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Original Paper

Ecological plasticity and stability of soybean varieties under climate change in Ukraine

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Due to the climate change, constant increase in air and soil temperatures, moisture deficiency, agricultural production requires highly adaptive varieties that would provide sufficient yields even under adverse environmental conditions. Our breeding work is aimed at creating varieties of this type. The paper presents the results of the long-term research on assessment of soybean varieties by their adaptability under different soil and climatic conditions by the yield, duration of the growing season and reproductive periods. The stability and plasticity of the researched varieties was determined using the Ebergard and Russell method. According to the research results, Artemida, Hoverla and Amethyst varieties were classified as highly plastic (bi >1) by the yield and they provided the yields of 1.95, 2.2 and 2.1 t.ha^{-1}. In terms of duration of the growing season (BBCH-10-99), Amethyst, Hoverla, Artemida and Vezha provided high adaptability. These varieties were characterized by the conservative reaction to the change in hydrothermal and soil conditions ensuring stable indicators by the duration of the growing season (BBCH-10-99), coefficient of pasticity (bi) was under 1. The longest flowering-maturation period (BBCH-60-99) was observed in the following varieties: Amethyst – 69.1, Hoverla – 69.0, and Artemida – 69.1 days. The flowering-maturation period (BBCH-60-99) was under one. By the duration of the flowering-maturation period (BBCH-60-99), Amethyst, Hoverla, and Artemida varieties had the highest values of homeostaticity (Hom1 and Hom2), in particular, they were 32.8, 3.64 in Artemida, 30.2, 3.76 in Amethyst, 27.15 and 3.02 in Hoverla varieties.

Keywords: adaptability, correlation, determination, homeostaticity, plasticity, stability, variance of stability, yield

1 Introduction

A considerable increase in air and soil temperatures, long periods between rains caused by the global warming characterized are resulting in a stressful state of plants and a sharp decrease in their productivity. Rapidly changing thermal and water regimes require a significant restructuring of the structure of agricultural production, which is based on the varieties of a new type (Silva et al., 2017).

Soybean is a unique protein-oil crop characterized by high adaptability to growing conditions, versatility of use and balance of protein in terms of amino acid composition and its functional activity (Poberezhets et al., 2021). Due to these characteristics and high productivity, soybean, compared to other annual leguminous and oilseed crops, ranks first in the world both in terms of cropping areas and gross grain harvest (Babych, 2011; Berset et al., 2013; Kaletnik & Lutkovska, 2020; Paziuk et al., 2021).

Breeding of varieties with the involvement of the source material of soybean (*Glycine max* (L.) Merr.) having high genetic yield potential and adaptability enables to grow this crop more effectively in all climatic zones of Ukraine, which is currently quite important for the country's economy. At the current stage of agricultural production, soybean breeding and genetic improvement is becoming especially relevant.

Modern tasks of breeding include the development of adaptive systems with developed self-adjustment mechanisms that can ensure stability of functioning and stability of the final product in specific environmental conditions. Management of adaptive systems is qualitatively different, but not due to the

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regulation of the external environment, but due to the influence on internal processes, i.e. management of biological processes of synthesis of organic matter, its transformation into useful products of growth and development and, in general, genotypic implementation of genetic information (Batista et al., 2015).

Therefore, the primary task of breeding is to develop varieties that combine high yield with relatively high resistance to adverse soil and climatic conditions and have a sufficiently high level of adaptation to the conditions of the growing region (Peltonen-Sainio et al., 2009; Lee et al., 2014; Silva et al., 2017; Mazur et al., 2019; Mazur et al., 2021a). A negative effect of adverse abiotic factors of the environment can be reduced as a result of the expansion of the variability of crop varieties and the increase of their adaptive potential (Batista et al., 2015; Mazur et al., 2021b; Honcharuk et al., 2022; Zhou et al., 2022;). Adaptive potential is characterized by the plant ability to survive and reproduce the functioning of genetic systems of ontogenetic and phylogenetic adaptations. Designing adaptive biosystems under conditions of ecological stability is a guaranteed basis for significantly increasing productivity and ecological sustainability (Mazur et al., 2022). The contribution of plant breeding to climate protection and adaptability to climate change is quite significant (Tai, 1971; Vollmann et al., 2005; Roux & Wehling, 2012; Biliavska et al., 2021; Belyavskaya et al., 2022). Cold-resistant soybean varieties with a deep root system (more than 1.5 m) have been developed for fairly early sowing periods, which makes it possible to form a seed yield before summer droughts (Biliavska, 2010). There were selected varieties having a deep root system (over 1.5 m), cold resistant – for quite early planting dates, which enables to form seed yield before summer droughts. There is an opportunity to increase soybean potential and yield even in the regions where pant breeding has been carried out for dozens of years (Vollmann et al., 2005).

Fast and early-ripening soybean varieties can produce high yields if they are drought resistant and able to shorten development phases in hot periods without any losses. It should be noted that under fairly high air temperatures (+35... +43 °C), due to morphological and chemical mechanisms, drought resistant varieties are able to activate the root system (increase the length of the root), change the angle of orientation of the leaf surface regarding the sun, and regulate the turgor process (Beil & Atkins, 1965; Berset et al., 2013; Silva et al., 2017).

Some studies have established that there is a positive relationship between plant height and such important farming characteristics as seed size and yield, in particular, seed size is an indicator of drought resistance of the crop variety (Schori et al., 2003).

Agriculture is becoming more ecologically oriented (Kovbasa et al., 2021), and to ensure a more complete use of the biological potential of plants, there appear new requirements for the diversity of breeding material to obtain adaptive, stably productive varieties of agricultural plants (Palamarchuk & Telekalo, 2018; Zhou et al., 2022). That is why the focus of breeding on resistance to adverse environmental factors involves a comprehensive assessment of the breeding material and is of particular importance at the current pace of climate change (Griffing, 1950; Riabukha & Kobyzieva, 2010; Mazur et al., 2021b).

Development of soybean varieties with a high adaptability to environmental conditions requires a comprehensive study of the source material in order to select samples that would combine tolerance to low temperatures, increased drought and heat resistance with high productivity. Such studies are an integral part of the selection process (Vollmann et al., 2005; Riabukha & Kobyzieva, 2010; Biliavska et al., 2021).

Populations developed on the basis of hybridization of varieties from different natural and ecological conditions are the most valuable forms for breeding, capable of combining high productivity and adaptability. This is due to the fact that certain gene complexes are formed in different natural zones, which ensure the highest productivity due to a rather effective use of the factors of the environment (Schori et al., 2003).

Poltava State Agrarian Academy pays much attention to the adaptability and productivity of soybean selection. Thus, the Head of the Laboratory of Soybean Breeding, Seed Production and Varietal Agrotechnics Liudmyla Biliavska together with the Institute of Feed Research and Agriculture of Podillia submitted to the State Register of Plant Varieties of Ukraine early high-yield varieties Agat, Amethyst, Almaz, Artemida, Aventurin, Aquamarine having high genetic potential and resistance to biotic and abiotic environmental factors (Biliavska, 2010; Biliavska et al., 2021; Belyavskaya et al., 2022).

Technologies for determining their adaptive potential are a specific area of modeling variety parameters, and ecological variety testing occupies one of the leading places among them (Biliavska et al., 2021; Mazur et al., 2022). Thus, according to many researchers, to provide objective and complete characteristics of varieties, it is necessary to use a combination of various statistical models and indicators, and variety adaptability should be considered from the point of view of plasticity, stability, and homeostasis (Wolf et al., 1980).

There, a complex assessment of soybean varieties in different soil and climatic conditions under contrast hydrothermal regime will enable to identify valuable genotypes, which will provide stable yields under adverse conditions of cultivation and increase in its level under optimization of the hydrothermal regime due to high indicators of adaptability (plasticity and stability). In addition, these forms are a valuable source material for the breeding intended for adaptability.

The purpose of the research was to conduct a comparative evaluation of soybean varieties, including individual breeding with direct consideration of their ontogenetic adaptation and realization of valuable farming traits.

