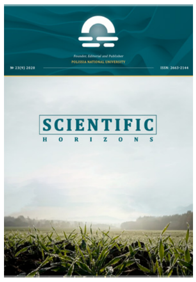
SCIENTIFIC HORIZONS

Journal homepage: https://sciencehorizon.com.ua
***Scientific Horizons*, 27(7), 62-74**



UDC 633.111"324":631.527
DOI: 10.48077/scihor7.2024.62

Assessment of the stability of common winter wheat breeding lines in multi-environment tests

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***Article's History*:**
Received: 01.02.2024
Revised: 01.06.2024
Accepted: 24.06.2024

Abstract. Climate change poses a challenge to agricultural production. To avoid production losses and exploit the emerging potential, adaptation in agricultural management will inevitably be required, in particular through the development of highly adapted and plastic varieties. To obtain wheat varieties combining productivity and stability, in 2018-2021, eight promising breeding lines of common winter wheat were studied in multi-environment eighteen trials at the V.M. Remeslo Myronivka Institute of Wheat of the National Academy of Agrarian Sciences of Ukraine using

***Suggested Citation*:**
Demydov, O., Zamlila, N., Novytska , N., Kirilenko, V., & Miliar, B. (2024). Assessment of the stability of common winter wheat breeding lines in multi-environment tests. *Scientific Horizons*, 27(7), 62-74. doi: 10.48077/scihor7.2024.62.

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three sowing dates after two preceding crops. Using ANOVA, it was established that environmental conditions had the highest reliable contribution to the yield variation (72.09%), genotype-environment interaction and genotype had significantly less (25.30% and 2.61%, respectively). The sowing dates for the preceding crops had a significant effect on the variation in the line productivity. Higher yields were received after green manure (mustard) in 2019 and 2020. The stable maximum level of productivity in terms of sowing dates was after preceding crop mustard as green manure for sowing on October 5 (the third term) and after maize for silage for sowing on September 25 (the second term). It was found that the conditions of the second sowing date were as an analytical background for selection of high-yielding lines of winter wheat. For practical breeding work, the breeding lines Lutescens 36921, Erythrospermum 36866, Erythrospermum 36802 were selected and released as new varieties Trudovnytsia Myronivska, MIP Vyshyvanka, and Gracia Myronivska, which have high yields and adaptability

Keywords: winter wheat; breeding line; genotype-environment interaction; statistical parameters

INTRODUCTION

The future of climate change and its associated impacts is highly unpredictable, which makes planning for mitigation and adaptation a bit complex. This necessitates the formulation of climate-resilient technologies involving an interdisciplinary approach according to the region. Suitable varieties need to be developed that could adapt to climatic variations, along with planned agronomic management and crop pest control. Farmers need to be educated regarding various climate-smart technologies and be provided training to simplify their use at the field level. Adaptive varieties are more resistant to adverse environmental factors, the influence of which determines up to 60-80% of yield variability between years. Heat stress and heat drought are the major yield limiting factors of wheat that reduces yield up to 24% and 48 %, respectively. Hence, there is a prior need for climate resilient breeding (Cortinovis *et al.*, 2020; Rossnerova *et al.,* 2020; Malhi *et al.,* 2021).

Yield level of the variety is an integrated criterion of its adaptability to specific environmental conditions. In addition to the productivity potential, its stability over the years based on the increased resistance of varieties against complex of limiting environmental factors is important. Yield stability is the major feature of modern wheat breeding programs due to significant fluctuations in average yield, especially under drought conditions. Breeders are working to develop varieties being more resistant and adaptive to environmental changes (Raza *et al.,* 2019; Bocci *et al.,* 2020). M. Roostaei *et al.* (2022) believe that addition of multi-environmental tests in breeding process increases its effectiveness and allows distinguishing the most promising genotypes based on the combination of yielding capacity and stability. In addition, evaluation of breeding lines (genotypes) in multi-environment tests, according to H. Awaad (2021) and S. Mahpara *et al.* (2022), allows obtaining the most complete information about yielding capacity and stability of breeding material.

