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Original Paper

Application Of Selection Indices For Creation Of Soybean Cultivars With Increased Drought Tolerance And Yield

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The article is devoted to the differentiation of soybean cultivars by yield levels in different years according to the hydrothermal regime and a number of indices which characterize the samples' resistance to drought. The research identifies genotypes with high and low levels of drought tolerance by various indices. The best soybean samples with high levels of drought tolerance have been distinguished according to the complex of indices, namely: Artemida, according to such indices as TOL, YRR, SSI, SSPI, YSI, ISR; Kniazhna – MP, YI, GMP, HMP, STI, DI, RDI, with the formation of a high yield; ♀ 284/88 x ♂ Vinnychanka, ♀ 4912/88 x ♂ Osoblyva – MP, TOL, YRR, SSI, SSPI, YI, YSI, HMP, GMP, STI, ISR, DI, RDI, with the formation of a high yield; Canatto – MP, YI, GMP, HMP, STI, DI, RDI, ATI, with the formation of a high yield; Kabott – MP, YI, GMP, HMP, STI, DI, RDI; Roksolana – MP, YI, GMP, HMP, STI, DI, RDI, ATI, with the formation of a high yield, under favorable and unfavorable conditions; Femida – TOL, YRR, SSI, SSPI, YSI, ISR; Vezha − TOL, YRR, SSI, SSPI, YSI, ISR; Kyivska 98 – MP, YI, GMP, HMP, STI, DI, RDI with the formation of a high yield, both under better and worse conditions; ♀ Zolotysta x ♂ WU 19 – MP, YI, GMP, HMP, STI, DI, RDI, with the formation of a high yield, as in the case with better conditions.

Keywords: soybean, selection indices, yield, drought tolerance, stress

1 Introduction

Modern soybean variety selection is aimed at increasing the yields, resistance to bio- and abiotic factors, optimizing the growing season, improving the commercial and technological qualities of seeds, and suitability for intensification of cultivation. New varieties are characterized by high homeostasis, reduced photoperiodic reaction, high productivity of photosynthesis and enzyme systems, the capacity to respond to fertilization by the synthesis of high-quality proteins, resistance to lodging, determinant or semi-determinant growth type, optimal branching, clusters with a large number of beans, well-grained beans and medium weight seeds (Mazur O. et al., 2023a).

The selection focused on increasing the yield involves the creation of grain and grain-mowing (universal) varieties of intensive type with soybean seed yield ranged from 3.5 to 4.0 t/ha for rainfed conditions, and 4.0–4.5 t/ha for irrigation conditions (Mazur V. et al., 2019; Mazur O. et al., 2023b).

Soybean variety selection envisages individual and mass selection, remote and intraspecific hybridization, experimental mutagenesis and a combination of these distinguished methods are most often used, genetic engineering methods, and heterosis selection (Carroll et al., 1985).

Selection in the breeding nursery F2 and F3, relies on both visual assessment and plant productivity or crop components, was considered by S. Boroievych to be ineffective and unreliable (Boroievich, 1990). The main traits for plant selection at the initial stages are the number of productive nodes, beans per node and the number of seeds in a bean, the number of beans per node, the number of beans per plant, seeds in a bean and the weight of 1000 seeds (Mazur V. et al., 2021a).

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The moisture loss because of evapotranspiration is gradually increasing, and this tendency will only get worse sooner or later, so the decrease in yield is the main challenge and, simultaneously, the basis for strengthening the selection process to adapt crops to climate change and, accordingly, rise their productivity under stressful conditions (Mazur V. et al., 2021b).

Identification and creation of drought-resistant genotypes belong to main tasks of selection programs, but the development of high-yielding varieties and the realization of their yield potential in arid conditions is an extremely difficult task for plant breeders. The development of drought-tolerant cultivars is hindered by low heritability of traits and the lack of effective selection strategies (Mazur V. et al., 2023).

The selection of drought-tolerant cultivars is quite difficult because of strong interactions between the environment and genotypes and limited knowledge about the role and functions of resistance mechanisms. Various methods are used to assess genetic modifications in drought tolerance. Some researchers believe that genotype selection should be carried out only in favorable conditions, while others – in arid environments (Betran et al., 2003; Branitskyi et al., 2022).

However, there are many researchers who use genotype selection in stressful and favorable conditions. Drought sensitivity of plants is defined as a function of reducing the yield under water stress compared to the potential yield (Clarke et al., 1992).

Consequently, to distinguish genotypes by drought resistance, different selection indices are used, which are based on plant productivity in stressful and optimal conditions, for the selection of drought-tolerant genotypes (Mazur O. et al., 2023a; Vdovenko et al., 2024).

In late 20th century and in the last decade, the segment of drought phenomena on the territory of Ukraine, and also in Europe on the whole, has increased meaningfully, and therefore the issue of combating such a negative phenomenon is gaining relevance (Mazur O. et al., 2023a).

Plants' response to water stress is determined by a number of factors, such as the stage of development, the duration and severity of the stress, and the genetic characteristics of the cultivar (Beltrano and Marta, 2008). CIMMYT researchers expanded the concept of drought tolerance as the yield ratio under the same drought conditions in different cultivar and proposed to consider it at the genetic level (Ribaut and Poland, 1999). In solving the problem of drought resistance, an adaptive cultivar is the cheapest and most accessible means of increasing yields in conditions of water scarcity (Mazur O. et al., 2023a).

Since direct assessment of the level of plants' agronomic drought tolerance is a time-consuming and laborious task, indirect laboratory methods for assessing biological resistance by physiological, anatomical, morphological and biochemical indicators are widely used in selection and introduction practice. These approaches consist in application of the biological property associated with this trait, but not in using the resistance to lack of moisture itself. Nowadays there are a number of indirect methods for assessing the drought tolerance of plants (Mazur O. et al., 2023a).