3 Material and methods

Taking into account the requirements for soybean cultivation conditions, soil and hydrothermal resources of Ukraine, the research was conducted in different soil and climatic conditions of Ukraine. According to Academician A. Babych, in the so-called "soybean belt", where 2/3 of soybean crops are located, there can be distinguished a zone of stable and unstable production of this crop on rich soils and a zone of guaranteed soybean production on irrigated soils (Babych et al., 2011). It includes those areas where 500–650 mm of precipitation falls per year; 250–400 mm in May-September; 180–200 mm during the period of flowering and formation of beans (Babych et al., 2011).

The research was carried out during the period of 2010–2021, which differed significantly in terms of hydrothermal regime, and at sites of variety testing located in different agro-climatic regions of Ukraine. This made it possible to establish the response of varieties to the amplitude of variability of environmental factors. Soil variations were represented by gray forest soils in Vinnytsia region, typical podzol chernozems in Poltava region, and podzol chernozems in Kyiv region.

The territory of the experimental field in Vinnytsia region is flat. The soil cover of the trial site is represented by gray forest mid-loamy soils. According to their morphological features, physical and physico-chemical indicators, they are typical both for Vinnytsia region and for the right-bank Forest-Steppe in general and are favorable for growing soybeans. According to the agrochemical survey, the arable layer of the soil has the following physico-chemical indicators: humus content (according to Tyurin) is 2.02–2.25%, alkaline hydrolyzed nitrogen (according to Cornfield) is 60–67 mg.kg^{-1} of soil, mobile phosphorus and exchangeable potassium (according to Chirikov) is 149–212 mg.kg^{-1} of soil and 80–92 mg.kg^{-1} of soil, respectively, the pH of the salt extract is 5.3–5.4. Hydrolytic acidity is 1.6–1.7 mg-eq per 100 g of soil^{-1}.

In the conditions of Poltava region on the territory of the trial site, the soil cover is podzol chernozem, and humus content in the arable soil layer (according to Tyurin) is 3.07–3.63%, the volume weight is 1.23 g.cm^{-3}, the specific weight is 2.7 g.cm^{-3}. Absorption capacity is 21–23 mg-equivalent per 100 g of soil, base saturation is 64%. Soil acidity is low (pH 5.8–6.0), hydrolytic acidity is 1.3–3.5 mg-equivalent per 100 g of soil. Field moisture content is 27.6%. The maximum reserve of productive moisture in a meter-long soil layer is 184 mm. Molecular moisture capacity is 12.0–13.5%, plasticity is within 19.4–31.6%. On average, the soil is provided with nitrogen, phosphorus and potassium. The amount of absorbed bases is 242... 297 mg.eq. per 100 g of soil^{-1}; the degree of soil saturation with bases is 84... 87%. The content of mobile forms of nitrogen (according to Cornfield) is 108 mg, the content of mobile phosphorus (according to Kirsanov) is 70...100 mg, potassium (according to Maslova) is 120...180 mg.kg^{-1} of soil.

The soil of the trial site in the conditions of Kyiv region is represented by typical low-humus heavy loam chernozem, which is characterized by the following agrochemical parameters: humus content in the 0–20 cm horizon is 5.15%, in the 20–40 cm horizon is 4.07%. 0–20 cm layer contains 161.7 mg.kg^{-1} of easily hydrolyzable nitrogen soil (according to Cornfield), 150.3 mg.kg^{-1} of mobile phosphorus (according to Chirikov), 208 mg.kg^{-1} of exchangeable potassium (according to Chirikov), the reaction of the soil solution is weakly acidic, the pH of the salt extract is 5.8. The depth of calcium carbonates is in the horizon of 80–120 cm, sometimes decreasing to 150–160 cm. Thus, according to the main agrochemical indicators, the soil of the research area is suitable for growing most agricultural crops, including soybeans.

The object of the research was soybean varieties: Amethyst, Hoverla, Artemida, Femida, Zolotysta, Vezha and Oriana included in the State Register of Varieties suitable for distribution in Ukraine. The author of the varieties Amethyst, Artemid and Vezha is the breeder L.H. Biliavska (Biliavska et al., 2021).

Mineral ammonium nitrate phosphate fertilizer NPK 16-16-16 was applied during sowing. The research was carried out according to the standard methodology (Volkodav, 2001).

One of the important complex methods of analysis is the analysis of stability and plasticity of the studied varieties, which was carried out according to the Eberhard-Russell method. This technique makes it possible to evaluate varieties not only by the values of average indicators, but also by plasticity (b), which reflects the regression of the variety to changing environmental conditions and the stability (Si^2) of this reaction. In the method used by us for the generalization of experimental data, the sum of squares of the interaction of each variety with environmental conditions is divided into two parts, namely the linear regression component (b) and the non-linear part, which is determined by the mean square deviation from the regression line (Si^2) (Eberhart & Russell, 1966; Tai, 1971).

According to the results of calculations of the indicators of plasticity (bi) and stability (Si^2), the following grouping ranks have been specified for the varieties:

1. indicators bi <1, Si^2 >0 – have better results under unfavorable conditions, unstable;
2. indicators bi <1, Si^2 = 0 – have better results under adverse conditions, stable;
3. indicators bi = 1, Si^2 = 0 – respond well to improving conditions, stable;
4. indicators bi = 1, Si^2 >0 – respond well to improving conditions, unstable;
5. indicators bi >1, Si^2 = 0 – have the best results under favorable conditions, stable;
6. indicators bi >1, Si^2 >0 – have the best results under favorable conditions, unstable.

Parameters of ecological adaptability of varieties were calculated according to the methodology (Volkodav, 2001; Mazur et al., 2021b).

Determination of homeostaticity and coefficient of agronomic stability (As) were calculated according to the methodology (Wolf et al., 1980).

A reliable assessment of the variety in terms of plasticity and stability involves studying the peculiarities of formation of its yield due to the changes in abiotic factors during the growing season (Volkodav, 2001). In our research, this essential requirement is confirmed, a significant difference has been established in precipitation (Figure 1) and hydrothermal coefficient (Figure 2).

The lowest indicators of the hydrothermal coefficient were observed in 2015, 2019 and 2020, when hydrothermal coefficient of precipitation (HCP) was 0.47, 0.51, 0.5; 0.86, 0.75, 0.9; 0.83, 0.73, 0.9, respectively. According to the average long-term values, HCP = 0.95, 1.05, 1.07, which was reflected in the indicators of the yield level of soybean varieties in different soil and climatic conditions of research (Table 1).

3 Results and discussion

A two-factor variance analysis made it possible to establish the significance (according to Fisher's test) of the influence of genotype and soil-climatic conditions and their interaction in a separate variance of the statistical processing of yield results (Table 1 and Table 2).

Yield capacity is a complex feature, which is directly influenced by the abiotic and biotic factors. When analyzing the yield level of soybean varieties in the conditions of trial sites and throughout research years, it was determined that the highest level of productivity was

