5031	356.8807	95.0492
Fb 2481	1.24**	28.79**	1.2423	46.3377	29.13	147.2577	331.5209	93.5870
Fb 2486	1.35**	685.76**	1.3531	1093.4540	–0.42	346.0680	2576.9080	90.3787
Fb 3270	0.52**	26.50**	0.5177	42.8251	1.50	210.7062	1048.1160	38.9100
BGE 002106	0.29**	33.31**	0.2898	53.5880	2.41	312.5915	2198.8200	78.9987
BGE 029055	0.27**	99.07**	0.2655	158.6011	10.40	343.0164	2542.4430	75.0066
BGE 032012	0.95	121.02**	0.9525	193.4120	23.81	150.9705	373.4545	92.5282
BGE 041470	0.73**	108.76**	0.7346	173.9030	38.61	172.8278	620.3135	110.6985
BGE 043776	0.76**	3.12**	0.7609	5.5056	2.60	139.8718	248.1039	91.2702
BGE 046721	1.21**	260.45**	1.2134	415.5642	3.81	203.9377	971.6716	86.1608
FbH 13	1.21**	164.59**	1.2063	262.8200	–0.31	177.3867	671.8013	87.0916
FbH 14	1.26**	120.22**	1.2585	192.1197	–0.01	174.5284	639.5201	96.0861
FbH 15	1.18**	27.04**	1.1827	43.5746	5.37	137.4564	220.8246	90.3847
FbH 16	1.56**	38.68**	1.5578	62.0823	17.32	242.8314	1410.9410	99.7928
BGP	1.03	1779.01**	1.0298	2835.8290	0.18	590.8681	5341.7100	60.5632
				Seed weight				
Fb 1896	0.96	50.19**	0.9646	80.5250	0.01	62.1813	153.0098	99.9013
Fb 1903	0.45**	151.91**	0.4489	242.6463	0.19	119.8607	804.4483	77.7036
Fb 1929	0.88*	0.20	0.8832	0.2065	0.08	50.0498	15.9948	71.2676
Fb 2481	0.87*	3.43	0.8672	5.9933	0.02	51.4193	31.4623	68.6158
Fb 2486	0.84**	286.87**	0.8370	457.7392	0.01	127.6183	892.0627	97.1530
Fb 3270	0.05**	38.11**	0.0542	61.1723	0.01	149.4923	1139.1100	30.5370
BGE 002106	0.87*	12.46**	0.8732	20.3965	0.01	53.6636	56.8105	93.8915
BGE 029055	0.89	66.65**	0.8991	106.7460	0.44	67.4573	212.5978	105.2589
BGE 032012	1.10	0.31	1.1015	0.0368	0.04	49.6832	11.8554	99.4171
BGE 041470	1.10*	55.42**	1.1146	88.8561	0.20	64.7745	182.2975	112.5134
BGE 043776	0.30**	27.19**	0.3008	43.8128	0.01	105.4840	642.0755	61.6103
BGE 046721	0.77**	31.03**	0.7666	49.9871	0.12	62.4878	156.4716	96.1664
FbH 13	1.15*	170.29**	1.1515	271.9284	0.05	96.2819	538.1455	63.2004
FbH 14	2.10**	301.70**	2.0977	481.2721	0.34	250.9772	2285.2930	75.4486
FbH 15	1.56**	176.57**	1.5569	281.9522	0.11	127.0596	885.7535	76.3140
FbH 16	1.62**	0.90	1.6207	1.9782	0.20	88.0090	444.7108	68.7624
BGP	1.46**	234.63**	1.4623	374.4689	0.16	132.7076	949.5417	78.5726

BGE 029055, in which most of the stability parameters characterized it as relatively stable.