The most complete and objective indicator of a plant's drought tolerance is its yield under conditions of water scarcity. To identify drought-tolerant cultivars in the field, several selection criteria have been proposed for providing the determination of grain yield in stressful and non-stressful conditions – resistance and susceptibility of genotypes to the effects of water scarcity. At the same time, a quantitative measure of drought tolerance is considered to be the degree of decrease in productivity under extreme conditions, compared to optimal growing conditions (Talebi et al., 2009).

According to the classification of (Fernandez, 1992) genotypes, depending on their yield under stressful and optimal conditions, are divided into four groups: 1) genotypes which demonstrate superiority under both conditions; 2) genotypes which have high indicators only under optimal conditions; 3) genotypes which are better only under stressful conditions; 4) genotypes with negative properties under both stressful and optimal conditions. It is worth mentioning that plants' drought tolerance is a relative characteristic, and to determine it the classification of cultivars is often used in selection practice.

In order to research cultivars by their response to drought, nowadays Ukrainian and foreign scientists widely use the index approach, that is based on samples' resistance and sensitivity to water stress. Drought tolerance indices, which cover the level of yield loss due to drought in comparison with optimal conditions, are applied to select drought-tolerant cultivars. They serve as indicators that comprehensively characterize the degree of decrease in plant yields against the dry soil compared to the wet soil. Determination of the cultivars' selective value by drought tolerance indices in case of increasing water deficit or rising temperature enables characterizing the level of their adaptability objectively and forecast their behavior in suitable environmental conditions. The literature describes a large number of drought tolerance indices, which are widely applied for various crops. The researchers compared these indicators with each other and studied their genetic parameters (Farshadfar and Sutka, 2003).

Comparing the yield estimates of the soybean cultivars in the competitive trial with the yield estimates of their initial samples in the breeding nursery shows the inefficiency of the selection of highly productive genotypes at the stage of small plots by direct indicators – the weight of seeds per plot or yield. While selecting soybeans for yield at the stage of small plots, it is noteworthy to use the harvest index as a criterion for selecting it, which has a significant positive relationship with the coenotic yield (Mazur O. et al., 2023a).

Besides direct estimates of the cultivars by yield, there are a number of indirect indicators for the selection of high-yielding genotypes at the early stages, among which the harvest index is most often distinguished (Mazur O. et al., 2023b).

Proposed the stress susceptibility index (SSI) in cereal crops, that typifies the level of sensitivity of a cultivar sample to various stress factors, including drought. This indicator helps to assess the relative susceptibility of each genotype in the research set, so the lower it is, the higher the drought tolerance level of the sample is (Fisher and Maurer, 1978).

Using SSI, found out significant differences in this indicator by years and ranked wheat genotypes by drought tolerance (Clarke et al., 1992).

Introduced an extended indicator called the Stress Tolerance Index (STI), which is applied to identify genotypes with high yields under both stressful and optimal conditions (Fernandez, 1992). This indicator characterizes the ability of the sample to maintain a stable level of yield regardless of stress factors. Some authors have used the stress tolerance index to determine drought tolerance in high-yielding varieties. Proposed the Modified Stress Tolerance Index (MSTI) by adjusting STI as mass (Farshadfar and Sutka, 2003).

The scientists proposed such indices as tolerance (TOL) – the difference in yield under non-stress and stress conditions, and medium productivity (MP) – the average yield of genotypes under stressful and optimal conditions. The TOL index indicates the loss of yield in absolute units because of drought, and its higher values demonstrate susceptibility to water stress. The medium productivity characterizes the potential yield of the genotype in dry and optimal years. The maximum values of MP and STI characterize the high selection value of genotypes, as evidenced by numerous researches (Rosielle and Hamblin, 1981).

The Yield Stability Index (YSI), is applied to assess the drought tolerance of soybean cultivars (Bouslama and Schapaugh 1984). This indicator is defined as the ratio of the yield under stress to the yield under optimal conditions. The application of the TOL and YSI indices assumes that selected on their basis genotypes will have the desired selection value under both stressful and optimal conditions (Sanjar and Yazdan, 2008). The stress yield index (YI) was introduced for the analysis of cereal crops, which is determined by the ratio of the yield of a cultivar under the influence of a stress factor to the average yield of the researched genotypes under similar conditions (Gavuzzi et al., 1997).

Scientists proved that the MP and STI indices are quite effective for the selection of valuable cultivars and represent the same ranking of genotypes by drought resistance. The selection by the TOL index turned out to be quite effective for the selection of stress-resistant cultivars, but with lower yields. The authors concluded that in the process of searching genotypes with maximum breeding value, the most important indices are MP, STI, TOL, YI and YSI.

The relative drought index (RDI) was suggested as a reliable indicator for determining the stress tolerance of varieties (Fisher and Maurer, 1978). The Drought Tolerance Index (DI) was proposed for determining genotypes with high yields under both stressful and optimal conditions. Geometric mean productivity (GMP) is often applied by breeders looking for relative productivity, as drought stress can differ due to severity over years (Lan, 1998).

The stress/non-stress production index (SNPI), stress susceptibility percentage index (SSPI) and abiotic tolerance index (ATI) were introduced to screen drought-tolerant genotypes in non-stress and stress conditions (Moosavi et al., 2008).

Soft wheat cultivars were used to find out significant positive correlations between grain yield in stress conditions (Ys) and STI, GMP, MP, HM indices, also between optimal yields (Yp) and STI, MP, GMP, TOL, HM, SSI indices. Simultaneously, a significant inverse relationship was noticed between Yp and YSI, DI (Lan, 1998; Moosavi et al., 2008).

The conducted researches (Mardeh et al., 2006) and correlation analysis evidenced a significant positive relationship between Yp and TOL, SSI, YRR indicators and a significant negative correlation of these indices with the value Ys. they also found out that cultivar selection on the basis of TOL, SSI and YRR low values can lead to a yield increase in drought conditions and a yield decrease in optimal conditions.