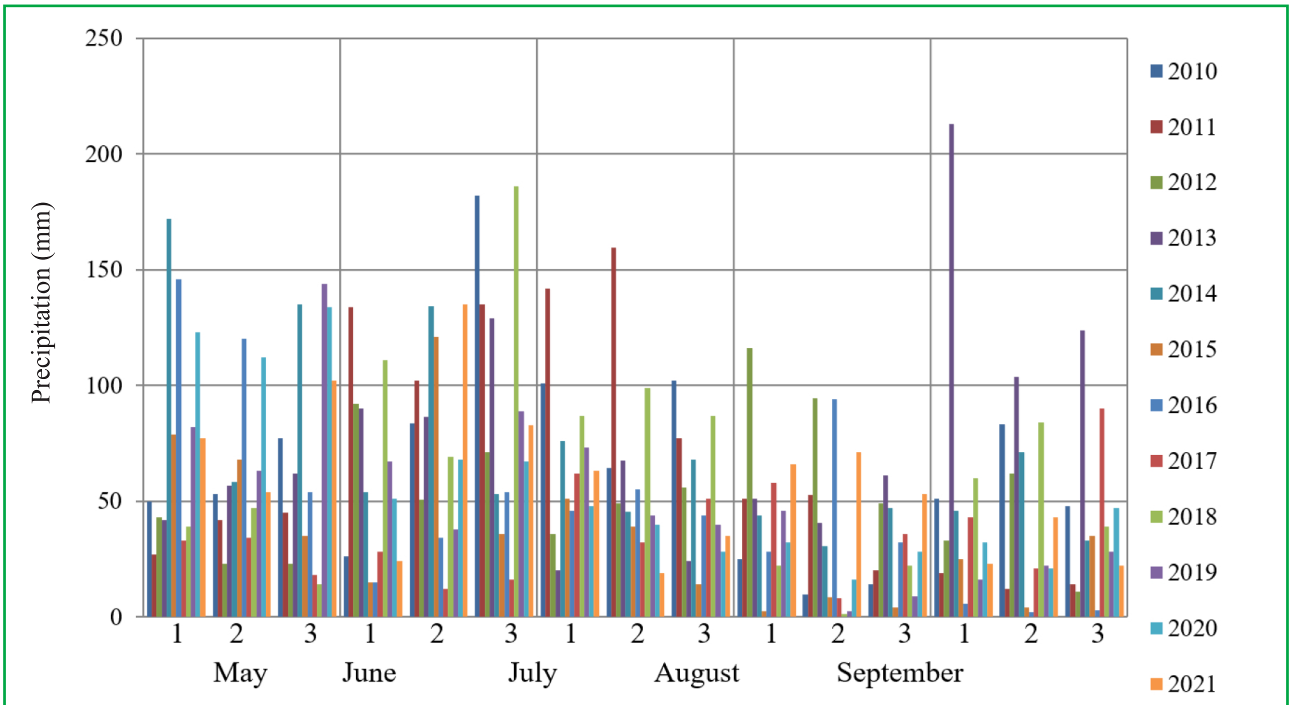

Figure 1 Amount of precipitation during the growing season (BBCH-10-99)
1 – Kyiv region, 2 – Poltava region, 3 – Vinnitsa region

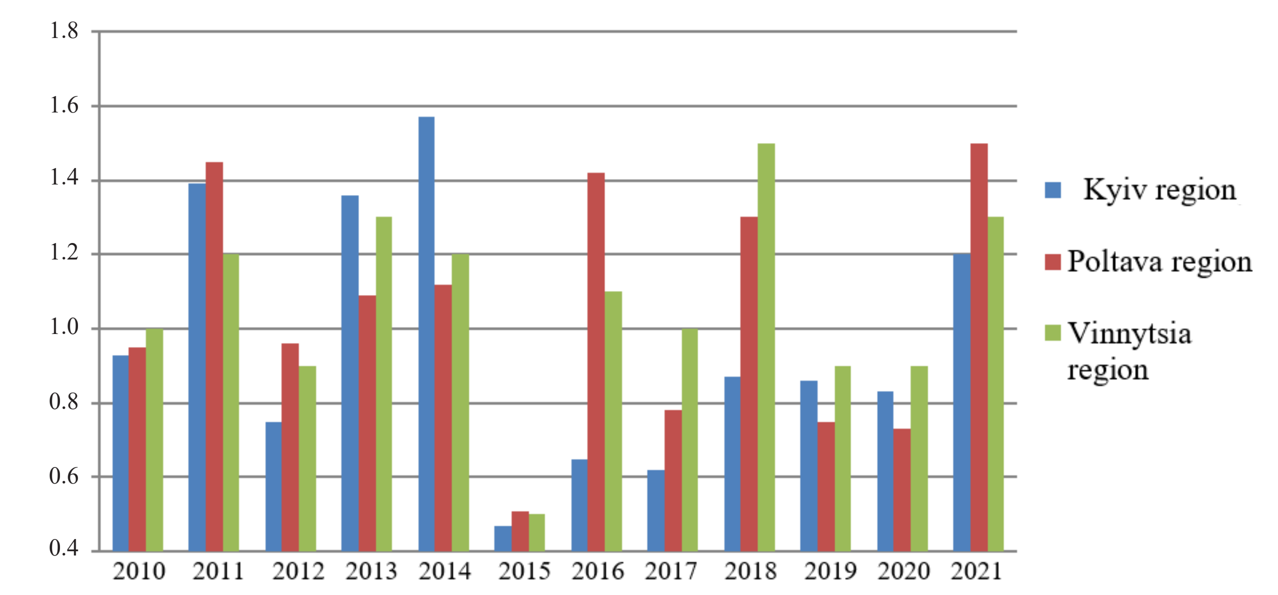

Figure 2 Hydrothermal coefficients during the growing season (BBCH-10-99) (May–September) 2010–2021

Table 1 The yield of soybean varieties under different hydrothermal conditions (t.ha^{-1})

Years	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
Kyiv region (50° 21′ 16″ north latitude 30° 27′ 16″ east longitude)												
Amethyst	1.91	1.92	1.53	1.79	1.82	1.43	2.0	1.74	2.0	1.82	1.72	2.21
Hoverla	2.02	2.05	1.61	1.88	1.93	1.51	2.55	2.0	2.5	1.93	1.81	2.56
Artemida	2.06	1.92	1.82	1.97	1.91	1.46	2.12	1.74	2.28	1.92	1.82	2.32
Femida	1.92	1.91	1.54	1.85	1.95	1.41	1.97	1.70	1.93	1.61	1.41	2.21
Zolotysta	1.85	1.86	1.46	1.74	1,92	1.33	1.91	1.67	1.91	1.63	1.42	2.12
Vezha	2.01	1.89	1.64	1.87	1.95	1.42	2.0	1.76	1.96	1.74	1.54	2.23
Oriana	1.83	1.83	1.38	1.72	1.91	1.29	1.86	1.61	1.83	1.51	1.41	2.14
Poltava region (49° 38′ 21″ north latitude 34° 54′ 10″ east longitude)												
Amethyst	2.38	2.53	2.1	2.0	1.96	1.64	2.5	1.96	2.16	2.02	1.92	2.62
Hoverla	2.7	2.9	1.96	2.05	2.12	1.67	2.62	2.4	2.65	2.11	2.01	2.8
Artemida	2.45	2.55	2.05	2.2	2.16	1.78	2.54	1.98	2.24	2.0	1.93	2.63
Femida	2.03	2.2	1.75	2.05	2.1	1.59	2.18	1.92	2.13	1.82	1.64	2.31
Zolotysta	1.98	2.04	1.66	1.94	2.06	1.54	2.1	1.84	2.12	1.81	1.6	2.33
Vezha	2.2	2.03	1.8	2.04	2.09	1.61	2.18	1.96	2.17	1.93	1.72	2.42
Oriana	2.0	2.02	1.58	1.88	2.04	1.49	2.02	1.83	2.01	1.72	1.53	2.23
Vinnytsia region (49° 11′ 31″ north latitude 28° 22′ 16″ east longitude)												
Amethyst	1.96	1.92	1.61	1.87	1.92	1.52	2.12	1.83	2.13	1.92	1.82	2.22
Hoverla	2.06	2.11	1.67	1.98	2.01	1.61	2.56	2.37	2.62	2,03	1.91	2.61
Artemida	2.12	2.02	1.9	2.02	1.98	1.55	2.32	1.85	2.46	1.95	1.83	2.2
Femida	1.98	2.03	1.63	1.97	2.0	1.47	2.06	1.81	2.02	1.92	1.84	2.13
Zolotysta	1.91	1.95	1.54	1.83	1.97	1.42	2.03	1.76	2.03	1,71	1.6	2.14
Vezha	2.05	1.98	1.73	1.99	2.03	1.53	2.13	1.85	2.08	1.83	1.73	2.22
Oriana	1.9	1.92	1.49	1.81	1.95	1.38	1.95	1.72	1.92	1.62	1.52	2.03

Table 2 Parameters of ecological plasticity and stability of soybean varieties by the yield (t.ha^{-1}), 2010-2021