With respect to the number of seeds per plant, BGE 029055, BGP and FbH 14 can be distinguished, which formed 35–41 seeds per plant. As in the previous trait, and in this one, accessions with an increased number of seeds showed clearly pronounced instability. However, the values of the parameters Si^2 and PP gave reason to consider that BGE 029055 (Si^2 = 9.85; PP = 68.89) and BGP (Si^2 = 14.03; PP = 57.37) had a breeding value. They had a high adaptive ability, which in conditions above the averages, could provide them with a high realization of the number of seeds per plant. Accessions Fb 2486 and BGE 046721 were determined as very stable, with the coefficient of linear regression significantly smaller than 1, parameter W_i close to 100 and number of seeds above the average for the group of tested accessions. Their low adap-

Table 3. Rank-parameter (Si_2) of the studied traits according to the model of Huehn (1990a, b)

Accessions	Plant height	1st pod height	Pods number	Seeds number	Pod lenght	100 seeds mass	Seed weight
Fb 1896	9	7	8	8	11	12	6
Fb 1903	11	9	14	11	7	11	12
Fb 1929	11	11	4	3	10	6	3
Fb 2481	10	15	7	2	11	6	5
Fb 2486	3	6	7	10	10	12	12
Fb 3270	14	14	14	12	13	9	12
BGE 002106	8	8	8	9	11	14	5
BGE 029055	7	12	8	10	7	12	7
BGE 032012	9	8	4	7	7	7	4
BGE 041470	8	8	4	6	11	8	6
BGE 043776	10	4	11	10	7	5	11
BGE 046721	5	8	11	9	10	9	9
FbH 13	10	2	11	10	11	8	9
FbH 14	9	10	17	17	11	8	16
FbH 15	11	7	12	12	10	5	14
FbH 16	8	12	11	11	12	10	10
BGP	13	15	12	9	11	13	14

Note: Si_2 = 1: better performance; Si_2 = 17: worst performance.

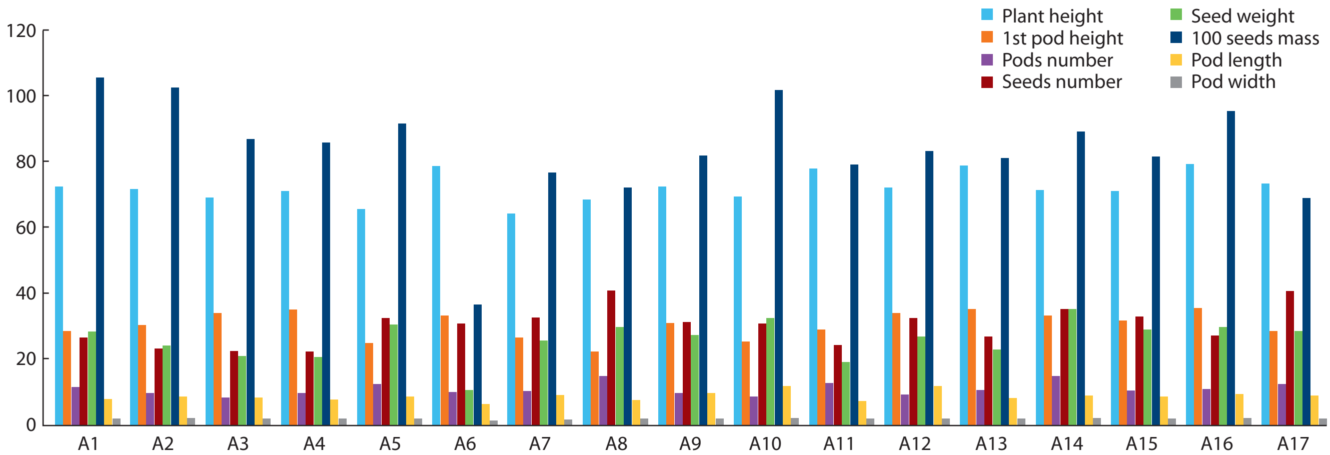

Fig. 1. Main quantitative traits in broad bean accessions (2016–2018).

Accessions: 1, Fb1896; 2, Fb1903; 3, Fb 1929; 4, Fb 2481; 5, Fb 2486; 6, Fb 3270; 7, BGE 002106; 8, BGE 029055; 9, BGE 032012; 10, BGE 041470; 11, BGE 043776; 12, BGE 046721; 13, FbH 13; 14, FbH 14; 15, FbH 15; 16, FbH 16; 17, BGP.

tive ability implied that they were not suitable for growing at a high level of agro-technology, but they can exhibit well in unfavorable environmental conditions.

