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Analysis of trait stability of soybean cultivated under various environmental conditions

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Abstract: Soybean (*Glycine max* (L.) Merrill.) yielding potential depends on environmental conditions (precipitation, temperature, soil). The aim of the work was to evaluate stability of yielding (and other traits) of three soybean cultivars (Abelina, SG Anser, Merlin) grown under the climatic conditions of central-eastern Poland. The studied material was obtain in a field experiment conducted at Łączka (52°15' N, 21°95' E) during the growing seasons of 2017–2019. Trait stability was determined based on Shukla's genotype stability variance and Wricke's ecovalence describing the genotype-by-environment interaction. For all the examined parameters, there were found significant differences between successive growing seasons, cultivars, and cultivars within study years. The greatest influence of environmental conditions (years) was determined for plant height (64%) and first pod height (54.2%). Stability parameters indicated that cv. Abelina was the most stable in terms of yielding, 1000 seed weight, seed number per pod and average seed number per pod, cv. SG Anser being the least stable in this respect.

Keywords: cultivar, environment, genotype-by-environment interaction, soybean, soybean yield, yield components

INTRODUCTION

Climate warming that has been observed recently and breeding progress have made it possible to grow soybean in Poland. Soybean cultivation is growing in popularity due to a wide variety of crop's applications as it can be used for fodder, consumption and industrial purposes (Sun *et al.*, 2015), but also because of the economic and ecological benefits the cultivation is associated with. Soybean plants are capable of fixing atmospheric nitrogen, which leads to increased soil nitrogen availability and, as a result, lower mineral fertiliser inputs (Graham and Vance, 2003; Sanginga, 2003; Vugt Van, Franke and Giller, 2017; Ciampitti and Salvagiotti, 2018).

The growth and development of crop plants is affected by environmental factors such as weather conditions, soil and husbandry. The soybean cultivars have substantial thermal requirements and need a long growing season. In order to germinate, the soybean plant needs temperatures of 7–8°C followed by 20–25°C during the period from emergence to flowering, and 22–25°C during flowering (Warzecha, 1983). Lewandowska (2019) claims that the temperature must be at least 10°C during the growing season of soybean if the plants are to grow and develop optimally. Soybean should be grown in well-worked fertile soil with good physical properties. The soil bed should be warm, aerated with good water retention. Too firm soils are less suitable for soybean cultivation as such conditions make seed germination and plant emergence more difficult. Soybean is not an acid-loving crop plant as it prefers a pH of 6–7 (Kravchenko and Bullock, 2000).

The conditions determine the variation in yield and other quantitative characteristics of cultivated plants. The environment can be understood as both the area and years of crop cultivation (Fraś *et al.*, 2018). The effect of environment on cultivar-related traits, called genotype-by-environment interaction (G×E), difficult to interpret as it is, should be carefully analysed (Annicchiarico, 2002; Mądry, 2003; Pour-Aboughadareh *et al.*, 2022; Elmerich *et al.*, 2023). An occurrence of such an interaction may cause poor performance of a cultivar that otherwise performs well under given cultivation conditions (Cotes *et al.*, 2002; Abalo *et al.*, 2003). This issue is of particular importance in case of soybean plants, which under temperate climatic conditions, are under threat from various stresses associated with low temperatures, photoperiod and short-term intermittent droughts (Staniak, Szpunar-Krok and Kocira, 2023). Despite the fact that breeding progress has made it possible to distinguish genotypes suited to various growing conditions, changeable weather patterns during the growing season render soybean cultivation in Poland potentially risky (Boros *et al*., 2021). Research has demonstrated that yield loss of soybean cultivars because of unstable weather is not the same due to their different response to growth conditions (Popović *et al*., 2013). Hence, it is of importance to learn and determine responses of cultivars to changeable conditions, particularly meteorological ones (air temperature and precipitation), as they represent the most important factors affecting yield performance.

With this in mind, it was attempted to evaluate the effect of the environment on yields of three soybean cultivars grown in central-eastern Poland, and analyse trait stability of the cultivars during three growing seasons.