Variety	Average yield (t.ha^{-1})	Coefficient			Variance of stability (Si^2)	Homeo-staticity		Components	
	year, trial sites	ecological plasticity (bi)	agronomic stability (As) (%)	variances (V) (%)		Hom 1	Hom 2	a_i	λi
Amethyst	1.95	1.02	86.1	13.9	0.07	7.19	6.04	0.01	0.75
Hoverla	2.2	1.39	82.6	17.4	0.02	5.76	4.11	0.08	2.29
Artemida	2.1	1.01	86.9	13.1	0.01	7.64	6.53	0.01	0.73
Femida	1.88	0.89	87.6	12.4	0.01	8.08	8.98	-0.01	0.63
Zolotysta	1.82	0.91	87.1	12.9	0.004	7.71	7.62	-0.01	0.47
Vezha	1.92	0.87	88,2	11.8	0.04	8.62	8.51	-0.02	0.54
Oriana	1.77	0.91	86.5	13.5	0.01	7.39	7.86	-0.01	0.68
Factor	Ff	F_T							
Variety	2,360.1	2.19							
Conditions	102.4	1.54							
Interaction variety – conditions	10.31	1.39							

achieved in the conditions of Poltava region in 2021, 2018, 2016, 2011, 2010 – 2.2–2.8; 2.01–2.65; 2.02–2.62; 2.02–2.9; 1.98–2.7 t.ha^{-1}. High productivity was also formed during these years in the conditions of Vinnytsia region – 2.0–2.6; 1.92–2.6; 1.95–2.56; 1.92–2.1; 1.9–2.1 t.ha^{-1}, as well as in Kyiv region – 2.1–2.56; 1.83–2.5; 1.86–2.55; 1.83–2.05 and 1.83–2.06 t.ha^{-1}. This indicates the most favorable conditions for moistening that occurred in the specified years of research (Figure 1).

The lowest productivity was formed in the conditions of 2015, 2019 and 2020 and it changed in the conditions of Poltava region – 1.49–1.78, 1.7–2.1 and 1.5–2.0 t.ha^{-1}, Vinnytsia region – 1.38 to 1.6, 1.6–2.0 and 1.5–1.9 t.ha^{-1} t.ha^{-1}, Kyiv region – 1.29–1.51, 1.5–1.9 and 1.4–1.8 t.ha^{-1}. The decrease in the yield level of soybean varieties is associated directly with the hydrothermal regime deterioration, namely, lack of precipitation (Figure 1).

It was established that the highest level of productivity in different soil and climatic conditions was provided by Hoverla variety – 2.2 t.ha^{-1}, so that the compliance of the plant genotype with the real conditions of existence for a long enough time to maximize the potential of this variety was the highest. It had the highest coefficient of plasticity (bi = 1.39). Therefore, the variety is best adapted to both the optimal and the minimum or maximum manifestation of environmental factors, compared to the varieties presented in the experiment.

The variance of stability (Si^2) was as close as possible to zero – 0.02. Almost similar yield (2.1 t.ha^{-1}) and indicators of plasticity (bi = 1.01) and stability (Si^2 = 0.01) were observed in Artemida variety. However, the highest homeostaticity (Hom – 0.16) among highly plastic soybean varieties, which characterizes the stability of the trait in the changing environmental conditions, by the ratio of the average arithmetic index to the coefficient of variation (V, %). So, in accordance with the given grouping, the fifth rank in terms of the yield capacity includes the following varieties: Artemida, Hoverla and Amethyst, in which the regression coefficient (bi) was more than 1, and the variance of stability of the trait was Si^2 = 0, that is, these varieties have better results under favorable growing conditions and are stable, they should be recommended for cultivation in conditions of high farming culture. Femida, Zolotysta, Oriana and Vezha varieties with a coefficient of plasticity (bi) of less than 1 and a variance of the trait stability Si^2 = 0 belong to the second rank in terms of the yield capacity. The coefficient of agronomic stability (As) in soybean varieties was >70%. All specified varieties were stable according to this criterion. However, by homeostaticity (Hom 1 i Hom 2), the highest indicators were observed Vezha variety – 8.62 and 8.51.

A complete analysis of the assessment of ecological plasticity and stability of genotypes based on ai and λ components presented graphically (Figure 3) proved that Amethyst, Hoverla and Artemida varieties of the 1st (I) zone belong to the genotypes with a high response to the changes in growing conditions. Thus, such varieties should be recommended for cultivation in conditions of high agricultural culture. However, on a low agricultural background, their yield decreases sharply. In contrast to them, Femida Zolotysta, Oriana and Vezha varieties placed coordinately in the 3rd (II) zone

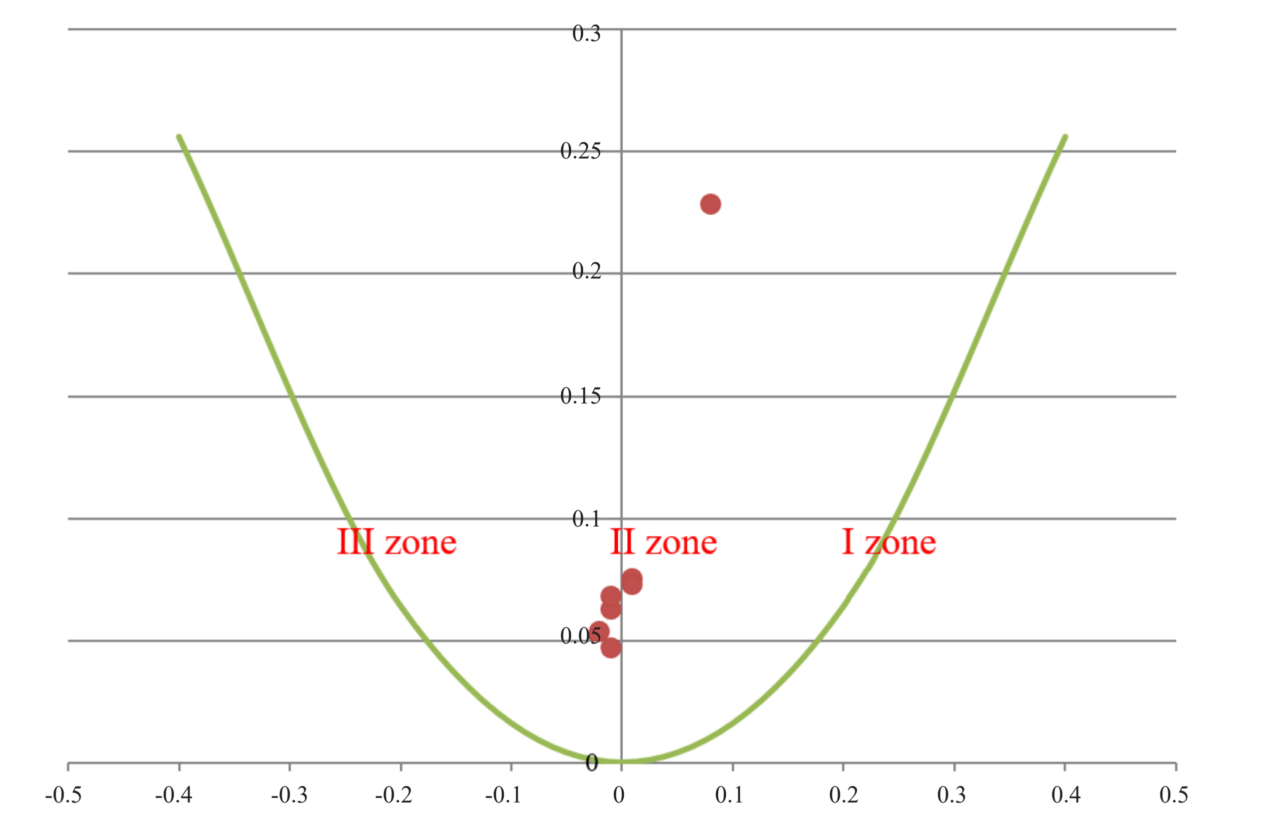

Figure 3 The division of soybean varieties into classes by plasticity (a_i) and stability (λ) of the yield

are more conservative in their response to changing environmental conditions. The position of these varieties corresponds to the so-called marginal zone of placement, respectively, at the junction of III and II as well as II and I zones, which is a certain expression of the internal reserve of plasticity and stability of the genotype and the need for its further study.

One of the most important economic characteristics that determines the degree of adaptability of plants to growing conditions, depending on their species, is the duration of the growing season.