Because of the lack of significance in the stability parameters of Eberhart and Russell (1966) regarding the trait of pod length for all accessions, the complex evaluation of ecological stability was made on the basis of the remaining parameters. According to the parameter values based on variance analysis and nonparametric method of Huehn (1990a, b), Fb 1903 and BGE 029055 outlined as the most stable, although they were one of the accessions with the shortest pods (see Table 3). A breeding compromise between the value of the trait and its stability (according to the indicator σ^2) can be found in BGE 046721 (σ^2 = 18.4) and BGE 032012 (σ^2 = 10.04). The ambiguous assessments according to the different types of parameters show that longer-term researches are needed to determine the environmental sustainability of this trait.

In terms of 100 seeds mass, Fb 1896 (105.48 g), Fb 1903 (102.34 g) and BGE 041470 (101.38 g) were clearly pronounced favorites, characterized by a high value of the trait (see Fig. 1). A comparison of the three types of stability parameters showed that Fb 1896 was unstable and largely variable (see Table 2). Its reaction to the environment is highly predictable. It is suitable for growing in favorable environmental conditions. If conditions deteriorate, it can give way to the other accessions and to form seeds with smaller mass. Accession Fb 1903 also had a high mass of 100 seeds, but its coefficient of linear regression bi was less than 1, so it can be defined as stable.

BGE 041470 was characterized by the fact that the coefficient bi (bi = 0.73) was closer to 1 (compared to Fb 1903), which determined it as closest to the "ideal" genotype for this trait. The stability parameters of Plaisted and Peterson (1979) and Annicchiarico (1992) confirmed the evaluation according to Eberhart and Russell (1966) and Tai (1979). This accession is of interest from a breeding point of view, combining a high mass of 100 seeds with ecological stability. It is suitable for growing in a wide range of environmental conditions.

Table 2 also presents data on the stability parameters of the seed weight per plant. FbH 14, FbH 16, Fb H 15 and BGP had high values of the regression coefficient (bi ≥ 1.5), which determined them as unstable. With close average productivity (see Fig. 1) and similar values for bi (bi = 1.10–1.15) were accessions FbH 13 and BGE 032012. More plastic, i. e. more responsive to favorable growing conditions was FbH 13. Plants of BGE 041470 formed seeds with relatively large mass and were characterized by a coefficient of linear regression slightly above 1. Because of these characteristics, this accession was of interest from a breeding point of view.

Accessions Fb 1896, Fb 1929, Fb 2481, Fb 2486, BGE 002106 and BGE 029055 had coefficients close to 1, but they were distinguished by low productivity. Fb 1903 and BGE 043776 were stable under changing environmental conditions, with regression coefficient values of bi = 0.45 and bi = 0.30, respectively. In addition, BGE 043776 was also characterized by a low variance, i. e. its empirical values approximate to the theoretical ones. The most stable (bi = 0.05), but with the lowest value of the considered trait was Fb 3270.

GGE biplot analysis

The differences in stability of the accessions and their adaptability to the environment are presented in a two-dimensional coordinate system (Fig. 2). The axial axis shows the main effects (environment and genotype), and the ordinate axis – the effects of their interaction (PC1 or PC2). On the vertices of the polygon are situated the accessions, which are furthest from the center. All accessions fall into this polygon. The lines separating the polygon of sectors represent a set of hypothetical environments. The accession, forming the polygon angle for each sector, has the highest value regarding the studied trait for the environment that falls within this sector.

In terms of the plant height, from the location of the accessions and environments (years), it is obvious that there is variability due to the influence of the environment and especially the climatic difference between the second (2017) and third (2018) experimental years. This result is in full compliance with the data from the variance analysis (see Table 1). The accessions, whose projections on the ordinate were close to the origin of the coordinate system, were stable and very weakly interact with the environment. These were Fb 1896, Fb 3270, BGE 002106, Fb 1929, BGP, FbH 15. By contrast, accessions Fb 1903 and BGE 043776 were the most distant therefore they were characterized by a specific reaction to the environment and low adaptation.

The result regarding the 1st pod height indicated that the first two components (PC1 and PC2) determined 90.3 % of the total variation of the trait as a result of GE interaction. The vertices of the polygon were occupied by Fb 1929, Fb 1903, BGE 002106, BGP, FbH 13, FbH 14 and FbH 15. Accessions FbH 16, BGE 043776 and BGE 002106 exhibited their biological potential the best during the third year. They were among the genotypes with the greatest environmental stability. Fb 2486, Fb 3270 and BGE 041470 developed relatively well in the first and second years. The location of the first year (closer to the center of the coordinate system) determined it as the most suitable environment for the broad bean development with respect to the considered trait.