The main advantages of the method of assessing drought tolerance in the application of the distinguished indices include the availability of the necessary data, the ability to study a large number of cultivars, the simplicity of calculations and determination of the yield – the most significant agronomic characteristic.

It is worth mentioning that calculation of all indices requires no more than four parameters – the yield of the cultivar under drought conditions and in a zone of sufficient moisture, and the average yield of cultivars under these conditions. The average yields of a group of cultivars are also used to characterize environmental conditions, the level of drought intensity, at the same time yield levels characterize the response of individual genotypes to the environmental impacts of drought (Mardeh et al., 2006).

Drought tolerance indices do not provide information about stress response mechanisms, which may differ depending on the genotype, so this can be attributed to disadvantages. It should be also noted that assessment of plant tolerance in a field is often a rather laborious task, it takes quite a long time, requires appropriate environmental conditions for the effective phenotypic manifestation of the desired trait, and therefore involves the use of significant material resources. The complexity of this method also lies in the spatial heterogeneity of the physical and chemical properties of the soil, as well as seasonal fluctuations in the amount of precipitation.
The purpose of the research deals with the identification of the best breeding samples of soybeans using breeding indices to form the starting material of synthetic selection in the creation of new productive and drought-resistant varieties, allocation of selection indices, the use of which is effective in the selection of soybeans for drought resistance.

2 Conditions and research methods

The researche were conducted on the experimental plots of the Department of Plant Production, Breeding and Bioenergy Crops of Vinnytsia National Agrarian University during a period of 2012-2021, which differed significantly in terms of hydrothermal conditions (figure 1). Among the research years to compare we have chosen two years: 2015 – dry (124 mm of rainfall during the growing season, HTC=0.5) and 2018 – optimal (total rainfall – 348 mm, HTC=1.5).

This enabled us to determine the response of soybean cultivars to the variability of environmental conditions. Soil differences in the experimental area were represented by gray forest soils.

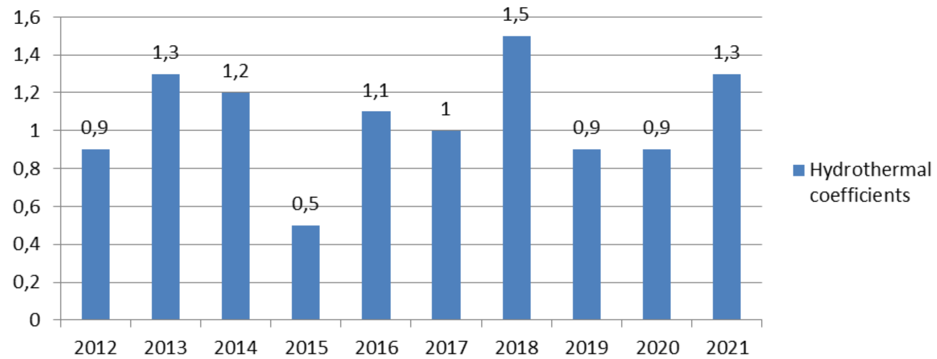

Fig. 1 Hydrothermal coefficients during the growing season (BBCH-10-99) (May–September) 2012–2021

Phenological observations and analysis of the yield's structural elements were conducted according to the (Volkodav, 2001).

Sowing of the nursery plant breeding began in the first decade of May manually with a row spacing of 45 cm on an area of 2.7 m^2. The repetition is 4-fold. The hybrid nursery was sown manually in the first decade of May. The row spacing is 45 cm, the distance between plants in a row is 10 cm. The area of the plot is 2.25 m^2. The repetition is 4-fold. The analysis of the soybean cultivars' resistance to stress conditions was carried out according to the indicators of fourteen drought tolerance indices: MP, TOL, YRR, SSI, SSPI, YI, YSI, GMP, HMR, STI, DI, RDI, ATI, ISR.

Yield and drought tolerance were calculated by application of different indices (Rosielle and Hamblin, 1981):

$$MP=\frac{Yp+Ys}{2}, \quad (1)$$

where MP – medium productivity; Yp – yield under optimal conditions; Ys − yield under stress conditions.

$$TOL= Yp – Ys, \quad (2)$$

where TOL – drought tolerance index (Rosielle and Hamblin, 1981).

$$YRR = 1 – \frac{Ys}{Yp}, \quad 3)$$

where YRR − yield reduction ratio (Golestani-Araghi and Assad, 1998).

$$SSI = (1–\frac{Ys}{Yp})/(1–\frac{\bar{Y}s}{\bar{Y}p}), \quad (4)$$

where SSI – stress susceptibility index; Ȳs – average yield of all cultivars under optimal conditions; Ȳp – average yield of all cultivars under stress conditions (Fisher and Maurer, 1978).

$$SSPI = [(Yp-Ys)/2\bar{Y}p]\times100\%, \quad (5)$$

where SSPI – stress susceptibility percentage index (Moosavi et al. 2008).

$$YSI = \frac{Ys}{Yp} \quad (6)$$

where YSI − yield stability index (Bouslama and Schapaugh,1984).

$$YI = \frac{Ys}{\bar{Y}s} \times100\%, \quad (7)$$

YI − yield index (Gavuzzi et al. 1997).

$$GMP = \sqrt{(Yp\times Ys)}, \quad (8)$$

GMP − geometric mean productivity (Fernandez,1992).

$$HMP = \frac{2(Yp\times Ys)}{(Yp+Ys)}, \quad (9)$$

HMP − harmonic mean productivity (Kristin et al. 1997).

$$STI = \frac{(Yp\times Ys)}{(\bar{Y}p)^2}, \quad (10)$$

where STI – stress tolerance index (Fernandez,1992).

$$DI = \frac{[Ys\times(\frac{Ys}{Yp})]}{\bar{Y}s}, \quad (11)$$

where DI – Drought Tolerance Index (DI) (Lan, 1998).

$$RDI = \frac{(Ys/Yp)}{(\bar{Y}s/\bar{Y}p)}, \quad (12)$$

where RDI – relative drought index (Fischer and Maurer, 1978).

$$ATI = [(Yp-Ys)/(\bar{Y}p/\bar{Y}s)]\times[\sqrt{(Yp\times Ys)}], \quad (13)$$

where ATI − abiotic tolerance index (Moosavi et al. 2008).

$$ISR= \frac{(Yp\times Ys)}{[(Yp-Ys)\times(1-Ys/Yp)],} \quad (14)$$

where ISR − integrated stress response (Tyshchenko A., Tyshchenko O., Liuta Yu., 2021).