It is well-known that the weather conditions affect the formation of phenophases of plant development and are interconnected with productivity, the level of which is controlled by the reaction of varieties to vegetation conditions, which depends on their adaptability.

The results of analysis of soil and climatic conditions were reflected in the formation of mean squares of the genotype and growing conditions and their interaction in the expression of formation of the duration of the growing season of soybean varieties. In particular, the significance (according to Fisher's criterion) of the influence of genotype and soil-climatic conditions and their interaction in the variance of dispersion analysis was determined.

The duration of the growing season (BBCH-10-99) in soybean varieties depended, first of all, on varietal characteristics and growing conditions (Table 3–4).

In the conditions of Kyiv region, the duration of the growing season of soybean varieties varied from 116 to 139 days, in the conditions of Poltava region from 101 to 128 days, and in the conditions of Vinnytsia region from 100 to 112 days.

A shorter growing season in terms of the years of research and trial sites was observed in the following varieties: Amethyst – 110.6, Hoverla – 113.6, and Artemida – 114.3 days, and a longer growing season was observed in the following varieties: Femida – 121.8, Zolotysta – 118.8, Vezha – 116.7, and Oriana – 116.4 days.

High adaptability to the growing conditions was provided by Amethyst, Hoverla, Artemida and Vezha varieties, and their coefficient of agronomic stability was the highest among the presented varieties and varied from 91.7 to 92.1%. These varieties can be distinguished by their conservative response to changes in hydrothermal and soil conditions, providing stable indicators by the duration of the growing season, the coefficient of plasticity (bi) was less than 1 (Table 4), i.e. according to the above-given grouping, they belong to the first

Table 3 Duration of the growing season (BBCH-10-99) of soybean varieties under different hydrothermal conditions (days)

Years	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
Kyiv region (50° 21′ 16″ north latitude 30° 27′ 16″ east longitude)												
Amethyst	123	122	120	121	122	120	125	120	126	123	119	127
Hoverla	129	128	120	126	127	117	129	124	127	126	123	128
Artemida	132	128	119	124	123	116	132	126	129	130	125	130
Femida	139	137	131	135	136	128	135	129	133	133	127	135
Zolotysta	135	133	125	131	133	123	132	127	130	130	125	132
Vezha	129	128	124	128	129	122	129	128	129	127	126	130
Oriana	131	130	125	127	129	123	128	127	131	125	127	131
Poltava region (49° 38′ 21″ north latitude 34° 54′ 10″ east longitude)												
Amethyst	105	112	106	104	103	101	107	103	108	106	102	109
Hoverla	109	114	104	109	110	103	111	109	111	110	108	112
Artemida	111	118	104	106	105	105	113	106	111	112	105	112
Femida	127	126	119	128	125	117	125	124	126	123	122	128
Zolotysta	124	121	118	121	122	116	122	117	121	119	115	123
Vezha	119	117	112	117	121	110	120	115	118	116	113	122
Oriana	116	113	111	115	119	111	117	114	116	114	111	122
Vinnytsia region (49° 11′ 31″ north latitude 28° 22′ 16″ east longitude)												
Amethyst	104	106	101	103	104	100	107	103	106	106	102	107
Hoverla	107	107	103	105	107	102	109	105	109	108	104	110
Artemida	109	107	103	108	107	102	111	107	111	110	106	112
Femida	110	107	105	109	108	104	111	107	110	109	105	112
Zolotysta	108	107	104	107	107	103	109	106	109	107	104	111
Vezha	107	106	103	106	106	102	108	105	108	106	103	111
Oriana	106	108	103	106	107	103	109	106	108	107	103	112

Table 4 Parameters of ecological plasticity and stability of soybean varieties according to the duration of the growing season (BBCH-10-99) (days), 2010–2021

Variety	Average duration of the growing season (days)	Coefficient			Variance of stability (Si^2)	Homeostaticity		Components	
	year, trial sites	ecological plasticity (bi)	agronomic stability (As) (%)	variances (V) (%)		Hom 1	Hom 2	a_i	λ_i
Amethyst	110.6	0.90	92.0	8.0	9.11	12.55	0.46	-0.46	3.93
Hoverla	113.6	0.95	92.1	7.9	4.96	12.58	0.47	-0.10	3.15
Artemida	114.3	0.96	91.7	8.3	12.56	12.06	0.40	-0.06	5.93
Femida	121.8	1.1	91.0	9.0	13.22	11.08	0.32	1.19	1.00
Zolotysta	118.8	1.05	91,6	8.4	6.39	11.94	0.37	0.58	2.84
Vezha	116.7	0.99	91.9	8.1	3.23	12.49	0.45	0.22	2.61
Oriana	116.4	1.0	91.8	8.2	2.51	12.46	0.44	0.26	2.15
Factor	Ff	$F_т$							
Variety	13,207	2.19							
Conditions	313.5	1.54							
Interaction variety – conditions	34.28	1.39							

group, providing the best results in adverse growing conditions.

Femida and Zolotysta soybean varieties, in which coefficient of plasticity (bi) was higher than one, and coefficients of agronomic stability (As) were lower than in the previous group of varieties and varied from 91.0 to 91.6%. The highest indicators of homeostaticity (Hom 1 i Hom 2) were provided by the following varieties: Hoverla – 12.58 and 0,47; Vezha – 12.49 and 0,45; Amethyst – 12.55 i 0.46. Regarding the variance of stability, which characterizes the dispersion (deviation) relative to the direction of the regression coefficient, all soybean varieties have a stability variance (Si^2) >0.

So, in accordance with the given grouping, the first rank in terms of the duration of the growing season (BBCH-10-99) includes Amethyst, Hoverla, Artemida and Vezha varieties, in which the coefficient of regression (bi) was less than 1, and the variance of stability of the trait was Si^2 >0, so it can be assumed these varieties have better results under adverse conditions growing. The sixth rank includes Femida and Zolotysta varieties, in which the coefficient of regression (bi) was more than 1, and the variance of the stability of the trait was Si^2 >0, so they provide better results of improving growing conditions.

Analysis of the assessment of ecological plasticity and stability of varieties by components ai and λ proved that Femida and Zolotysta varieties, i.e. those of the 1st rank, belong to genotypes with a high reaction to changes in growing conditions (Figure 4). Thus, these varieties should be recommended for cultivation in conditions of high agricultural culture. However, the duration of the growing season (BBCH-10-99) in these varieties is sharply reduced on a low agricutural background. The position of Vezh and Oriana varieties, which are located in the 2nd (II) zone, corresponds to the so-called marginal zone of placement, respectively, at the junction of III and II as well as II and I zones, which is a certain expression of the internal reserve of plasticity and stability of the genotype and the need for its further study. In contrast to them, Amethyst, Hoverla and Artemida varieties, which coordinates are located in the 3rd (III) zone, are more