The accessions, which were characterized by a number of pods above the average, had positive values of the first principal component (PC1 > 0) and a value of PC2, tending to zero, were suitable for growing in different environments. In this trait, the accessions reacted differently to changing environmental conditions. In the most favorable position were those located in the quadrant, limited by the positive part of the abscissa (PC1) and the ordinate (PC2). From the accessions with a larger number of pods (FbH 14, BGP and BGE 029055), BGE 029055 can be preferred because of its lower variability. Fb 1903 and Fb 3270 were in the group of stable genotypes, however, they formed relatively few pods (10). A considerable part of the accessions had high (positive or negative) values of PC2, so they can be identified as having specific adaptability to the environment.

The graphical analysis of the stability in terms of the number of seeds per plant gave an analogous assessment obtained from the stability parameters. BGE 029055, BGP and FbH 14 had an increased number of seeds and occupied an extreme right position of the coordinate system, which determined them as the most productive and at the same time the most variable. Accessions Fb 1896 and Fb 1929 were one of the lowest productive, and their location close to the center of the coordinate system suggests a slight influence of the environment on the trait manifestation. In close proximity to them, with almost the same stability, were accessions Fb 2486 and BGE 046721. In breeding terms, they were more valuable because they formed a larger number of seeds.

GGE biplot analysis regarding 100 seeds mass showed that Fb 1929, BGE 032012 and BGE 043776 were located close to the origin of the coordinate system. They had low values on PC2 and PC1. This placement defined them as very stable, but they had a small mass of 100 seeds. BGE 041470 also had a small projection on PC2, but it was with a much higher value on the axial axis due to its larger mass of 100 seeds. Accessions Fb 1896 and Fb 1903 were distinguished with a high mass of 100 seeds and specific adaptability.

With regard to the trait of seed weight per plant, the first position was occupied by BGE 041470, characterized by a very good combination between stability and level of the trait. Accessions Fb 2486, FbH 16, FbH 14, Fb 1896 and BGE 029055 were distinguished by relatively good productivity and stability, and can be recommended as suitable for growing conditions. The most pronounced variability of the considered trait had FbH 13 and FbH 15, and BGE 032012 was characterized by the best stability but with very low productivity.