3 Experimental research results

In the selection of leguminous plants for drought tolerance, not only the high drought tolerance of plants plays an important role as the plants' capacity to tolerate significant overheating and dehydration and survive during drought with the slightest decrease in yield, but also the formation of the maximum yield in stress conditions.

Medium productivity (MP) indicates its realization by the genotype in both favorable and unfavorable hydrothermal conditions of cultivation. Thus, higher values (MP) are confirmation of the high yield potential of the samples. According to this value, the best soybean cultivars have been selected (Table 1): ♀ 284/88 x ♂ Vinnychanka – 2.39, ♀ 4912/88 x ♂ Osoblyva – 2.32, Vinnychanka – 2.21, ♀ Chandr x ♂ Podilska 1 – 2.15 t/ha. Consequently, these samples have provided high yields, both under unfavorable and favorable growing conditions.

The drought tolerance index (TOL), yield reduction ratio (YRR), stress susceptibility index (SSI), and stress susceptibility percentage index (SSPI) are similar in nature and indicate the loss of yield caused by drought: the first and second in absolute values, the third in percentages.

It is worth to emphasize that the lowest values of the yield reduction ratio (YRR), stress susceptibility index (SSI) and stress susceptibility percentage index (SSPI) were observed in samples which did not show a high level of average yield, but were characterized by the lowest yield loss under unfavorable growing conditions.

Table 1 The best soybean cultivars selected according to the yield reduction ratio (YRR), stress susceptibility index (SSI), stress susceptibility percentage index (SSPI) and yield stability index (YSI)

These cultivars included the following samples: Artemida – 0.29; 0.75; 11.95, Femida – 0.30; 0.77; 11.58; Amethyst – 0.31; 0.79; 12.50; Oriana – 0.31; 0.79; 11.40; Vezha – 0.32; 0.82; 12.87; Zolotysta – 0.32; 0.83; 12.50. It should be noted that soybean cultivars with the highest medium productivity

Cultivars	Yield, t/ha				Indices			
	Ys	Yp	MP	TOL	YRR	SSI	SSPI	YSI
Artemida	1.55	2.20	1.88	0.65	0.29	0,75	11.95	0.70
Femida	1.47	2.10	1.79	0.63	0.30	0.77	11.58	0.70
Amethyst	1.52	2.20	1.86	0.68	0.31	0.79	12.50	0.69
Oriana	1.38	2.00	1.69	0.62	0.31	0.79	11.40	0.69
Vezha	1.50	2.20	1.85	0.70	0.32	0.82	12.87	0.68
Zolotysta	1.42	2.10	1.76	0.68	0.32	0.83	12.50	0.67
♀ 284/88 x ♂ Vinnychanka	1.91	2.87	2.39	0.96	0.33	0.85	17.65	0.67
Podilska 1	1.65	2.54	2.10	0.89	0.35	0.89	16,36	0.65
♀ 4912/88 x ♂ Osoblyva	1.83	2.81	2.32	0.98	0.35	0.89	18.02	0.65
♀ Chandr x ♂ Podilska 1	1,68	2,61	2.15	0.93	0.35	0.91	17.10	0.64
Vinnychanka (st)	1.71	2.70	2.21	0.99	0.36	0.93	18,20	0.63
Osoblyva	1.59	2.52	2.06	0.93	0.36	0.94	17.10	0.63
Average	1.6	2.40	2.0	0.8				
S	0.16	0.30	0.23	0.15				
S absolute	0.05	0.08	0.07	0.04				
S relative	2.91	3.65	3.33	5.5				
V, %	10.1	12.6	11.5	19.1				
$LSD_{0.05}$	0.12	0.15	0.14	0.13				
$LSD_{0.01}$	0.21	0.27	0.25	0.23				

(MP) did not have low values of the yield reduction ratio (YRR), stress susceptibility index (SSI) and stress susceptibility percentage index (SSPI). Thus, these indicators turned out to be higher and amounted to: ♀ 284/88 x ♂ Vinnychanka – 0.33; 0.85; 17.65; ♀ 4912/88 x ♂ Osoblyva – 0.35; 0.89; 18.02; ♀ Chandr x ♂ Podilska 1 – 0.35; 0.91 and 17.1; Vinnychanka – 0.36: 0.93 and 18.20. Consequently, the best samples with low yield loss, both in absolute values (TOL) and as a percentage (SSPI), did not have a high level of medium productivity (MP). Particularly, Artemida – 1.88, Femida – 1.79, Amethyst – 1.86, Oriana – 1.69; Vezha – 1.85; Zolotysta – 1.76 t/ha. Moreover, these samples had the lowest drought tolerance index (TOL), i.e., they had the lowest decrease in yield under the influence of drought, in particular: Artemida – 0.65, Femida – 0.63, Amethyst – 0.68, Oriana – 0.62; Vezha – 0.70; Zolotysta – 0.68 t/ha. Therefore, low TOL and SSPI values mean high stress tolerance, but there is a very high probability that higher-yielding soybean samples under stress conditions, although the have higher TOL and SSPI indices, may not be identified as drought tolerant. Our research results have been also confirmed by the experimental data obtained by scientists (Tyshchenko et al., 2021).

Furthermore, researching the drought tolerance indices of maize, detailed that a low tolerance index (TOL) does not certainly mean a high yield of a cultivar in stress conditions, since the yield of a particular variety can be low in optimal conditions and display a smaller reduction in yield while stress (Moghaddam and Hadizadeh, 2002).