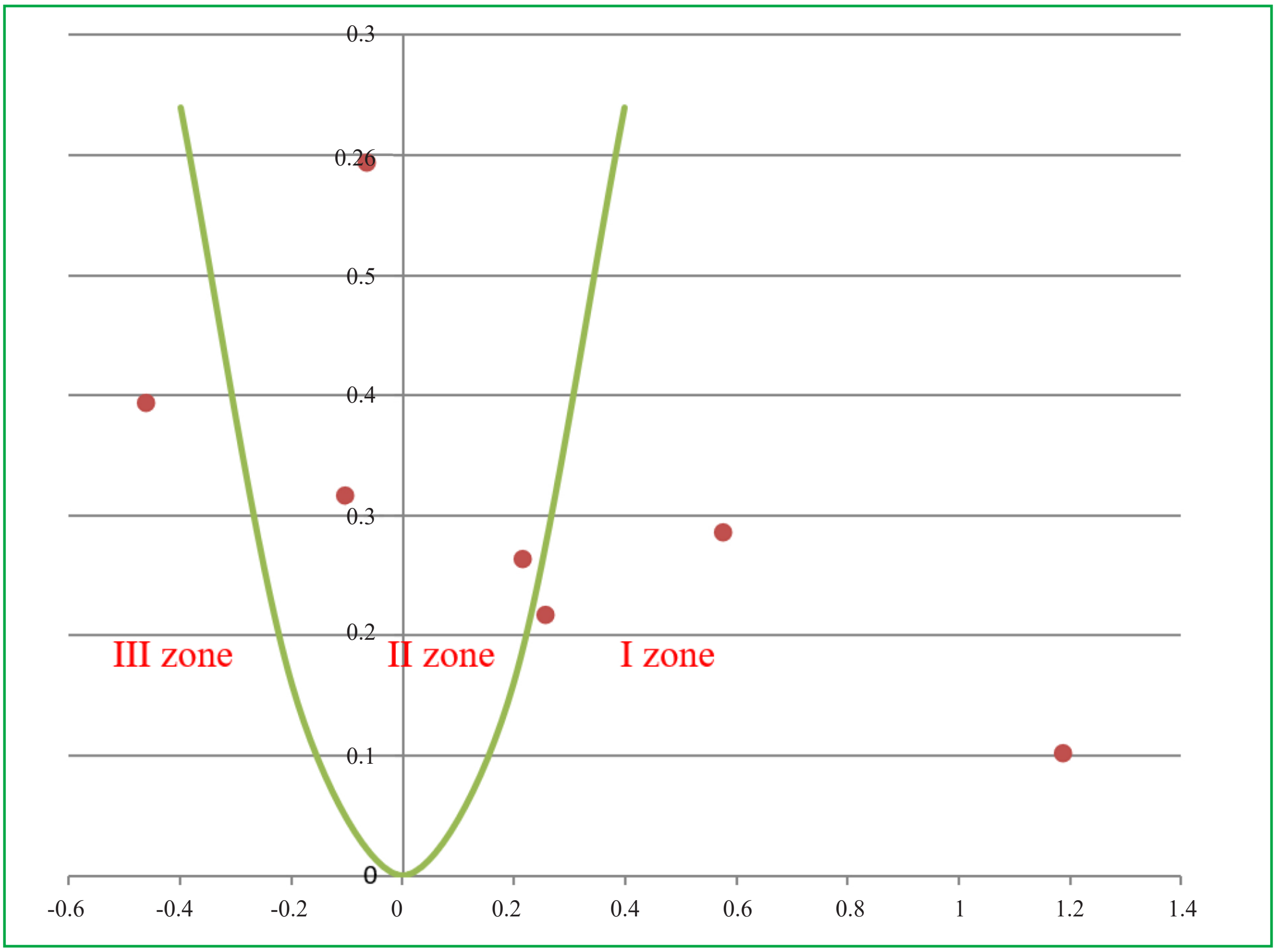

Figure 4 The division of soybean varieties into classes according to plasticity (ai) and stability (λ) of the duration of the growing season (BBCH-10-99)

conservative in their reaction to changing environmental conditions.

The total duration of the growing season of soybeans consists of two clearly distinguishable phases "germination-flowering" (BBCH-10-59) and "flowering-maturation" (BBCH-60-99). Their value for achieving maximum productivity is not the same. Breeders should strive to develop varieties with a short total vegetative period, but a long "flowering-maturation" (BBCH-60-99) period. Under such duration of vegetation phases, optimal conditions for the formation of beans and filling of grain are developed. A long reproductive period (BBCH-60-99) enables plants to better compensate crop losses from adverse conditions that may occur during this period. As a rule, "flowering-maturation" (BBCH-60-99) phase lasts for 60–70 days. Therefore, if a dry period occurs, for example, at the end of June (intense flowering), the losses from this can be partially reduced if there are optimal conditions in July or August. Compensation occurs due to a decrease in the number of beans that fall during the process of filling seeds and abortion, as well as due to the formation of large grains. It should be noted that in the process of ontogenesis an excessive number of soybean fruit elements – flowers and beans – are formed, and most of them fall off in the process of further growth and development. Such dynamics of formation of flowers and beans in the process of ontogenesis developed during the evolution of this crop. Therefore, the periods with an optimal set of environmental factors in the process of generative growth provides the opportunity to fully realize the potential capabilities of the genotype due to a significant reduction in the fall of fruit elements. Information about the forms having minimal loss of these indicators under stressful conditions is also of great value for the breeder as this indicates their increased drought resistance (Silva et al., 2017).

Shifting the soybean flowering to the earlier period, while preserving the overall duration of the growing season (BBCH-10-99), makes it possible to increase drought

Table 5 Duration of the flowering-maturation period (BBCH-60-99) of soybean varieties under different hydrothermal conditions (days)

Years	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
Kyiv region (50° 21′ 16″ north latitude 30° 27′ 16″ east longitude)												
Amethyst	70	73	73	72	71	71	73	72	73	71	72	72
Hoverla	73	74	72	73	70	70	72	73	74	70	71	71
Artemida	72	72	70	69	69	68	71	70	73	72	71	72
Femida	73	72	71	67	67	66	67	66	67	66	66	67
Zolotysta	76	73	73	74	74	72	74	73	75	76	72	77
Vezha	73	70	69	70	71	68	73	71	72	70	69	71
Oriana	73	72	70	74	78	70	79	71	74	70	71	72
Poltava region (49° 38′ 21″ north latitude 34° 54′ 10″ east longitude)												
Amethyst	68	70	69	68	67	66	68	67	68	68	67	68
Hoverla	70	71	68	67	68	65	67	68	67	67	66	67
Artemida	70	71	67	68	67	66	69	66	68	71	70	71
Femida	67	69	62	62	61	60	62	61	62	63	62	63
Zolotysta	71	68	68	69	69	67	69	68	70	67	67	71
Vezha	68	65	64	65	66	63	68	65	67	65	64	68
Oriana	68	70	65	71	72	64	74	66	68	67	64	69
Vinnytsia region (49° 11′ 31″ north latitude 28° 22′ 16″ east longitude)												
Amethyst	67	68	65	67	67	67	68	68	69	68	67	67
Hoverla	69	69	66	68	66	66	67	69	69	67	66	68
Artemida	68	68	64	66	67	66	69	68	69	69	69	69
Femida	66	64	60	61	62	60	63	62	63	63	62	67
Zolotysta	65	63	61	63	61	59	65	62	64	63	61	67
Vezha	62	60	58	61	59	57	62	61	64	62	60	64
Oriana	64	62	60	62	64	62	67	64	68	65	63	64

Table 6 Parameters of ecological plasticity and stability of soybean varieties by the duration of the flowering-maturation period (BBCH-60-99) (days), 2010-2021

Variety	Average duration of the flowering-maturation period (days)	Coefficient			Variance of stability (Si^2)	Homeo-staticity		Components	
	year, trial sites	ecological plasticity (bi)	agronomic stability (As) (%)	variances (V) (%)		Hom 1	Hom 2	a_i	λ_i
Amethyst	69.1	0.66	96.7	3.3	1.04	30.02	3.75	-0.05	1.01
Hoverla	69.0	0.71	96.3	3,7	1.65	27.15	3.02	-0.04	1.08
Artemida	69.1	0.54	96.9	3.1	1.66	32.8	3.64	-0.07	1.83
Femida	64.5	0.90	94.7	5.3	3.85	18.96	1.45	-0.01	2.09
Zolotysta	68.5	1.50	92.7	7.3	2.90	13.78	0.81	0.09	2.77
Vezha	65.7	1,37	93.3	6.7	1.34	14.88	0.93	0.07	1.47
Oriana	68.3	1.33	93.2	6.8	4.71	14.64	0.77	0.06	3.17
Factor	Ff	F_T							
Variety	1,187	2.19							
Conditions	62.99	1.54							
Interaction variety – conditions	12.75	1.39							

resistance due to the early transition to the critical water consumption generative phase.

The longest flowering-maturation period was observed during the years of research in the conditions of Kyiv region, which varied from 66 to 79 days, Poltava region from 60 to 74 days, Vinnytsia region from 57 to 69 days (Table 5). Among the soybean varieties, the longest flowering-maturation period (BBCH-60-99) was observed in Amethyst variety – 69.1, Hoverla variety – 69.0, and Artemida variety – 69.1 days. Shorter period was observed in Femida variety – 64.5, Vezha – 65.7, Oriana – 68.3 and Zolotysta – 68.5 days.