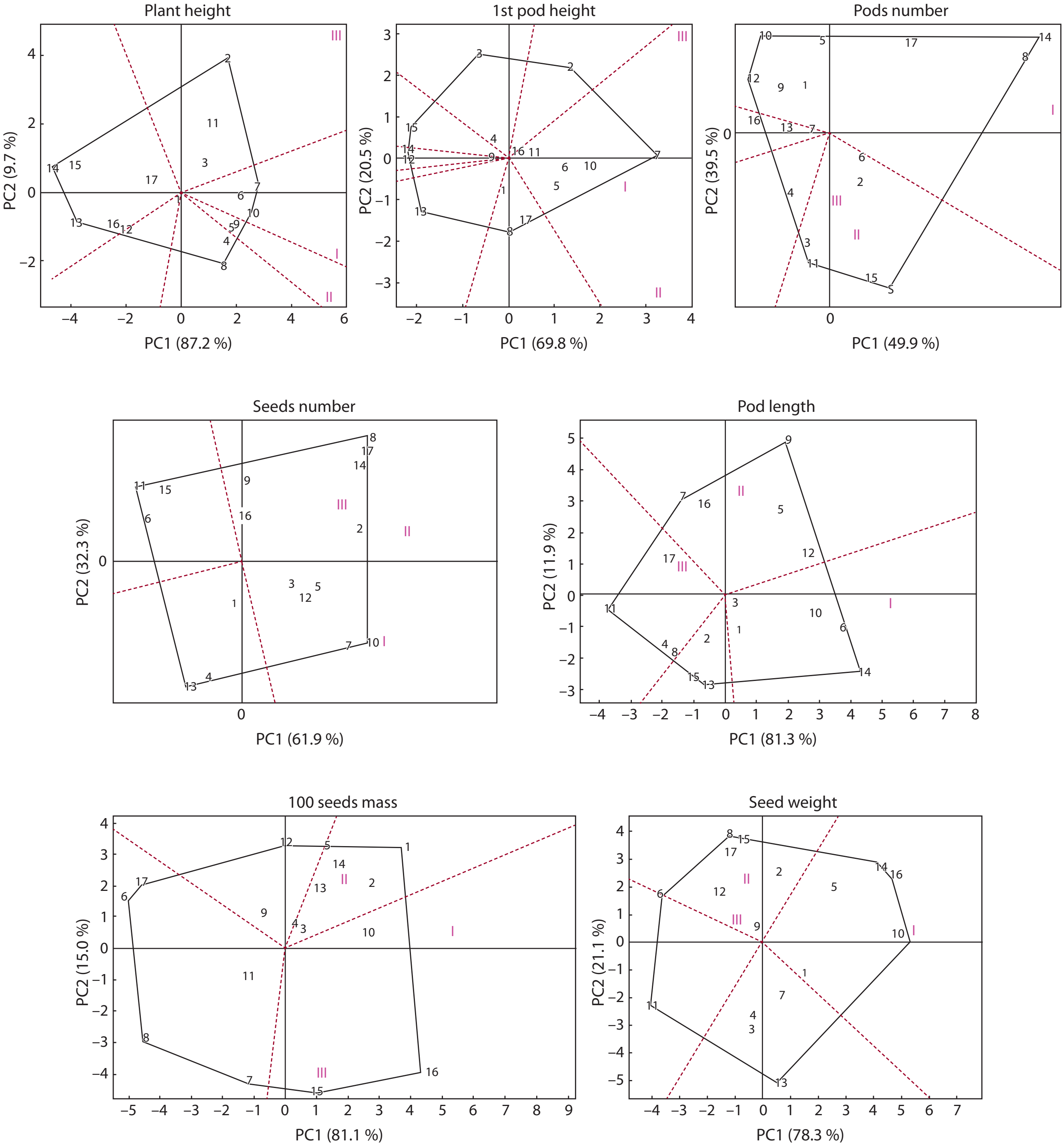

Fig. 2. GGE biplot analysis regarding the studied traits in broad bean accessions.

Accessions: 1, Fb1896; 2, Fb1903; 3, Fb 1929; 4, Fb 2481; 5, Fb 2486; 6, Fb 3270; 7, BGE 002106; 8, BGE 029055; 9, BGE 032012; 10, BGE 041470; 11, BGE 043776; 12, BGE 046721; 13, FbH 13; 14, FbH 14; 15, FbH 15; 16, FbH 16; 17, BGP.

In Figure 3, *a*, the X axis (or the line of the average yield of the broad bean accessions) passes through the beginning of the coordinate system with an arrow indicating the positive end of the axis. The axis Y of the coordinate system (axis of stability) also passes through the beginning of the coordinate system perpendicular to the X axis. Thus, the average yield of the accessions can be estimated from the projection of their markers along the X axis, and the stability – from the projection along the Y axis. Accessions FbH 14, BGE 041470, Fb 2486 had the highest average yield, and Fb 3270, BGE 043776, Fb 2481 and Fb 1929 – the lowest one. The yield in FbH 14, BGE 041470, BGE 029055, Fb 1896 and Fb 1929 was the most variable, whereas Fb 2481, FbH 16 and BGE 046721 were distinguished with high stability.

The graphical analysis also enables to be determined accessions that combine high yield and stability. The center of