Analyzing the yield stability index (YSI), i. e. the ratio of the yield level under stress to the yield level in favorable conditions, with ranged from 0.63 to 0.70 for the following soybean cultivars: Artemida – 0.70, Femida – 0.70, Amethyst – 0.69, Oriana – 0.69; Vezha – 0.68, Zolotysta – 0.67, ♀ 284/88 x ♂ Vinnychanka – 0.67. However, among the selected samples, only Artemida, Amethyst and ♀ 284/88 x ♂ Vinnychanka formed a higher level of yield under unfavorable conditions – 1.55; 1.52; 1.91 t/ha, and under favorable growing conditions a high level of yield (2.87 t/ha) was formed in case of ♀ 284/88 x ♂ Vinnychanka, and Artemida and Amethyst gave low yield (2.20 t/ha), which led to high index values. This means that the YSI index should be used only in comparison with others, because higher-yielding samples in drought conditions may not be included in the drought-tolerant group.

Thus, on the bases of the research results the evaluation of soybean samples by the breeding indices of yield reduction ratio (YRR), stress susceptibility index (SSI) and yield stability index (YSI) of soybean samples provided the most synchronous arrangement of the sequence of breeding value of soybean samples in terms of drought tolerance. In our opinion, this will enable the purposeful and comprehensive application of these indices in drought tolerance breeding.

The geometric mean productivity (GMP), yield index (YI) and harmonic mean productivity (HMP) indicate the yield of a particular sample under unfavorable growing conditions compared to the average yield of samples researched under these conditions, but they are calculated using different formulas.

According to these indices, the Kniazhna cultivar stood out with indicators 116.90, 2.44, 2.38; ♀ 284/88 x ♂ Vinnychanka – 115.20, 2.34, 2.29; Canatto – 114.60, 2.41, 2.34; Roksolana – 114.50, 2.41, 2.34; Kyivska-98 – 114.00, 2.39, 2.32, respectively. In our opinion, these indices most fully characterize the cultivars' drought tolerance, as well as the high level of yield under stress: Kniazhna – 1.94; ♀ 284/88 x ♂ Vinnychanka – 1.91; Canatto – 1.90; Roksolana – 1.90; Kyivska-98 – 1.89 t/ha. A significant increase in the level of yield under favorable growing conditions was also observed: Kniazhna – 3.08; Canatto – 3.06; Roksolana – 3.05; Kyivska-98 – 3.02 t/ha (Table 2).

The stress tolerance index (STI) with a range of variability from 0.70 to 0.81 characterizes the genotypes capacity to form a stable level of yield despite stressors.

Scientists recommend applying the stress tolerance index (STI) to screen high-yielding genotypes in both stress and non-stress conditions, they also advise using it in breeding programs (Fernandez, 1992).

According to this indicator, the following samples stood out: Kniazhna – 0.81, Canatto – 0.79, Viktoryna – 0.79, Roksolana – 0.78, Kyivska -98 – 0.77, Kabott – 0.77.

Thus, the selected soybean cultivars formed the highest level of yield, both under favorable and unfavorable growing conditions, namely, Kniazhna – 1.94 and 3.08, Canatto – 1.90 and 3.06, Viktoryna – 1.89 and 3.11, Roksolana – 1.90 and 3.05, Kyivska-98 – 1.89 and 3.00, Kabott – 1.89 and 3.00 t/ha.

The simultaneous use of breeding yield indices (YI) and harmonic productivity (HMP) ensured that soybean samples were arranged in synchronous order according to their breeding value and drought tolerance.

Table 2 The best soybean cultivars selected according to the yield index (YI), geometric mean yield (GMP), harmonic mean productivity (HMP), stress tolerance index (STI)

Cultivars	Yield, t/ha				Indices			
	Ys	Yp	MP	TOL	YI	GMP	HMP	STI
Kniazhna	1.94	3.08	2.51	1.14	116.90	2.44	2.38	0.81
♀ 284/88 x ♂ Vinnychanka	1.91	2.87	2.39	0.96	115.20	2.34	2.29	0.74
Canatto	1.90	3.06	2.48	1.16	114.60	2.41	2.34	0.79
Roksolana	1.90	3.05	2.48	1.15	114.50	2.41	2.34	0.78
Kyivska-98 (st)	1.89	3.02	2.46	1.13	114.00	2.39	2.32	0.77
Kabott	1.89	3.00	2.45	1.11	114.00	2.38	2.32	0.77
Viktoryna	1.89	3.11	2.50	1.22	113.90	2.42	2.35	0.79
4912/88	1.87	2.95	2.41	1.08	112,80	2.35	2.29	0.75
♀ 4912/88 x ♂ Osoblyva	1.83	2.81	2.32	0.98	110.34	2.27	2.21	0.70
Omega Vinnytska	1.83	2.98	2.41	1.15	110.34	2.34	2.27	0.74
♀ Zolotysta x ♂ WU-19	1.82	2.98	2.40	1.16	109.74	2.33	2.26	0.73
Myth	1.80	3.10	2.45	1.30	108.53	2.36	2.28	0.75
Diadema	1.80	2.95	2.38	1.15	108.53	2.30	2.24	0.72
Pysanka	1.80	2.96	2.38	1.16	108.53	2.31	2.24	0.72
Biliavka	1.80	2.97	2.39	1.17	108.53	2.31	2.24	0.72
Terek	1.80	2.98	2.39	1.18	108.53	2.31	2.24	0.72
Average	1.85	2.99	2.42	1.13				
S	0.05	0.08	0.05	0.80				
S absolute	0.01	0.02	0.01	0.02				
S relative	0.65	0.66	0.54	1.78				
V, %	2.63	2.67	2.16	7.12				
$LSD_{0.05}$	0.13	0.12	0.14	0.1				
$LSD_{0.01}$	0.24	0.22	0.26	0.18				