A reliable influence of genotype differences of varieties and soil and climatic conditions, as well as their interaction on the duration of the flowering-maturation period (BBCH-60-99) was established, which was reflected in the mean squares of the two-factor variance analysis (Table 6). The above-mentioned factors allow us to evaluate soybean varieties by the duration of the flowering-maturation period (BBCH-60-99) applying various methods of assessing indicators of ecological plasticity and stability.

One of the important indicators characterizing plant resistance to adverse environmental factors is homeostasis, i.e. the ability of the genotype to minimize the effects of adverse environmental conditions. It is a universal property in the system of relationships between the genotype and the environment (Biliavska et al., 2021).

Homeostaticity of a variety is indicated by its ability to maintain low variability of traits and is determined by the ratio of the average value to the coefficient of variation (V %), and the coefficient of agronomic stability directly depends on the value of the coefficient of variance, the smaller it is, the higher the stability of the genotype is. It should be noted that Amethyst, Hoverla and Artemida varieties were characterized by the highest agronomic stability (As), which is confirmed by the sequence of distribution of varieties and by homeostaticity (Hom). Thus, the highest agronomic stability was noted in the

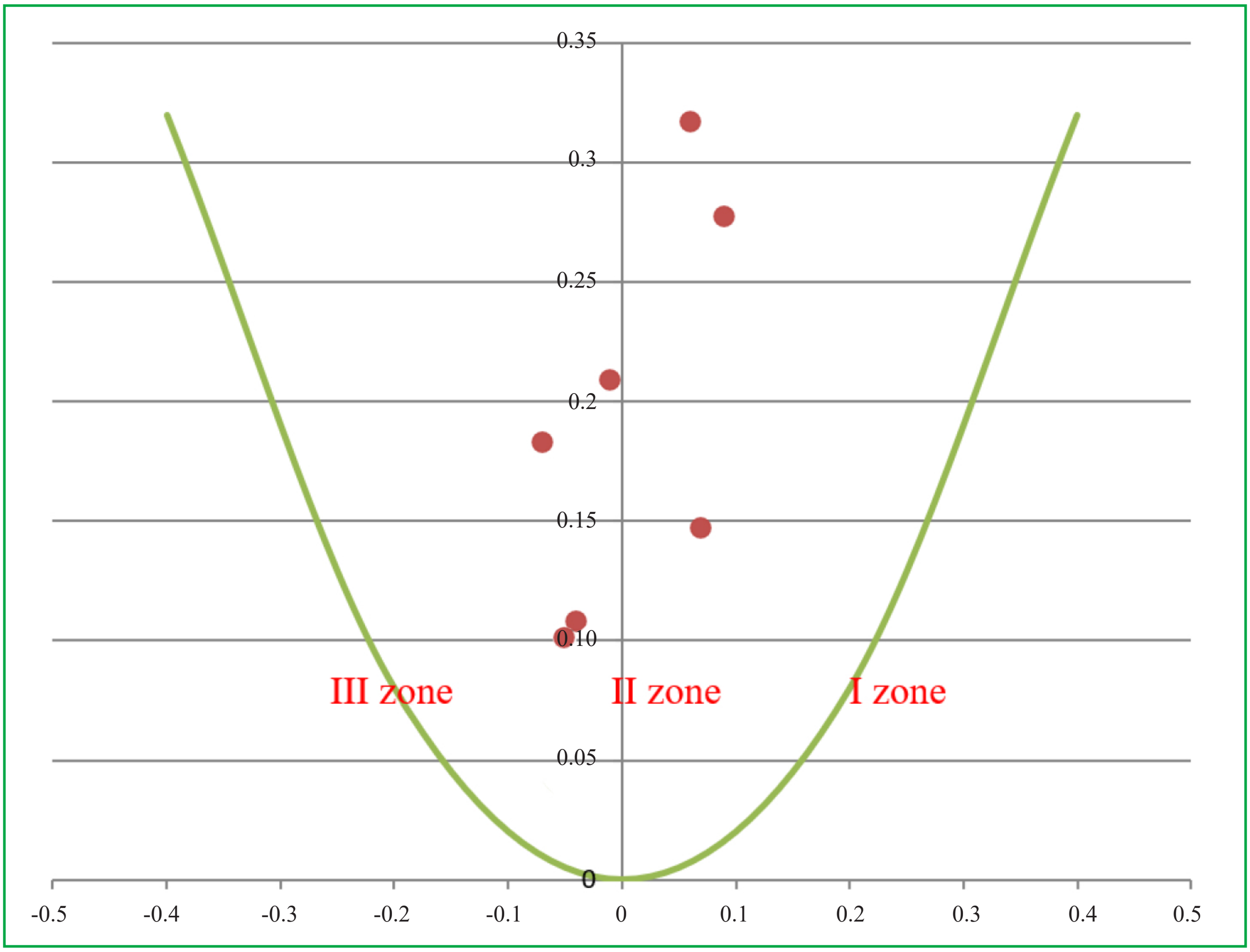

Figure 5 Division of soybean varieties into classes according to plasticity (a_i) and stability (λ) of the duration of the "flowering-maturation" period (BBCH-60-99), (days)

following varieties: Artemida – 96.9, Amethyst – 96.7 and Hoverla – 96.3. A similar distribution in these varieties was noted for homeostaticity (Hom 1 and Hom 2): Artemida – 32.8, 3.64; Amethyst – 30.2, 3.75 and Hoverla – 27.15 and 3.02. Thus, the highest agronomic stability was observed in the following varieties: Artemis – 96.9, Amethyst – 96.7 and Hoverla – 96.3. A similar distribution in these varieties was observed for homeostaticity (Hom 1 and Hom 2): Artemis – 32.8, 3.64; Amethyst – 30.2, 3.75 and Hoverla – 27.15 and 3.02. A more conservative response of these varieties to the changes in hydrothermal and edaphic growing conditions was also observed, the coefficient of ecological plasticity (bi) <1, i.e. according to the above-given grouping, they belonged to the first group, providing better results under unfavorable growing conditions. These varieties provided a long period of flowering and ripening (BBCH-60-99) which, compared to other varieties, was less dependent on the agricultural background of cultivation. It should be emphasized that Amethyst, Hoverla and Artemida varieties (Table 1) provided the highest level of productivity, namely 1.95, 2.2 and 2.1 $t.ha^{-1}$, as well as the longest flowering-maturation period (BBCH-60-99) of 69.1; 69.0 and 69.1 $t.ha^{-1}$.

Analysis of assessment of ecological plasticity and stability of the duration of the flowering-ripening period (BBCH-60-99) by components ai and λ proved that Zolotista, Vezha and Oriana varieties of the 1st (I) zone belong to genotypes with a high response to changes in growing conditions. Thus, these varieties should be recommended for cultivation in conditions of high agricultural culture. However, the duration of the flowering-ripening period (BBCH-60-99) is sharply reduced on a low agricutural background. In contrast to them, Amethyst, Hoverla and Artemida varieties placed coordinately in the third (III) zone are less variable in response to changing environmental conditions. The position of Femida variety, which coordinated are paced in the 2nd (II)zone, corresponds to the so-called marginal zone of placement, which is a certain expression of the internal reserve of plasticity and stability of the genotype and the need for its further study.

The indicator of stability determines the variance from the average group constant: a negative value compared to the average indicator characterizes this variety as stable; its deviation with the maximum approach to zero indicates its plasticity, while its positive value and its quantitative growth defines it as highly plastic.

Therefore, according to the given grouping regarding the variance from the average group constant, Artemida and Amethyst varieties, as well as Hoverla and Femida varieties were characterized by the highest stability with a gradual transition from plastic to highly plastic Zolotysta, Vezha and Oriana varieties.

4 Conclusions

According to the results of calculations of indicators of plasticity (bi) and stability (Si^2) of the yield of varieties, two grouping ranks were distinguished: 2nd rank – varieties with indicators bi <1, $Si^2 = 0$ have better results under adverse conditions and are stable, they include Femida, Zolotysta, Vezha and Oriana; 5th rank – varieties with indicators bi >1, $Si^2 = 0$ have the best results under favorable conditions and are stable, they included Amethyst, Hoverla and Artemida varieties, which provided the highest level of productivity – 1.95, 2.2 and 2.1 $t.ha^{-1}$.