T. Olivoto *et al.* (2019), B. Vaezi *et al.* (2019) note that in multi-environment trials (MET) when a set of genotypes is tested (examined) in a set of environments (locations, years, or its combination), the main purpose of plant breeding is to recommend genotypes for specific environments or to discriminate these mega-environments. Successful (innovative) varieties must be adapted to a wide range of environmental conditions for stable fulfilment of their genetic potential and effective use of crop management systems. The yield of each variety in any environment is the sum of the environment main effect (E), the genotype main effect (G) and the genotype × environment interaction (GE or GEI) (Pourdad & Moghaddam, 2020). Increasing the adaptability of varieties with stable yielding capacity and product quality in the genotype-environment interaction (GEI) is still a leading problem of breeders. As a component of the total phenotypic variance, GEI negatively affects heritability. A high effect of GEI leads to a lower heritability, thus breeding progress will be limited. Genotype-environment interaction (GEI) complicates the process of selecting better genotypes (Xiong *et al.,* 2020; Naik *et al.,* 2022). GEI can be divided into two groups: cross qualitative interaction (when genotype ranks change from one environment to another) and uncrossed quantitative interaction (changes in genotype productivity value without a change in the rank order of the genotypes in various environments). In this context, if the response of a genotype to the environment parallels the average response of all genotypes, it is identified as stable (Kang, 2020).

Existing methods for determining stability (regression analysis, non-linear regression analysis, multivariate analysis, and non-parametric statistics) with the interaction of the genotype with the environment, help breeders to determine the best genotypes for which it is minimal, allow of their phenotypic response to environmental changes (Coan *et al.,* 2022; Pour-Aboughadareh *et al.,* 2022; Bosi *et al.,* 2022). There are two main statistical models and approaches for analysing and interpreting the interaction of genotype with environment. Parametric stability statistics (univariate and multivariate) are mainly used in breeding studies, they are based on distributional assumptions regarding the influence of the environment, genotypes, and their interaction. The second group is non-parametric stability statistics that do not require initial assumptions. Nonparametric statistics are evaluated based on average values of the response and the ranking of the genotypes. Non-parametric statistics are easy to use and facilitate interpretation of the GEI, adding or deleting one or more genotypes has little effect on the results. To analyse the data of multi-environment tests, statistical parameters are used, one of the most well-known is the regression analysis according to S.A. Eberhart and W.A. Russell (1966) and G.C. Tai (1977), which allow identifying three parameters of productivity and environmental stability: the average value of genotype, indicators of linear and non-linear reactions to environment. The main effects and multiplicative interaction (AMMI) and genotype × environment interaction (GGE) biplot models, which are based on the method of principal components, have been widely used to characterise GEI and estimate yield stability (Khan *et al.,* 2021; Adham *et al.,* 2022). AMMI and GGE biplot explain a larger share of genotype-environment interaction compared to statistical parameters.

The purpose of the study was to identify breeding lines of winter common wheat that combine the potential of productivity and stability in years with contrasting weather conditions, when using different preceding crops and sowing dates.

MATERIALS AND METHODS

The study was conducted at the Myroniv Wheat Institute named after V. M. Remeslo of the National Academy of Agrarian Sciences of Ukraine during 2018-2021. The material for the study included the breeding lines of winter wheat in the competitive test: G1 (Podolianka (standard), G2 (Erythrospermum (ER) 36802), G3 (Lutescens (LUT) 36756), G4 (Lutescens 36921), G5 (Erythrospermum 54866), G6 (Lutescens 37090), G7 (Lutescens 528/03), G8 (Lutescens 54875), G9 (Lutescens 36926). Sowing was performed with the seeder SN-10 (Ukraine) with the seeding rate of 5 million viable seeds per 1 ha in three terms (September 15, September 25, October 3–5) after two preceding crops (mustard as green manure (GM), maize for silage (CR)). In general, for three years, yield indicators of lines were obtained in 18 environments (E). Plots were placed systematically, with four replications, sample area was 10 m^2. The crop was direct harvested with the "Hege 125" (Zürn Harvesting, Germany) and transfer to standard (14 %) grain moisture.