According to the drought tolerance index (DI), which is used to determine genotypes with high yields both under stress conditions and optimal, as well as the relative drought index (RDI), which is a reliable indicator for determining the stress tolerance of cultivars, the following samples have stood out: ♀ 284/88 x ♂ Vinnychanka – 0.77 and 1.09; Kniazhna – 0.74 and 1.03; ♀ 4912/88 x ♂ Osoblyva – 0.72 and 1.07; Kabott – 0.72 and 1.03; 4912/88 – 0.71 and 1.04; Kyivska-98 – 0.71 and 1.03; Canatto – 0.71 and 1.02; Roksolana – 0.71 and 1.02. It should be noted that these samples provided the highest level of yield under unfavorable growing conditions: ♀ 284/88 x ♂ Vinnychanka – 1.91, Kniazhna – 1.94, Kabott – 1.89, 4912/88 – 1.87, Kyivska-98 – 1.89, Canatto – 1.90, Roksolana – 1.90, Victoryna – 1.89 t/ha (Table 3).

Moreover, low yield loss under the drought influence in absolute values (TOL) was typical for soybean cultivars with a high relative drought index (RDI).

In particular, for such samples: Artemida – 1.16, ♀ 284/88 x ♂ Vinnychanka – 1.09, ♀ 4912/88 x ♂ Osoblyva – 1.07, 4912/88 – 1.04, Anthracite – 1.04.

The yield loss in these cultivars was the smallest among the presented soybean samples and amounted to: Artemida – 0.65, ♀ 284/88 x ♂ Vinnychanka – 0.96, ♀ 4912/88 x ♂ Osoblyva – 0.98, 4912/88 – 1.08, Anthracite – 1.02 t/ha.

According to the obtained research results, the use of the drought index (DI) and the mean productivity index (MP) will ensure the consistent placement of soybean samples by breeding value before drought. The application of the reconnaissance drought index (RDI) and the tolerance index (TOL) will provide minimal yield losses due to drought at the maximum expression of the first index.

Table 3 The best soybean cultivars selected according to the drought tolerance (DI) and relative drought tolerance (RDI) indices

Cultivars	Yield, t/ha				Indices	
	Ys	Yp	MP	TOL	DI	RDI
♀ 284/88 x ♂ Vinnychanka	1.91	2.87	2.39	0.96	0.77	1.09
Kniazhna	1.94	3.08	2.51	1.14	0.74	1.03
♀ 4912/88 x ♂ Osoblyva	1.83	2.81	2.32	0.98	0.72	1.07
Kabott	1.89	3.00	2.45	1.11	0.72	1.03
4912/88	1.87	2.95	2.41	1.08	0.71	1.04
Kyivska-98 (st)	1.89	3.02	2.46	1.13	0.71	1.03
Canatto	1.90	3.06	2.48	1.16	0.71	1.02
Roksolana	1.90	3.05	2.48	1.15	0.71	1.02
Victoryna	1.89	3.11	2.50	1.22	0.69	0.99
Almaz	1.80	2.85	2.33	1.05	0.69	1.03
Omega Vinnytska	1.83	2.98	2.41	1.15	0.68	1.00
Anthracite	1.77	2.79	2.28	1.02	0.68	1.04
Annushka	1.78	2.86	2.32	1.08	0.67	1.02
♀ Zolotysta x ♂ WU-19	1.82	2.98	2.40	1.16	0.67	1.00
Diadema	1.80	2.95	2.38	1.15	0.66	1.00
Artemida	1.55	2.20	1.88	0.65	0.66	1.16
Average	1.83	2.91	2.37	1.07		
S	0.09	0.21	0.15	0.13		
S absolute	0.02	0.05	0.04	0.03		
S relative	1.25	1.82	1.57	3.1		
V, %	5.0	7.3	6.3	12.4		
$LSD_{0.05}$	0.13	0.12	0.13	0.12		
$LSD_{0.01}$	0.23	0.21	0.24	0.21		

The abiotic tolerance index (ATI) ranged from 1.69 to 1.87 (Table 4). In some cultivars the highest values of this index are connected with the maximum yield under favorable growing conditions, and in other samples they are related to the maximum yield under unfavorable growing conditions. The highest indicators of the abiotic tolerance index were observed in the following soybean cultivars: Myth – 1.87, and a high level of yield under favorable growing conditions – 3.10 t/ha.

The sample ♀ Medea x ♂ Hoverla – 1.82, had a high level of yield under the worst conditions – 1.90 t/ha, Viktoryna – 1.80, the highest level of yield under the best conditions – 3.11 t/ha, ♀ Kyivska 97 x ♂ Hoverla – 1.75 and the maximum level of yield under unfavorable growing conditions – 1.92 t/ha, Canatto – 1.90, as well as the highest yield levels in our researches under both favorable and unfavorable growing conditions (3.06 and 1.90 t/ha), and the highest average yield (2.48 t/ha). This also applies to the Roksolana cultivar – 1.69, as well as high yield levels under both favorable and unfavorable growing conditions (3.05 and 1.90 t/ha).

In our opinion, the abiotic tolerance index (ATI) characterizes the selected cultivars under both the best and worst growing conditions. However, the synchronous dependence of its value and quantitative indices of the yield level in, both under favourable and unfavourable growing conditions, and indicators of average yield was not noted.

Having analyzed the research results, we have determined the integrated stress response (ISR), which characterizes the selected cultivars in terms of stress resistance not by a smaller yield difference under better and worse conditions. ISR takes into consideration the formation of a high level of yield under stress too.

Thus, the samples of soybean cultivars with the highest values of the integrated stress response (ISR) were characterized by the lowest yield loss when grown under unfavorable growing conditions compared to growing them under optimal hydrothermal conditions (Table 5).