STUDY MATERIALS AND METHODS

The material for analysis consisted of plants of three soybean cultivars (Abelina, SG Anser, Merlin) grown at Łączka (N 52°15', E 21°95') in three successive growing seasons 2017–2019. They are medium early cultivars. Cv. Abelina is recommended for cultivation all over Poland. It is characterised by rapid growth, uniform maturation and a very high yielding potential. Cv. SG Anser is recommended for growing in central and southern Poland. It develops many seeds per pod and has a high 1000 seed weight, both properties being a condition of high yields. Plants are of average height and highly resistant to lodging. Due to protein structure and flavour-related properties, the cultivar is recommended for food production purposes. Cv. Merlin produces high yields all over the country. Due to its hardiness, it can be cultivated in areas which are thermally more difficult.

A field experiment was set up as a split-plot design with three replications on soil classified as a Haplic Luvisol according to the World Reference Base for Soil Resources (FAO, 2015). The soil was characterised by an average organic carbon, total nitrogen and phosphorus contents, a high potassium content and a low plant-available magnesium content (Tab. 1). In each year, the following fertilisers was applied taking into account the soil availability of each nutrient: nitrogen at the rate which corresponded to 30 kg N introduced into the soil, 30 kg P and 90 kg K per ha. Soybean crop was preceded by maize in each study year. Seeds were planted in 9 m^2 plots with the between-row spacing of 22 cm, the seeds being deposited at the depth of around 4 cm. There were sown 70 seeds per m^2. The sowing dates were 4 May 2017, 5 May 2018 and 1 May 2019. Plots were maintained weed-free using the soil herbicide Stomp Aqua 455 CS (pendimetalina 455 g·dm^{-3}) which was applied up to 5 days post-sowing at the rate of 1.5 dm^3 per ha, and Focus Ultra 100 EC (cykloksydym 100 g·dm^{-3}) applied during vegetation at the rate of 2 dm^3 per ha.

Prior to harvest, random samples were collected from each plot (20 plants per each plot) to determine pod number per plant (pcs), first pod height (cm), plant height (cm), 1000 seed weight (g). Pod height was measured from ground level to the point where the first pod was attached at the lowest node. After the harvest, the yield obtained from each experimental plot (9 m^2) was converted into Mg per ha. A 1000 seed weight (g) determined at the seed moisture of 15%.

Table 1. Selected soil properties in the layer 0–0.25 m prior to the commencement of the experiment in 2017–2019

Soil properties	Year		
	2017	2018	2019
pH (in KCl)	6.9	7.1	7.2
C_{org} (g·kg^{-1})	9.0	8.9	9.3
N_t (g·kg^{-1})	0.75	0.77	0.81
Fe_t (g·kg^{-1})	995	990	997
B_t (g·kg^{-1})	0.70	0.68	0.74
P_{av} (mg·kg^{-1})	55.8	57.1	56.2
K_{av} (mg·kg^{-1})	132.8	130.3	131.6
Mg_{av} (mg·kg^{-1})	26.5	25.9	26.4

Source: own study.

Meteorological conditions during the study period are presented in Table 2.

Table 2. Distribution of precipitation (mm) and temperature (°C) in 2017–2019

Month	Precipitation			Temperature		
	2017	2018	2019	2017	2018	2019
April	82	52	9	7.1	12.5	9.4
May	46	26	114	13.1	16.4	13.0
June	56	75	29	17.6	18.3	21.5
July	76	96	40	17.6	19.7	18.0
August	53	29	72	19.0	19.9	19.3
September	112	42	42	13.9	15.2	14.0
Sum/average (Apr.–Sept.)	425	320	306	14.7	17.0	15.9

Source: own study.