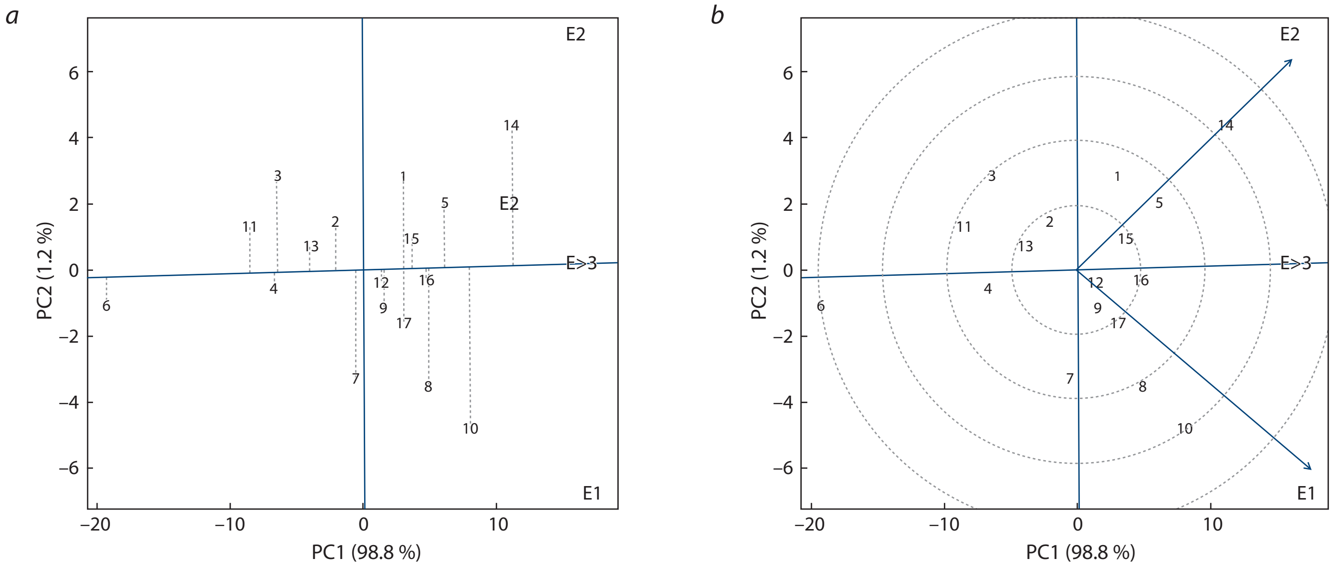

Fig. 3. GGE biplot analysis regarding seed yield in broad bean accessions.

Accessions: 1, Fb1896; 2, Fb1903; 3, Fb 1929; 4, Fb 2481; 5, Fb 2486; 6, Fb 3270; 7, BGE 002106; 8, BGE 029055; 9, BGE 032012; 10, BGE 041470; 11, BGE 043776; 12, BGE 046721; 13, FbH 13; 14, FbH 14; 15, FbH 15; 16, FbH 16; 17, BGP.

Table 4. Correlation coefficients between stability parameters and seed weight per plant in broad bean accessions

Parameter	bi	Si^2	a_i	λ_i	σ^2	PP	W^2	W_i	Si_2
Si^2	0.442								
a_i	0.99**	0.442							
λ_i	0.442	0.99**	0.442						
σ^2	0.465	0.273	0.465	0.273					
PP	0.348	0.769**	0.348	0.769**	0.309				
W^2	0.348	0.769**	0.348	0.769**	0.309	0.99**			
W_i	0.248	0.016	0.248	0.016	0.290	–0.395	–0.395		
Si_2	0.118	–0.299	0.263	0.759**	0.258	0.882**	0.882**	–0.371	
Seed weight per plant	0.530*	0.226	0.530*	0.226	0.369	0.111	0.111	0.335	0.162

Note: bi, Si^2 – Eberhart and Russell (1966); a_i, λ_i – Tai (1979); σ^2 – Shukla (1972); PP – Plaisted and Peterson (1979); W^2 – Wricke (1965); W_i – Annicchiarico (1992); Si_2 – Huehn (1990a, b). Significant at ** $p < 0.01$, * $p < 0.05$.

the concentric circles (Fig. 3, *b*) presents the position of the "ideal" genotype, which is defined by the projection of the environment axis determined by the longest vector of genotypes with yield above the average and lower projection of the perpendicular line (low variability in all environments). More preferred is this one, which is closer to the "ideal" genotype. In our study, BGE 046721, BGE 032012, FbH 13, Fb 1903, FbH 15 and FbH 16 were located closer to the center of the concentric circles, so they can be defined as close to the ideal type with regard to the magnitude and variability of seed yield compared to the rest accessions.

Correlation analysis

The results of the correlation dependences between seed weight per plant and the stability parameters were presented in Table 4. The average productivity of the accessions positively, strongly and significant correlated with the parameters bi ($r = 0.530$) and a_i ($R = 0.530$). For the remaining parameters (especially PP, W^2 and Si^2), the correlation was also positive but statistically insignificant and weaker.

The coefficient of regression bi interacted positively with the other parameters, especially with the parameter a_i ($r = 0.990$). The parameter Si^2 (Eberhart, Russel, 1966) was in positive dependence with λ_i ($r = 0.99$), PP ($r = 0.769$) and W^2 ($r = 0.769$). Strong positive correlations at a high level of statistical significance were found between W^2 and the parameters λ_i ($r = 0.769$) and PP ($r = 0.990$).