According to the indicators of plasticity (bi) and stability (Si^2) of the duration of the growing season (BBCH-10-99), two grouping ranks were distinguished among the presented soybean varieties: 1st rank – indicators bi <1, Si^2 >0, they have better results under unfavorable conditions, they include Amethyst, Hoverla and Artemida varieties. Their coefficient of agronomic stability was the highest among the presented varieties and varied from 91.7 to 92.1%. These varieties were distinguished by their conservative response to the changes in hydrothermal and soil conditions, providing stable indicators by the duration of the growing season; 6th rank – varieties with indicators bi >1, Si^2 >0 have the best results under favorable conditions, they are unstable, and they include Femida, Zolotysta, Vezha and Oriana varieties.

According to the results of calculations of indicators of plasticity (bi) and stability (Si^2) of the duration of the flowering-ripening period (BBCH-60-99), two grouping ranks were distinguished among the studied varieties: 1st rank – indicators bi <1, Si^2 >0, these varieties have better results under unfavorable conditions, they include Amethyst – 69.1, Hoverla – 69.0 and Artemida – 69.1 days. The duration of their flowering-ripening period (BBCH-60–99) was the longest compared to other varieties. These varieties have the highest indicators of homeostaticity (Hom 1 and Hom 2), in particular, Artemida – 32.8, 3.64; Amethyst – 30.02, 3.75 and Hoverla – 27.15, 3.02. Thus, the specified varieties are the most valuable for their use in breeding programs when creating new soybean varieties. 6th rank – varieties with indicators bi >1, Si^2 >0, they have the best results under favorable conditions, they are unstable and they include Zolotysta, Vezha and Oriana varieties.

Thus, cultivation of highly adaptive soybean varieties Artemida, Amethyst and Hoverla will ensure highly efficient soybean production.

References

Babych, A. O. et al. (2011). *Selection, production, trade and use of soybean in the world*. Ahrarna nauka.

Batista, R.O. et al. (2015). Adaptability and stability of soybean genotypes in off-season cultivation. *Genetics and Molecular Research*, 14(3), 9633–9645.

Beil, G. M., & Atkins, R. E. (1965). Inheritance of guantitative characters in grain sorghum. *Iova State Journal*, 39, 3.

Belyavskaya, L. et al. (2022) Soybean growing under inoculation by *Bradyrhizobium japonicum* strains in the Forest-steppe and Steppe zones of Ukraine. *Zemdirbyste-Agriculture*, 109(3), 203–210. https://doi.org/10.13080/z-a.2022.109.026

Berset, E. et al. (2013). Selektion der soja und deren symbiosepartner auf kühletoleranz und effizienz der biologischen Stickstoff-Fixierung. *Bonn*,13, 122–125.

Biliavska, L.H. (2010). Adaptability of soybean varieties of Poltava breeding under climate change. *Scientific and Technical Bulletin*, 15, 33–38.

Biliavska, L. et al. (2021). Adaptability and breeding value of soybean varieties of Poltava breeding. *Bulgarian Journal of Agricultural Science*, 27(2), 312–322.

Eberhart, S.A., & Russell, W.A. (1966). Stability parameters for comparing varieties. *Crop Science*, 6(1), 36–37. https://doi.org/10.2135/cropsci1966.0011183X000600010011x

Griffing, B. (1950). Analysis of guatitative gene-acrion by constant parent regression and related techniques. *Genetics*, 35, 303–321.

Honcharuk, I. et al. (2022). Peculiarities of reproduction of Pinus Nigra arn. *Bulletin of the Transilvania University of Brasov, Series II: Forestry, Wood Industry, Agricultural Food Engineering*, 15(1), 33–42. https://doi.org/10.31926/but.fwiafe.2022.15.64.1.3

Kaletnik, G., & Lutkovska, S. (2020). Innovative Environmental Strategy for Sustainable Development. *European Journal of Sustainable Development*, 9(2), 89–98. https://doi.org/10.14207/ejsd.2020.v9n2p89

Kovbasa, V. et al. (2021). Functions derivation of stresses in the soil and resistance forces to the motion of a plough share for cavity creation. *UPB Scientific Bulletin, Series D: Mechanical Engineering*, 83(3), 305–318.

Lee, Ch. et al. (2014). Soybean variety selection. *Agriculture and Natural Resources Publications*, 3(133), 1–6.

Mazur, O. et al. (2022). Garden pea yield and its quality indicators depending on the technological methods of growing in conditions of Vinnytsia region. *Acta Fytotechnica et Zootechnica*, 25(3), 226–241. https://doi.org/10.15414/afz.2022.25.03.226-241

Mazur, V.A. et al. (2019). Influence of the assimilation apparatus and productivity of white lupine plants. *Agronomy Research*, 17(1), 206–219.

Mazur, V. et al. (2021a). Agroecological stability of cultivars of sparsely distributed legumes in the context of climate change. *Scientific Horizons*, 24(1), 54–60. https://doi.org/10.48077/scihor.24(1).2021.54-60

Mazur, V. et al. (2021b). Ecological suitability peas (*Pisum sativum*) varieties to climate change in Ukraine. *Agraarteadus*, 32(2), 276–283. https://doi.org/10.15159/jas.21.26

Palamarchuk, V., & Telekalo, N. (2018). The effect of seed size and seeding depth on the components of maize yield structure. *Bulgarian Journal of Agricultural Science*, 24(5), 785–792.

Paziuk, V. et al. (2021). Substantiation of the energy efficient schedules of drying grain seeds. *Bulletin of the Transilvania University of Braşov. Series II: Forestry, Wood Industry, Agricultural Food Engineering*, 14(2), 137–146. https://doi.org/10.31926/but.fwiafe.2021.14.63.2.13

Peltonen-Sainio, P. et al. (2009). Are there indications of climate change induced increases in variability of major field crops in the northernmost European conditions? *Agricultural and Food Science*, 18(3-4), 206–222. https://doi.org/10.2137/145960609790059424

Poberezhets, J. et al. (2021). Effect of probiotic supplement on nutrient digestibility and production traits on broiler chicken. *Agraarteadus*, 32(2), 296–302. https://doi.org/10.15159/jas.21.28

Riabukha, S.S., & Kobyzieva, L.N. (2010). Soybean breeding and seed production. In Kyrychenko, V.V. (ed.) *Special selection and seed production of field crops*. Plant Production Institute named after V.Ya. Yuriev of NAAS (pp. 336–378).

Roux, S., & Wehling, P. (2012). Beitrage der Pflanzenzuchtung zum Klimaschutz und zur Anpassung an den Klimawandel. *Journal of Cultivated Plants*, 64(8), 286–294. https://doi.org/10.5073/JfK.2012.08.02

Schori, A. et al. (2003). Soybean: selection, agronomie et production en Suisse. *Revue suisse d'Agriculture*, 35(2), 69–76.

Silva, K.B. et al. (2017). Adaptability and stability of soybean cultivars for grain yield and seed quality. *Genetics and Molecular Research*, 16(2), 1–15.

Tai, G.C.C. (1971). Genotypic stability analysis and its applikcation to potato regional trials. *Crop. Sci.*, 11(2), 184–185. https://doi.org/10.2135/cropsci1971.0011183X001100020006x

Volkodav, V.V. (2001). *Methods of the state varietal testing of crops*. Alefa.

Vollmann, J. et al. (2005). *Anpassung der sojabohne an besondere qualitätsanforderungen*. Tagung 2005 der Vereinigung der Pflanzenzüchter und Saatgutkaufleute Österreichs HBLFA Raumberg – Gumpenstein (pp. 47–51).

Wolf, V.G. et al. (1980). *Methodical recommendations on the application of mathematical methods for the analysis of experimental data on the study of combinatorial ability*. HSSU.

Zhou, J. et al. (2022). Improve Soybean Variety Selection Accuracy Using UAV-Based High-Throughput Phenotyping Technology. *Frontiers in Plant Science*. 12, 1–14.