In order to evaluate the effect of the environment (growing seasons) on soybean plant yield and yield characteristics, results were analysed statistically following the AMMI (Additive Main effects and Multiplicative Interaction) model which allows both estimation of the overall effect of genotype-by-environment interaction and its division into several interaction effects according to individual environments. The AMMI procedure combines two methods: analysis of variance and singular value decomposition in a unique model, additive components for the main effects of genotypes (G), environments (E) and multiplicative components for the interaction effect (G×E) (Arciniegas-Alarcón *et al*., 2010; Gauch Jr. *et al*., 2011; Gauch Jr., 2013). Moreover the model provides a simple interpretation of the obtained results using a graphic tool called a biplot (Zobel, Wright and Gauch, 1988).

Statistical calculations were performed in Statistica 13.3 software with the Package for Natural Sciences, ver. 13.5.

Moreover, for characteristics that displayed a significant genotype-by-environment (G×E) interaction, Shukla's genotype stability variance (s_i^2) (Shukla, 1972) and Wricke's ecovalence (W_i) (Wricke, 1965) were calculated, the latter one describing an interaction between the *i*-th genotype and the environment. Genotype stability variance measures environmental variation of the *i*-th genotype in the *j*-th environment whereas Wricke's ecovalence reflects the share of each genotype in the sum of squares of the G×E interaction (Wricke, 1965; Pietrzykowski, Mądry and Warzecha, 1996).

Genotype stability variance of the *i*-th genotype in the *j*-th environment is calculated following (Eq. 1):

$$s_i^2 = \frac{\sum_j \left(\bar{y}_{ij} - \bar{y}_{j.}\right)^2}{s-1} \quad (1)$$

Wricke's ecovalence is computed as follow (Eq. 2):

$$W_i = \sum_j \left(\bar{y}_{ij} - \bar{y}_{i.} - \bar{y}_{.j} + \bar{\bar{y}}_{..}\right)^2 \quad (2)$$

where: $\bar{y}_{ij}$ = the mean of a trait across *n* replicates for the *i*-th genotype in the *j*-th environment, $\bar{y}_{i.}$ = the mean for the *i*-th genotype, $\bar{y}_{.j}$ = the mean for the *j*-th environment, $\bar{\bar{y}}_{..}$ = the overall mean, *s* = the number of environments (growing seasons).

RESULTS AND DISCUSSION

For normal growth and development, soybean requires optimum environmental conditions (particularly temperature and precipitation) during the growing season (Ku *et al*., 2013) which determine the yielding potential (Bhatia *et al*., 2006).

Environmental conditions and cultivars accounted for, respectively, over 25 and 8% of variation in yield, with the over 50-percent share of genotype-by-environment interaction in this variation (Tab. 3). According to Ergo *et al.* (2021), a combination of drought- and temperature-related stresses during seed fill may disturb photosynthesis and, in this way, hinder metabolism, which results in a decline in seed weight and number causing poorer soybean yields.

As shown in Figure 1a the best conditions of soybean yielding prevailed in 2017, the highest yields being produced by cv. Merlin. The location of objects relative to the interaction principal component axis (Fig. 1b) indicates they participated in the formation of the interaction effect. Cv. Abelina is the closest to the axis, which indicates that the cultivar can be viewed as the most stable, as confirmed by the stability parameters: Shukla's variance and Wricke's ecovalence (Tab. 4). The growing season in 2017, 2018 and 2019 was the most conducive to the yielding of, respectively, cv. Abelina, SG Anser and Merlin.

A different average yield response in years was empirically confirmed in soybean and other crop plants by the following authors: Yan and Rajcan (2002), Ron De *et al.* (2004) and Navabi *et al.* (2006).

Also research by Boros *et al.* (2021) demonstrated a substantial effect of meteorological conditions during the growing season on soybean yielding. The author claims that warm spring and more regular distribution of air temperatures and precipitation in the summer months are preferable from the standpoint of yield performance and physical characteristics. By contrast, heavy rainfall in May and June followed by low precipitation in July, and accompanied by relatively high air temperatures until late August had an adverse effect on the aforementioned characteristics, and contributed to reduced seed yield (by 1.05 $Mg \cdot ha^{-1}$). Also Vogel *et al.* (2021a; 2021b) mentioned that morphological characteristics such as nodes per main stem, branch number and total node number begin to develop during the vegetative growth stage and substantially affect pod formation.