Table 4 The best soybean cultivars selected according to the abiotic tolerance index (ATI)

Cultivars	Yield, t/ha				Indices
	Ys	Yp	MP	TOL	ATI
Myth	1.80	3.10	2.45	1.30	1.87
♀ Kyivska 97 x ♂ KyVin	1.86	2.94	2.40	1.08	1.83
♀ Medea x ♂ Hoverla	1.90	2.96	2.43	1.06	1.82
Viktoryna	1.89	3.11	2.50	1.22	1.80
♀ Ustia x ♂ Hoverla	1.79	2.87	2.33	1.08	1.77
♀ Kyivska 97 x ♂ Hoverla	1.92	2.94	2.43	1.02	1.75
PSB 8	1.72	2.98	2.35	1.26	1.74
Canatto	1.90	3.06	2.48	1.16	1.71
♀ Soyer2-95 x ♂ Hoverla	1.86	2.88	2.37	1.02	1.71
Roksolana	1.90	3.05	2.48	1.15	1.69
Kyivska-98 (st)	1.89	3.02	2.46	1.13	1.65
Average	1.86	2.99	2.42	1.13	
S	0.06	0.09	0.06	0.09	
S absolute	0.02	0.03	0.02	0.03	
S relative	1.9	0.91	0.75	2.77	
V, %	3.3	2.8	2.3	8.3	
$LSD_{0.05}$	0.12	0.14	0.13	0.11	
$LSD_{0.01}$	0.21	0.25	0.24	0.2	

Table 5 The best soybean cultivars selected according to the integrated stress response (ISR)

Cultivars	Yield, t/ha				Indices
	Ys	Yp	MP	TOL	ISR
Artemida	1.55	2.20	1.88	0.65	17.75
♀ 284/88 x ♂ Vinnychanka	1.91	2.87	2.39	0.96	17.07
Femida	1.47	2.10	1.79	0.63	16.30
♀ Kyivska 97 x ♂ Hoverla	1.92	2.94	2.43	1.02	15.95
Amethyst	1.52	2.20	1.86	0.68	15.91
♀ 4912/88 x ♂ Osoblyva	1.83	2.81	2.32	0.98	15.04
♀ Soyer 2-95 x ♂ Hoverla	1.86	2.88	2.37	1.02	14.82
Vezha	1.50	2.20	1.85	0.70	14.81
♀ Medea x ♂ Hoverla	1.90	2.96	2.43	1.06	14.81
Kyivska-98 (st)	1.89	3.02	2.46	1.13	13.49
Average	1.74	2.62	2.18	0.88	
S	0.2	0.38	0.29	0.19	
S absolute	0.06	0.12	0.09	0.06	
S relative	3.57	4.66	4.21	6.94	
V, %	11.3	14.8	13.3	21.9	
$LSD_{0.05}$	0.13	0.16	0.14	0.1	
$LSD_{0.01}$	0.23	0.29	0.24	0.18	

Thus, the highest values of the integrated stress response (ISR) were observed in the following soybean cultivars: Artemida – 17.75, with yield loss under unfavorable growing conditions – 0.65 t/ha, Femida – 16.30, with yield loss under worse growing conditions – 0.63 t/ha, Amethyst – 15.91, with yield loss under unfavorable growing conditions – 0.68 t/ha, Vezha – 14.81, with yield loss under worse growing conditions – 0.70 t/ha. ♀ 284/88 x ♂ Vinnychanka – 17.07, with yield loss under stress – 0.96 t/ha, ♀ 4912/88 x ♂ Osoblyva – 15.04, with yield loss under worse growing conditions – 0.98 t/ha, ♀ Kyivska 97 x ♂ Hoverla – 15.95, with yield loss – 1.02 t/ha, ♀ Soyer 2-95 x ♂ Hoverla – 14.82, with yield loss – 1.02 t/ha, ♀ Medea x ♂ Hoverla – 14.81, with yield loss – 1.06 t/ha.

4 Conclusions

As the result of the conducted experimental researches, a number of the best soybean cultivars with high levels of drought tolerance have been distinguished according to the complex of indices: Artemida by such indices as TOL, YRR, SSI, SSPI, YSI, ISR; Kniazhna – MP, YI, GMP, HMP, STI, DI, RDI, with the formation of a high yield, both under favorable and unfavorable conditions; ♀ 284/88 x ♂ Vinnychanka, ♀ 4912/88 x ♂ Osoblyva – MP, TOL, YRR, SSI, SSPI, YI, YSI, HMP, GMP, STI, RDI, DI, ISR, with the formation of a high yield, both under better and worse conditions; Canatto – MP, YI, GMP, HMP, STI, DI, RDI, ATI, with the formation of a high yield, both under favorable and unfavorable conditions; Kabott – MP, YI, GMP, HMP, STI, DI, RDI, with the formation of a high level of yield, both under better and worse conditions; Roksolana – MP, YI, GMP, HMP, STI, DI, RDI, ATI, with the formation of a high level of yield, both under favorable and unfavorable conditions; Femida – TOL, YRR, SSI, SSPI, YSI, ISR; Vezha − TOL, YRR, SSI, SSPI, YSI, ISR; Kyivska 98 – MP, YI, GMP, HMP, STI, DI, RDI with the formation of a high level of yield, both under better and worse conditions; ♀ Zolotysta x ♂ WU 19 – MP, YI, GMP, HMP, STI, DI, RDI, with the formation of a high yield, as in the case with better conditions.

Having compared different indices, we came to the conclusion that it is inexpedient to take only one of them, and for a more accurate assessment of genotypes by drought resistance, it is appropriate to use their complex. MP, YI, GMP, HMP, SSI, STI, DI have been selected as the main indices, which can be recommended to apply while assessing breeding material for drought resistance. YSI, RDI, TOL, SSPI, YRR, ISR can be used as supplementary with the main indices. The ATI index cannot be used to analyse genotypes for drought tolerance.

On the basis of the distinguished selection indices the application of the best soybean samples in practice will enable obtaining the starting material for synthetic selection for creation of new productive and drought-tolerant soybean cultivar. Moreover, for selection practice, we recommend using the indices, we have researched, to identify breeding material considering drought tolerance and yield when grown in different hydrothermal conditions.