Environmental parameters as background for selection, indicators of adaptive capacity and stability of genotypes were determined according to the method of O.V. Kilchevskii and L.V. Khotylyeva (1985). According to this methodology, the differentiating ability of the environment was characterised using the following parameters: productivity (impact) of the environment d_k; the variance of the differentiating ability of the environment σ^2DAE_k; differentiating ability of the environment σDAE; indicator of the relative differential ability of the environment S_{ek}; compensation coefficient of the k^{th} environment K_{ek}. To assess the response of breeding lines to changes in environmental conditions, the indicators were determined: general adaptive ability GAA, specific adaptive ability SAA, relative stability of the genotype S_{gi}, indicator of breeding value of the genotype BVG; genotype compensation coefficient C_{gi}; regression coefficient b_i and mean square deviation S^2_{di} (Eberhart and Russel, 1966); coefficient of determination R^2 (Pinthus, 1973); stability variance σ_i^2 (Shukla, 1972); ecovalence W_i (Wricke, 1962); genotype superiority indicator P_i (Lin and Binns, 1988); non-parametric stability indicators $S_i^{(1)}$ and $S_i^{(2)}$ (Huehn, 1990). To rank the lines (R) and determine the adaptability, the method of non-parametric statistics of G.W. Snedecor (1961) was used. The average value ($\overline{X}$) of yield in the experiment and the average numerical value of statistical indicator was used as a basis to compare when analysing. The best value of the parameter corresponds to the number one ranking. The distribution of genotypes by productivity connection and adaptability in multi-environment tests is analysed using the AMMI model, which allows for variance analysis and singular distribution (Gauch, 2013; Negash *et al.,* 2013).

The sowing period 2018-2019 was characterised with severe air-soil drought that continued until mid-October, which negatively affected the initial growth of plants and largely caused the grain loss of winter crops. Meteorological conditions during the years of the study were contrasting, which made it possible to obtain an objective assessment of adaptive properties of the lines under study (Fig. 1).

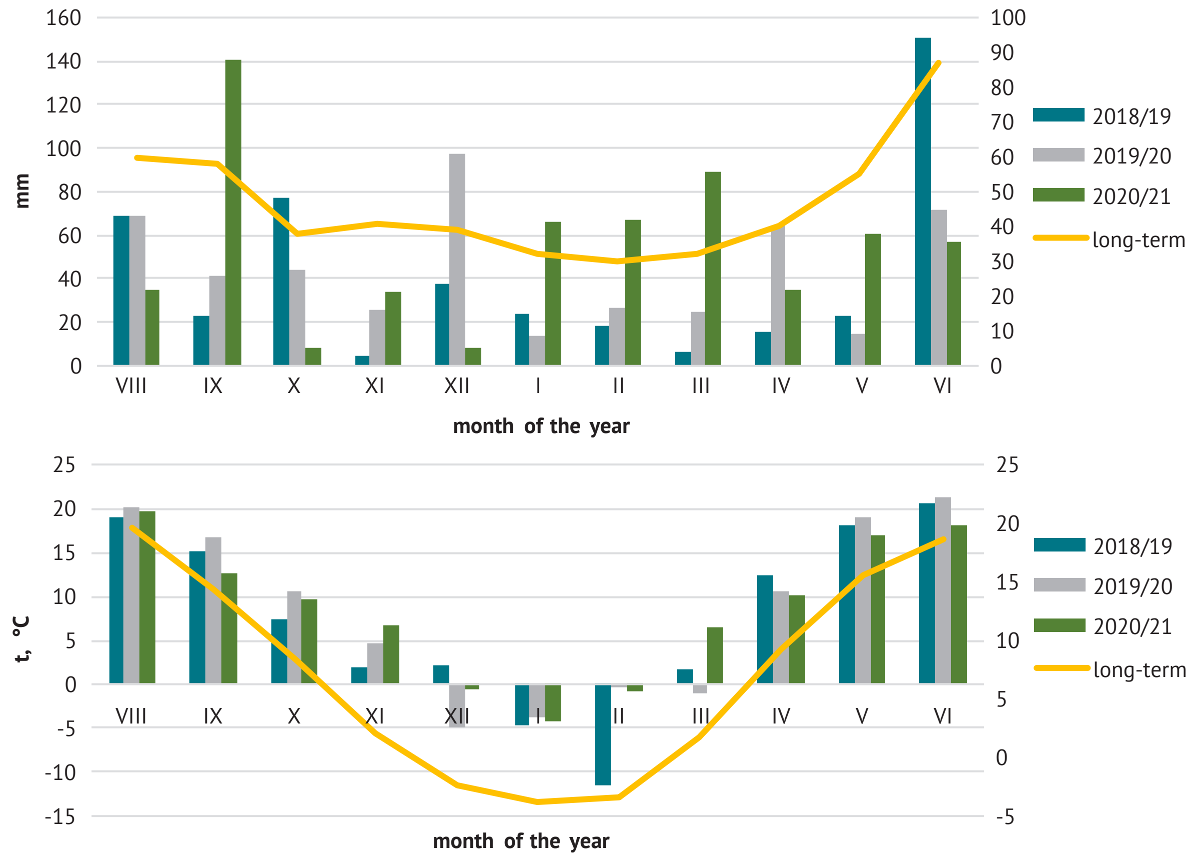

***Figure 1**. Weather conditions of the growing season, 2018-2021*
***Source:** data according to meteostation Myronivka of this study*

The experimental studies of plants (both cultivated and wild), including the collection of plant material, were performed following institutional, national, or international guidelines. The study followed the standards of the Convention on Biological Diversity (1992) and the Convention on Trade in Endangered Species of Wild Fauna and Flora (1979).