Table 3. Share of sources of variation in the total variance for soybean traits (%), values of mean squares and *F* values checking the significance of factors for the AMMI model

Effect	Soybean yield			1000 seed weight			Plant height			First pod height			Pod number per plant		
	MS	*% var.*	*F*	*MS*	*% var.*	*F*	*MS*	*% var.*	*F*	*MS*	*% var.*	*F*	*MS*	*% var.*	*F*
Total	0.30	100.00	–	643	100.0	–	407.7	100.0	–	13.46	100.0	–	32.81	100.0	–
Season	0.99	25.76	10.2*	1926	7.5	8.47*	10430.0	64.0	31.07*	291.81	54.2	24.49*	132.69	10.1	6.70*
Replicates (season)	0.10	7.52	1.88	227	2.7	0.49	335.7	6.2	4.46	11.91	6.6	5.18	19.81	4.5	0.81
Cultivar	0.33	8.60	6.46*	2367	9.2	5.12*	1907.8	11.7	25.32*	89.72	16.7	39.04*	127.87	9.7	5.26*
Cultivar × season (G×E)	0.97	50.12	18.8*	2750	21.4	5.95*	239.2	2.9	3.18*	22.73	8.44	9.89*	94.94	14.5	3.90*
IPC1	1.25	48.76 (97.2)	18.8*	3643	21.2	5.94 (99.3)	308.0	2.8	3.18 (96.6)	30.20	8.41 (99.7)	9.89*	122.58	14.0 (96.8)	3.90
IPC2	0.11	1.37 (2.72)	2.05	72	0.1	8.47	33.0	0.1	0.44 (3.4)	0.31	0.02 (0.3)	0.14	12.04	0.5 (3.2)	0.50
Random error	0.05	7.99	–	462	59.3	–	75.3	15.2	31.07	2.30	14.1	–	24.31	61.1	–

Explanations: * = significant effect at $p \leq 0.05$; shares of individual IPC relative to the interaction are given in brackets; *MS* = mean square; *% var.* = per cent of variation; *F* = value of Fisher's test with ANOVA.
Source: own study.