The only negative correlations were established between the parameter Si_2 (Huehn, 1990a, b) and Si^2 (Eberhart, Russel, 1966) ($r = –0.299$) and W_i ($r = –0.371$), as well as between W_i and respectively PP ($r = –0.395$) and W^2 ($r = –0.395$).

Discussion

According to (Ilchovska, 2008), for a more objective assessment of the genotype-environment interaction, the studied cultivars (genotypes) should be studied in a wider range of environmental conditions. Some researchers (Yan, Tinker, 2006; Farshadfar et al., 2011) considered that in order to monitor the model of interaction between genotype and environment, and to better interpret the results, it is appropriate to use the biplot analysis. This polygonal graphic model represented the behavior and the interaction of genotypes in different environments, the differentiation of environment and also the specific environment for each of the genotypes studied.

The data obtained in this study regarding the interaction of genotype and environment confirmed the results of researches in other crops. In spring vetch, Sayar (2017) found that the factor 'environment' had the greatest impact on the yield, followed by the GE interaction and the factor 'genotype'. The presence of a considerable share of the factor 'environment' on the manifestation of main quantitative traits was reported by Tilahun et al. (2015) and Kanouni et al. (2015) in chickpeas, and by Sayar and Han (2016) in peas. Mortazavian et al. (2014) expressed an opinion that the stability analysis of the traits acquires important meaning when the effect of GE interaction is considerable.

The results of the correlation analysis of the data in our study were in support of the conclusions reached by other authors (Paula et al., 2014; Bornhofen et al., 2017) regarding the presence of positive relationships between the stability parameters and some main quantitative characteristics. According to Annicchiarico (2002), one of the possible explanations of this fact is that these methods (to determine the parameters mentioned) are related to the concept of static stability, which is obtained independently of the average expression of a given trait. The choice (made by these methods) may lead to the selection of stable but not necessarily productive genotypes.

Cargnelutti et al. (2009) concluded that the significant positive relationships between the parameters of the different methods showed that, in terms of stability, genotypes were evaluated in a similar way. The authors stated that the methods can provide much information and that only one method for stability evaluation would be sufficient to select the best genotypes. However, even in a strong relationship between the methods, the genotype position could be different in the different methods.

According to Balashova et al. (2013), one of the main tasks in the breeding of leguminous crops, including broad bean, was the seed yield stabilization. The authors considered that this problem can be solved by changing the idiotype of plants. According to them, one of the reasons for reducing the grain yield was the excessive increase in height and the lodging of plants. This was due to the fact that cultivars continue their vegetative growth after the formation of reproductive organs, especially in humid climatic conditions. For this reason, breeders' efforts should be directed to changing the plant habitus and development of highly productive determinant forms.

Conclusions

The results of the variance analysis in 17 broad bean accessions showed a significant genotype × environment interaction for all quantitative traits (excluding pod width). The factor environment had the greatest impact on the phenotypic manifestation of the traits, followed by the factors genotype and genotype × environment interaction.

In terms of plant height and 1st pod height, accessions FbH 16 and FbH 13 can be determined as high (79 cm, 35 cm) and ecologically stable (bi = 0.76, bi = 0.79). BGE 029055 was low variable, with high values of the number of pods (15) and seeds (41) per plant.

Accessions FbH 14, FbH 16, FbH 15 and BGP were distinguished by high seed weight per plant (from 28.36 to 34.93 g), but they exhibited instability (bi > 1) under unfavorable environmental conditions. In contrast, Fb 1903, BGE 043776 and Fb 3270 were very stable (bi < 1) but low-productive. Intermediate positions occupied accessions Fb 1896, Fb 1929, Fb 2481, Fb 2486, BGE 002106 and BGE 029055, which had the coefficient of linear regression close to 1, but they were also low-productive. Interesting from a breeding view point was BGE 041470, which is characterized by high values of 100 seeds mass (101.38 g) and seed weight per plant (32.14 g), as well as with relative stability (bi = 1.10).

GGE biplot analysis determined accessions BGE 046721, BGE 032012, FbH 15 and FbH 16 as a promising breeding material combining high and stable seed yield.

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