RESULTS AND DISCUSSION

The crops of the first sowing period had irregularities in plant growth and development, partially sparse plantings and that also affect the yield of the lines. The condition of crops in the following periods was satisfactory. The increased temperature regime contributed to the slow vegetation of winter crops, which continued until mid-January. The conditions that prevailed during the overwintering period were conducive to the resumption of vegetation, which occurred approximately two weeks earlier than the long-term average.

In the spring, the best indicators of vegetative mass and productivity formation were observed during sowing on September 25 (II) after maize (CR) and on October 5 (III) after mustard (GM). The second half of the growing season took place under elevated temperature regime and sufficient moisture supply. The maximum average yield according to the growing season was obtained for the third sowing period (6.55 t/ha, GM) and the second one (6.77 t/ha, CR). The minimum yield was obtained for sowing in the first term, 5.77 t/ha and 5.27 t/ha, respectively. In general, according to the preceding crops, the average yield was at the same level (Table 1).

***Table 1**. Yield of soft winter wheat breeding lines, 2018-2021*

Code genotype line	Sort, breeding line	Year / sowing dates 2019/13 2020/14									Average value
		2018/2019			2019/2020			2020/2021			
		I*	II	III	I	II	III	I	II	III	
		Mustard as green manure (GM)									
G1	Podolyanka St	5.12	6.01	6.50	3.40	5.26	5.84	4.91	3.61	5.12	5.09
G2	ER 36802	6.38	6.33	6.94	4.38	6.38	6.90	6.48	5.37	6.38	6.17

Table 1. Continued

Code genotype line	Sort, breeding line	Year / sowing dates 2019/13 2020/14									Average value
		2018/2019			2019/2020			2020/2021			
		I*	II	III	I	II	III	I	II	III	
		Mustard as green manure (GM)									
G3	LUT 36756	5.97	6.29	6.36	4.97	6.07	6.76	5.48	3.42	5.97	5.70
G4	LUT 36921	6.06	6.56	6.73	4.67	5.82	5.68	6.44	5.03	6.06	5.89
G5	ER 54866	6.01	5.22	5.77	3.80	6.54	5.91	5.36	4.92	6.01	5.50
G6	LUT 37090	5.83	6.58	6.99	4.39	5.47	6.19	4.86	3.11	5.83	5.47
G7	LUT 528/03	4.80	6.18	6.35	4.17	5.46	6.32	5.27	2.96	4.80	5.15
G8	LUT 54875	6.14	6.31	7.00	3.62	4.51	4.95	6.01	3.69	6.14	5.37
G9	LUT 36926	5.66	5.46	6.28	4.41	5.42	5.71	5.27	3.06	5.66	5.21
Average value		5.77	6.10	6.55	4.20	5.66	6.03	5.56	3.91	5.77	5.51
		Maize for silage (CR)									
G1	Podolyanka St	5.02	6.40	6.21	3.27	5.61	5.68	5.50	4.96	5.20	5.32
G2	ER 36802	5.10	7.14	5.86	3.13	6.34	5.80	6.23	6.75	6.56	5.88
G3	LUT 36756	5.42	7.13	6.41	4.45	6.60	5.28	6.42	8.30	6.79	6.31
G4	LUT 36921	5.79	6.69	6.66	3.89	4.80	4.97	5.76	6.85	5.53	5.66
G5	ER 54866	5.00	6.42	6.56	4.32	6.34	5.97	5.83	6.83	6.36	5.96
G6	LUT 37090	5.37	7.19	6.60	3.89	5.70	5.39	6.22	6.65	6.24	5.92
G7	LUT 528/03	5.00	6.65	6.47	3.82	4.85	5.91	5.26	6.36	5.91	5.58
G8	LUT 54875	5.29	6.70	6.82	3.12	4.84	5.64	5.40	5.75	5.90	5.50
G9	LUT 36926	5.48	6.59	6.40	4.11	5.59	5.20	4.62	6.39	5.63	5.56
Average value		5.27	6.77	6.44	3.78	5.63	5.54	5.69	6.54	6.01	5.74
Average value		5.52	6.43	6.50	3.99	5.64	5.78	5.62	5.22	5.89	5.62
Average value			6.15			5.13			5.58		5.62
LSD_{05}			0.84			0.72			1.10		0.80