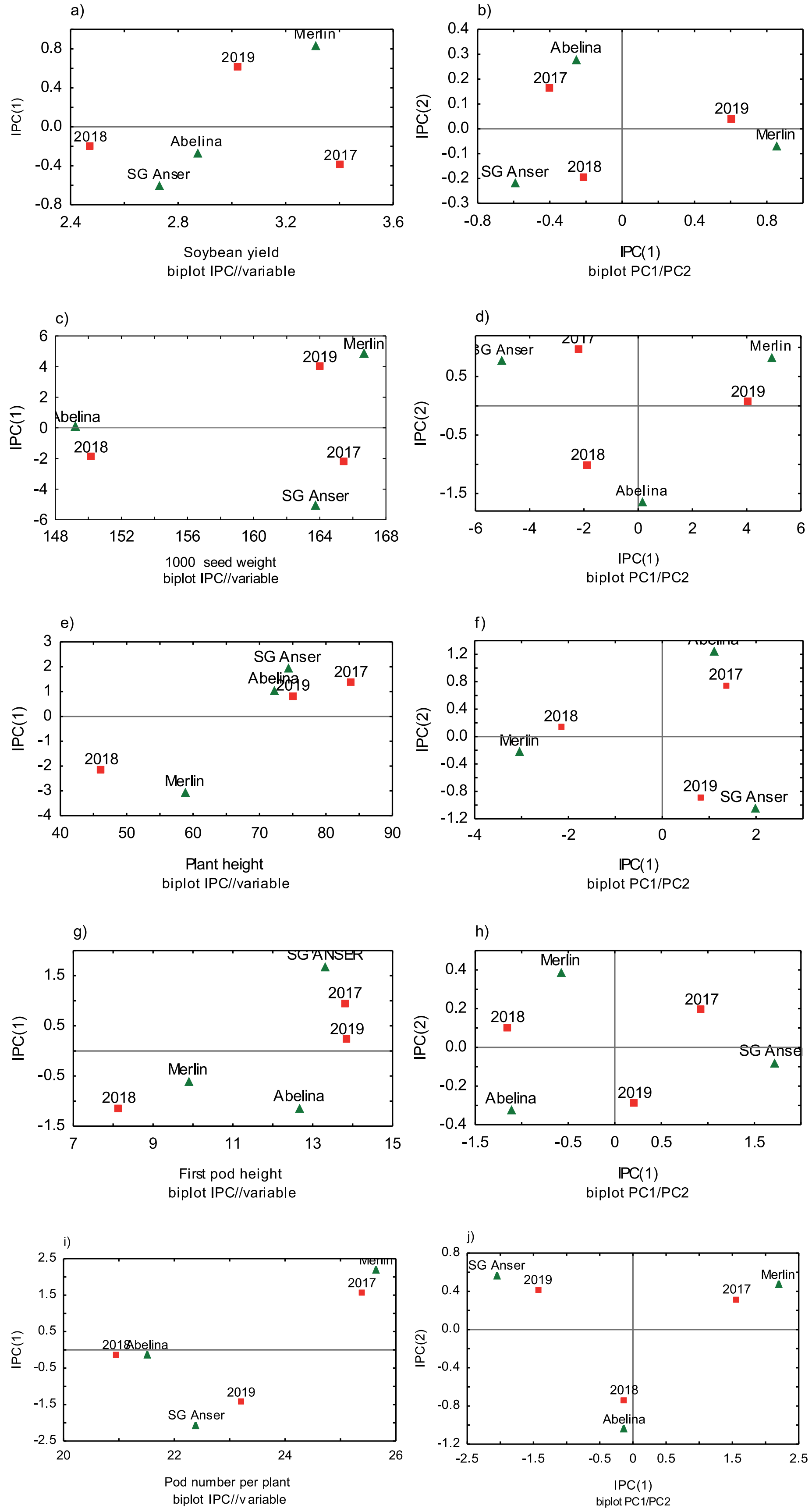

Fig. 1. Biplots obtained in AMMI analysis for: a) biplot IPC/variable for grain yield, b) biplot PC1/PC2 for grain yield, c) biplot IPC/variable for 1000 grain weight, d) biplot PC1/PC2 for 1000 grain weight, e) biplot IPC/variable for plant height, f) biplot PC1/PC2 for plant height, g) biplot IPC/variable for first pod height, h) biplot PC1/PC2 for first pod height, i) biplot IPC/variable for number per plant, j) biplot PC1/PC2 for number per plant; source: own study

Table 4. Parameters of stability of soybean characteristics displaying genotype-by-environment interaction

Characteristic	Stability parameters	Cultivar (genotype)		
		Abelina	SG Anser	Merlin
Soybean yield	s^2_i 1)	0.316	0.304	0.252
	W_i 2)	0.343	0.468	0.234
1000 seed weight	s^2_i 1)	47.57	538.61	396.18
	W_i 2)	88.83	1062.93	774.24
Plant height	s^2_i 1)	475.67	543.44	192.87
	W_i 2)	932.03	1065.75	373.43
First pod height	s^2_i 1)	5.11	25.22	7.15
	W_i 2)	8.26	45.93	11.91
Pod number per plant	s^2_i 1)	2.450	8.310	25.083
	W_i 2)	3.875	14.752	48.101

1) s^2_i = genotype stability variance; 2) W_i = Wricke's covalence.
Source: own study.