References

Beltrano J. & Marta G.R. (2008). Improved tolerance of wheat plants (Triticum aestivum L.) to drought stress and rewatering by the arbuscularmycorrhizal fungus Glomusclaroideum: Effect on growth and cell membrane stability. *Brazilian Journal of Plant Physiology*, 20 (1) 29-37. http://dx.doi.org/10.1590/S1677-04202008000100004

Betran F.J. et al. (2003). Genetic analysis of inbred and hybrid grain yield under stress and non-stress environments in tropical maize. *Crop Science*, 43, 807-817. https://doi.org/10.2135/cropsci2003.8070

Boroievich S. 1990. Principles and methods of plant breeding. *Amsterdam New York* : Elsevier. 368 p.

Bouslama M. & Schapaugh W.T. (1984). Stress tolerance in soybean. Part 1: Evaluation of three screening techniques for heat and drought tolerance. *Crop Science*, 24 (5), 933-937.

Branitskyi Y. et al. (2022). Improvement of technological methods of switchgrass (Panicum virgatum L.) growing in the Vinnytsia region. *Acta Fytotechnica et Zootechnica*, 25 (4), 311–318. DOI.org/10.15414/afz.2022.25.04.311-318. https://doi.org/10.15414/afz.2022.25.04.311-318

Carroll B.J. et al. (1985). Isolation and properties of soybean [Glycine max (L.) Merr.] mutants that nodulate in the presence of high nitrate concentrations. *Proc. Natl. Acad. Sci. U.S.A.*, 82, 4162-4166

Clarke J.M. et al. (1992). Evaluation of methods for quantification of drought tolerance in wheat. *Crop Science*, 32 (3), 728–732. https://doi.org/10.2135/cropsci1992.0011183X003200030029x

Farshadfar E. & Sutka J. (2003). Multivariate analysis of drought tolerance in wheat substitution lines. *Cereal Research Communication*, 31 (1), 33-40.

Fernandez G.C.J. (1992). Effective selection criteria for assessing plant stress tolerance. Adaptation of Vegetables and other Food Crops in Temperature and Water Stress: *proceedings of the international symposium*. 13–16 August 1992. Shanhua, 257-270.

Fisher R. A. & Maurer R. (1978). Drought resistance in spring wheat cultivars. 1. Grain yield responses. *Australian Journal of Agricultural Research*, 29 (5), 897-912. http://dx.doi.org/10.1071/AR9780897

Gavuzzi P. et al. (1997). Evaluation of field and laboratory predictors of drought and heat tolerance in winter cereals. *Canadian Journals of Plant Science*, 77 (4), 523-531.

Golestani-Araghi S. & Assad M.T. (1998). Evaluation of four screening techniques for drought resistance and their relationship to yield reduction ratio in wheat. *Euphytica*, 103 (3), 293-299.

Kristin A.S. et al. (1997). Improving common bean performance under drought stress. *Crop Science*, 37 (1), 43-50.

Lan J. (1998). Comparison of evaluating methods for agronomic drought resistance in crops. *Acta Agriculturae Boreali-occidentalis Sinica*, 7, 85-87.

Mardeh A. S. et al. (2006). Evaluation of drought resistance indices under various environmental conditions. *Field Crop Research*, 98 (2), 222-229.

Mazur O. et al. (2023a). Genetic determination of elements of the soybean yield structure and combining ability of hybridization components. *Acta Fytotechnica et Zootechnica*, 26 (2), 163-178. https://doi.org/10.15414/afz.2023.26.02.163-178

Mazur O. et al. (2023b). Ecological plasticity and stability of soybean varieties under climate change in Ukraine. *Acta Fytotechnica et Zootechnica*, 26 (4), 398-411. https://doi.org/10.15414/afz.2023.26.04.398-411

Mazur, V. *et al.* (2021a). Quality of pea seeds and agroecological condition of soil when using structured water. *Scientific Horizons*, 24 (7), 53-60. https://doi.org/10.48077/scihor.24(7).2021.53-60

Mazur, V. *et al.* (2021b). 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.* (2023). Ecological and economic aspects of the formation of highly productive soybean crops. *Journal of Ecological Engineering*. 24(12),124-129. https://doi.org/10.12911/22998993/173008

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

Moghaddam A. & Hadizadeh M.H. (2002). Response of corn (*Zea mays L*.). Hybrids and their parental lines to drought using different stress tolerance indices. J. *Seed and plant improvement*, 18 (3), 255-275.

Moosavi S.S. et al. (2008). Introduction of new indices to identify relative drought tolerance and resistance in wheat genotypes. *Desert (Biaban)*, 12 (2), 165-178.

Ribaut J.-M. & Poland D. (1999). Molecular approaches for the genetic improvement of cereals for stable production in water-limited environments. A *Strategic Planning Workshop held at CIMMYT. CIMMYT Publishing*, El Batan.

Rosielle A.A. & Hamblin J. (1981). Theoretical aspects of selection for yield in stress and non-stress environments. *Crop Science*, 21 (6), 943-946.

Sanjar P.E.A. & Yazdan S.A. (2008). Evaluation of wheat (Triticum aestivum L.) genotypes under pre- and post-anthesis drought stress conditions. *Journal of Agricultural Science and Technology*, 10 (2), 109-121.

Talebi R. et al. (2009). Effective selection criteria for assessing drought stress tolerance in durum wheat (Triticum durum Desf.). *General and Applied Plant Physiology*, 35 (1), 64-74.

Tyshchenko A.V. et al. (2021). Assessment of alfalfa genotypes by seed productivity for drought tolerance. *Tavria Scientific Bulletin*, 120, 157-164.

Vdovenko, S. *et al.* (2024). Organic cultivation of carrot in the right-bank Forest-Steppe of Ukraine. *Scientific Horizons*, 27(1), 62-70. https://doi.org/10.48077/scihor1.2024.62

Volkodav V.V. (2001). Methods of the state varietal testing of crops. Alepha.