Note: ** – sowing dates: I – September 15, II – September 25, III – October 5*
Source: *compiled by the authors of this study*

In 2019-2020, the post-sowing period was wet, which had a positive effect on the emergence of seedlings and the density of plant stands. Unstable temperature conditions were observed in winter. The amount of precipitation exceeded the average every month. After the snowfall, areas of snow mould (within 5-25%) and rotting (or asphyxiation) were found on the winter crops, which led to their sparseness, especially for the first sowing period. During the late spring vegetation resumption (April 1, two days later than the long-term date), the duration of forced winter dormancy was the longest, which had a negative impact on the growth, development, and productivity of plants (crops were sparse, plants were weakened). The weather conditions of the spring-summer period had more negative influence on the formation of yielding capacity (a sharp drop in the temperature regime and deficiency of effective rainfall). The higher yield of the line was formed after green manure (GM). The maximum yield after GM was obtained for the third sowing period (6.03 t/ha) and after maize for the second and third one (5.63 t/ha and 5.54 t/ha, CR). The minimum yield was obtained for the first sowing period (4.20 t/ha and 3.78 t/ha after GM and CR, respectively).

The growing season of 2020-2021 was specific with untypical cool weather with excessive rainfall during the sowing period (September), which delayed grain germination and the emergence of winter wheat seedlings. A relatively warm winter and the significant intense rainfall in May led to lodging, and complicate grain ripeness. The weather conditions of the spring-summer period (early resumption of spring vegetation; absence of long dry periods) contributed to the formation of high yield of winter wheat grain. The level of productivity after green manure (GM) for the first and third sowing dates was at almost the same level (5.56 t/ha and 5.77 t/ha). The minimum yield according to the growing season (3.91 t/ha, GM, the second sowing period) was formed as a result of the sharp decrease in air temperature, oversaturation of soil moisture, and the increase in its density during sowing, which caused delay in seedling emergence, decrease in plant density and led to their weak growth and development as compared to other sowing dates. Grain yield after maize (CR) according to the sowing dates was 5.69 t/ha, 6.54 t/ha, and 6.01 t/ha, respectively. Summarising the findings of the study, the variability of plant vegetation conditions in different growing seasons significantly affected the yield of breeding lines of winter common wheat. The minimum yield 2.96 t/ha was obtained for G7 (Lutescens 528/03) in the environment E8 (2020-GM-II); maximum yield – 8.30 t/ha was obtained for G3 (Lutescens 36756) in the environment E17 (2021-CR-II).

According to the level of expression and yield stability in combination with other agronomic traits in contrasting conditions in 2018-2021, the breeding lines G5 (Erythrospermum 54866), G2 (Erythrospermum 36802), and G4 (Lutescens 36921) were selected and submitted for State Variety Testing as the new winter wheat varieties MIP Vyshyvanka, MIP Hratsiia and Trudivnytsia Myronivska. According to the growing seasons, for the two preceding crops the highest average yield (6.15 t/ha) was obtained in the relatively favourable 2018-2019 (albeit under elevated temperature regime but with sufficient moisture supply), the lowest average yield (5.13 t/ha) was obtained in 2019/20 because of drought during the grain filling period. According to the preceding crops, the average yield of the breeding lines was higher (by 1.10 t/ha) after maize for silage (CR) in the more humid autumn and summer periods of 2020-2021. Sowing dates affected the increase in yield variability (Fig. 2).