The share of cultivar in 1000 seed weight variation was over 9%, it being around 7.5% for the environment and over 21% for the G×E interaction. The years 2017 and 2019 were the most conducive in this respect. Cv. Merlin and SG Anser had higher 1000 seed weight values than the genotype mean whereas for cv. Abelina it was similar to the genotype mean (Fig. 1c). As the share of this mean in the interaction effect was small (location close to the interaction axis), the cultivar can be considered stable (Fig. 1d). Cv. Abelina was the least influenced by the growing season conditions. In turn, cv. Merlin was the least stable in this respect as the calculated s^2_i values and Wricke's ecovalence were the highest (Tab. 4).

The variation in plant height was mainly affected by the environment (64%), cultivar-related traits and effects of cultivar-by-environment interaction accounting for, respectively, 11.7 and 3% of the variation (Tab. 3). Drought prevailing in 2018 resulted in the lowest plants, on average (Fig. 1e). Inhibited water uptake by plants due to drought stress limits the development of morphological traits, including internode formation, this in turn affecting plant height (Vogel, 2021a; Vogel, 2021b). Differences in tolerance to temperature-related stress between genotypes have been reported by Gass *et al.* (1996) and Karges *et al.* (2022). The average height of cv. Merlin, Abelina and SG Anser was predominantly affected by the growing conditions in, respectively, 2018, 2017 and 2019. It is impossible to indicate a cultivar which preserved stability in terms of this characteristic, as confirmed by the position of the cultivars relative to the environmental principal component axis (Fig. 1f), and the values of s_i^2 and W_i (Tab. 4). Soybean yield stability is under threat due to predicted climate change associated with an increased frequency of extreme events, in particular draught (Hao *et al.*, 2010; Dai, 2013; Foyer *et al.*, 2016). As a result, research on draught-resistant soybean cultivars seems to be necessary (Ku *et al.*, 2013; Kunert *et al.*, 2016).

Variation in first pod height was in 54.2, 16.7 and 8.44% accounted for by the effect of, respectively, the environment, cultivar and G×E interaction. Of the interaction components, IPC (1) explained 99.7% of the interaction variation, and IPC(2) accounted for barely 0.3% (Tab. 3). IPC(1) was close to 0 for cv. SG Anser, which confirms that the cultivar is stable in terms of first pod height (Fig. 1g). The highest average values of this characteristics were determined for cv. SG Anser and Abelina, and in 2017 and 2019 (Fig. 1h). Evaluation of stability parameters for first pod height revealed marked differences between values of genotype stability variance and Wricke's ecovalence for the test cultivars (Tab. 4).

The share of environment and genotype in the variation of pod number per plant was around 10%, it being 14.5% for the G×E interaction. Only the first principal component IPC(1) was significant, and it accounted for 96.8% of interaction variation (Tab. 3).

On average, the greatest number of pods per plant was obtained for cv. Merlin, and under the 2017 growing conditions when the weather was the most favourable to this cultivar (Fig. 1i). The 2018 and 2019 growing seasons were the most conducive resulting in the largest number of pods formed by, respectively, cv. Abelina and SG Anser (Fig. 1j).

The value of IPC (1) for cv. Abelina was close to 0, which confirms that it is stable in terms of pod number per plant as evidenced by the lowest values of Wricke's ecovalence and genotype variance (Tab. 4). Susceptibility to draught-induced stress is different for different crop cultivars and species (Tuberosa and Salvi, 2006; Farooq *et al.*, 2009; Fathi and Tari, 2016). Also Desclaux, Huynh and Roumet (2000) claim that periods of drought-related stress affect soybean cultivars in terms of their height. In turn, pod number per unit of dry vegetative matter was significantly influenced by stress during pod elongation.

CONCLUSIONS

1. The conducted analysis of genotypes demonstrated that, in terms of yielding and yield-related characteristics, the greatest stability was displayed by medium early cv. Abelina so it can be recommended for cultivation under conditions of central-eastern Poland.
2. Significance of genotype-by-environment interaction is indicative of differences in the response of the test soybean genotypes to weather conditions. The G×E interaction was the greatest contributor to differences in soybean yield and 1000 seed weight.
3. The environment associated with meteorological conditions during the growing season, and the cultivar were the greatest determinants affecting plant height and first pod height.

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