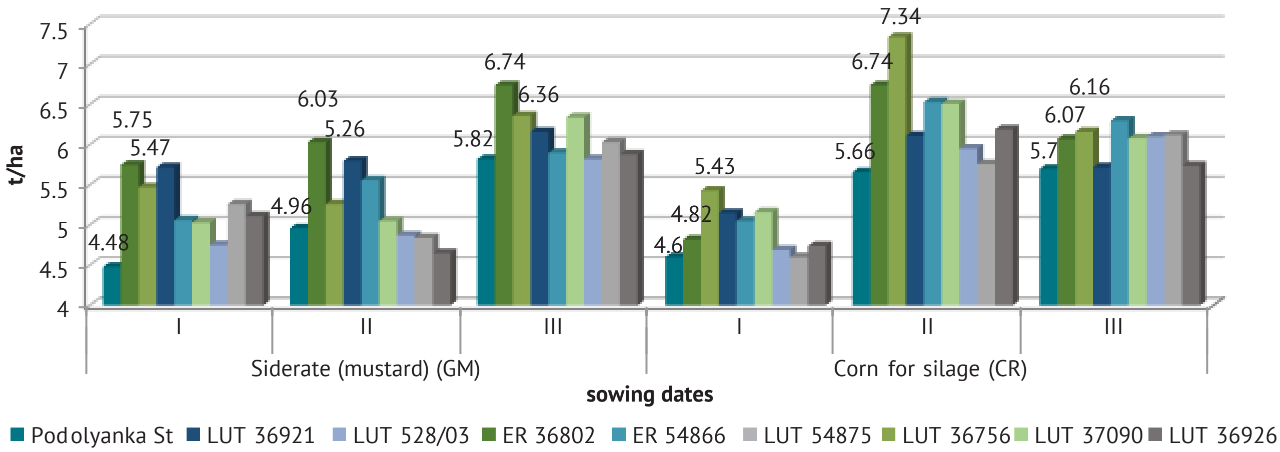

***Figure 2**. Average yield of breeding lines of soft winter wheat depending on the predecessor and sowing date, 2018-2021*

***Note:** sowing dates: I – September 15, II – September 25, III – October 5*

***Source:** compiled by the authors of this study*

The difference between the average yield values was 0.78 t/ha (GM) and 1.5 t/ha (CR) in 2018-2019; 1.83 t/ha (GM) and 1.79 t/ha (CR) in 2019-2020; 1.86 t/ha (GM) and 0.85 t/ha (CR) in 2020-2021. At the same time, the maximum level of yielding capacity in the terms of sowing dates after the preceding crops was stable: after the green manure (GM) the maximum level of average yield was for sowing at the third date (October 5), after maize for silage (CR) it was for at the second date (September 25). The ANOVA of the AMMI model confirms that in the experiment, which combined years with different weather conditions, the most part in yield variability was determined for the factor of environmental conditions (72.09%), followed in descending order by the genotype-environment interaction (25.30%), and genotype (2.61%) (Table 2).

***Table 2**. Results of AMMI model yield ANOVA for winter common wheat breeding lines, 2018-2021*

Factor	SS	Part of sum square, %	df	MS	F*
ENV	537.40	72.09	17	31.61	80.74
GEN	19.46	2.61	8	2.43	6.21
ENV*GEN	188.62	25.30	136	1.39	3.54
PC1	72.77	37.92	24	3.03	139.54
PC2	39.87	20.77	22	1.81	83.41
PC3	28.67	14.93	20	1.43	65.96
PC4	19.33	10.07	18	1.07	49.42
PC5	15.09	7.86	16	0.94	43.40
PC6	7.39	3.85	14	0.53	24.29

***Note:** ENV, environment; GEN, genotype; ENV*GEN, "genotype-environment" interaction; SS, sum square; df, degrees of freedom; MS, mean square; F, Fisher s test; PC1...PC6, principal components; *reliable at the 0.01 % level of significance*

***Source:** compiled by the authors of this study*

Environmental parameters as a background for the differentiation of breeding lines of winter wheat indicate that environmental conditions E5, E3, and E17 were the most productive (d_k = 1.16, 0.94, 0.93, accordingly), E10, E14, E7 were the least productive (d_k = -1.83, -1.70, -1.41, accordingly). In 2018-2019 in environments E1 (2019-$GM_{green\ manure}$-$I_{sowing\ date}$) and E5 (2019-CR_{maize}-$II_{sowing\ date}$), the highest indicators are typical for analysing backgrounds: variation of differentiating ability (σ^2DAE_k = 0.24 and 0.08, respectively); differentiating ability (σDAE = 0.49 and 0.27); relative differentiating ability (S_{ek} = 4.14 and 1.11); compensation effect (K_{ek} = 1.36 and 0.76), but they differed in terms of environmental productivity (d_k = 0.17 and 1.16) (Table 3).

***Table 3**. Environmental parameters as a background for evaluation and selection of winter wheat lines, 2018-2021*

Environment		Parameter of the environment						Background for assessment
		$u + d_k$	d_k	σ^2DAE_k	σDAE	S_{ek}	K_{ek}	
E1	2019-GM-I	5.77	0.17	0.24	0.49	4.14	1.36	A
E2	2019-GM-II	6.10	0.50	0.20	0.45	3.31	1.25	S
E3	2019-GM-III	6.55	0.94	0.15	0.38	2.26	1.07	L
E4	2019-CR-I	5.27	-0.33	0.05	0.23	1.01	0.64	L
E5	2019-CR-II	6.77	1.16	0.08	0.27	1.11	0.76	A
E6	2019-CR-III	6.44	0.84	0.06	0.24	0.91	0.67	S
E7	2020-GM-I	4.20	-1.41	0.24	0.49	5.68	1.36	L
E8	2020-GM-II	5.66	0.05	0.37	0.61	6.51	1.69	A
E9	2020-GM-III	6.03	0.42	0.34	0.58	5.56	1.61	S
E10	2020-CR-I	3.78	-1.83	0.23	0.48	6.09	1.33	L
E11	2020-CR-II	5.63	0.02	0.46	0.68	8.26	1.89	A
E12	2020-CR-III	5.54	-0.07	0.10	0.31	1.79	0.87	S
E13	2021-GM-I	5.56	-0.04	0.35	0.59	6.32	1.65	S
E14	2021-GM-II	3.91	-1.70	0.86	0.93	21.98	2.58	A
E15	2021-GM-III	5.48	-0.13	0.29	0.54	5.30	1.50	L
E16	2021-CR-I	5.69	0.09	0.30	0.55	5.33	1.53	S
E17	2021-CR-II	6.54	0.93	0.79	0.89	12.14	2.47	A
E18	2021-CR-III	6.01	0.40	0.25	0.50	4.14	1.39	L
Average		5.61	0.00	0.30	0.51	5.66	1.42	

***Note:** (u + dk), average yield for environment; dk, performance (impact) of environment; σ2DAEk,variance of differentiating ability of environment; σDAE, differentiating ability of environment; Sek, indicator of relative differentiating ability of environment; Kek, compensation coefficient of the kth environment; A, analysing background; S, stabilising background; L, levelling background*

***Source:** compiled by the authors of this study*

The conditions of 2019-2020 were distinguished with the lowest productivity of environments (d_k = -1.83-0.42) in the experiment. The highest differentiating ability was characteristic the environment E8 and E11 of the middle (II – 25.09) sowing dates after both preceding crops according to the indicators σ^2DAE_k (0.37 and 0.46), σDAE (0.61 and 0.68), S_{ek} (6.51 and 8.26), and K_{ek} (1.69 and 1.89). These backgrounds can be characterised as analysing ones. In 2020-2021, the environments E14 and E17 were characterized as analysing with the highest, almost at the same level, variance of differentiating ability (σ^2DAE_k = 0.86 and 0.79, respectively), differentiating ability (σDAE = 0.93 and 0.89, respectively), with strong compensation effect (K_{ek} = 2.58 and 2.47, respectively) and the maximum relative differentiating ability in the experiment (S_{ek} = 21.98 and 12.14, respectively). Of these, the first environment was low-productive (d_k = -1.70), while the second was high-productive (d_k = 0.93).

The add of multi-environmental tests in breeding process increases its effectiveness and allows singling out the most promising lines of winter common wheat based on the combination of yielding capacity and stability. The results of the analysing environments as a background for the comparison of breeding lines of winter common wheat by the level of grain yield and stability parameters indicate that there were three types of background in the experiment, namely, analysing, levelling and stabilising. The analysing background was both under favourable and stressful conditions, but the stabilising background was under conditions when breeding lines have formed the average level of productivity. The environments E1 (2019-GM-I), E5 (2019-CR-II), E8 (2020-GM-II), E11 (2020-CR-II), E14 (2021-GM-II), E17 (2021-CR-II) with the highest values of statistical parameters were characterised with the maximum destabilising effect on yield level; they ensured the contrast in genotype response and contributed to the selection of the best ones. Parametric and non-parametric statistical indicators revealed that the genotypes under study differed significantly in response to the conditions of different years. Their ranks (R) confirm the assessment of the examined parameters and allow differentiating between genotypes. The maximum general adaptive ability (GAA_{gi}) was noted in the lines G2 (0.42) and G3 (0.35) (Table 4).

***Table 4**. Characterisation and ranking of breeding lines of winter wheat according to the parameters of adaptive ability and stability for the trait of yield, 2019-2021*

Line code	GAA_{gi} – R	$\sigma^2(SAA)_{gi}$ – R	S_{gi} – R	BVG_i – R	C_{gi} – R
G1	-0.40-9	0.76-4	16.7-5	2.51-7	1.26-4
G2	0.42-1	0.85-5	15.3-4	3.18-3	1.41-5
G3	0.35-2	1.06-7	17.2-6	2.78-5	1.76-7
G4	0.14-3	0.55-2	12.9-1	3.44-1	0.92-2
G5	0.07-4	0.54-1	13.0-2	3.39-2	0.90-1
G6	0.01-5	1.09-8	18.6-8	2.39-8	1.81-8
G7	-0.19-6	0.88-6	17.3-7	2.52-6	1.46-6
G8	-0.19-7	1.10-9	19.3-9	2.17-9	1.82-9
G9	-0.20-8	0.65-3	14.9-3	2.91-4	1.08-3
Average	0.00	0.83	16.1	2.81	1.38

***Note:** GAAgi, effect of general adaptive ability; σ2(SAA)gi, dispersion (variance) of the specific adaptive ability; Sgi, %, indicator of relative stability of the ith genotype; BVGi, comprehensive indicator of breeding value of genotype; Cgi, genotype compensation coefficient; R, rank (genotype ranking)*
***Source:** compiled by the authors of this study*

The breeding line G8 was characterised with low stability at high value of the dispersion of specific adaptive ability $\sigma^2(SAA)_{gi}$ (1.10; rank 9) which was inferior to others in terms of relative stability Sg_i and breeding value of genotype BVG_i) (rank 9). The highest values of these indicators (ranks 1 and 2) were noted in G4 (0.55, 12.9, 3.44, respectively) and G5 (0.54, 13.0, 3.39). The remaining lines were unstable at high values of σ^2SAA_{gi} (>0.83, average) and compensation coefficient ($C_{gi} > 1$). The compensation coefficient close to one was noted in lines G4 and G5, therefore, when selecting for yield stability, they (lines) should be taken.

Relative stability within the average level of variability in the experiment ($Sg_i < 16.1$) was most pronounced in the lines G4 (12.9 %) and G5 (13.0 %). The lines G4, G5, and G2 with high grain yield and grain stability were better in BVG in combination with indicators GAA_{gi} and $\sigma^2(SAA)_{gi}$. With a high yield, but due to its low stability, the line G3 had an average level of breeding value ($BVG_i = 2.78$). The lines are of the most practical value if their high GAA_{gi} is combined with low yield variability under different conditions, that is, they stably form high grain yield. The lines G4, G5, and G2 best meet these criteria; the latter has high general adaptive ability, average level of yield stability and is sensitive to improving the agrotechnical conditions. According to the low indicators of coefficient of variation (CV%), the lines G4 and G2 were the most stable (15.11% and 16.50%) (Table 5).

***Table 5**. Characterisation and ranking of breeding lines of winter wheat according to parametric and non-parametric indicators of plasticity and stability*

Code	$\bar{X}$ – R	CV – R	b_i –R	S^2_{di} – R	R^2 – R	σ_i^2 – R	W_i – R	P_i – R	$S_i^{(1)}$ – R	$S_i^{(2)}$ – R
G1	5.41-7	19.31-5	1.13-4	2.07-3	0.70-5	0.38-6	5.64-7	0.89-9	0.22-1	6.01-4
G2	5.91-1	16.50-2	0.85-5	1.18-1	0.69-6	0.35-5	5.28-6	0.36-1	0.36-6	7.37-6
G3	5.73-2	18.84-4	1.49-8	6.01-7	0.79-3	0.26-3	4.12-4	0.50-3	0.22-1	5.59-3
G4	5.69-4	15.11-1	0.91-2	2.73-6	0.74-4	0.25-2	4.01-2	0.57-5	0.33-4	6.24-5
G5	5.56-5	18.21-3	1.02-1	2.39-4	0.63-7	0.46-7	6.73-8	0.57-5	0.35-5	8.82-8
G6	5.54-6	20.89-7	1.11-3	2.66-5	0.88-1	0.19-1	3.18-1	0.64-6	0.25-2	5.31-2
G7	5.40-8	19.99-5	0.75-6	1.77-2	0.79-3	0.27-4	4.18-5	0.81-7	0.25-2	5.18-1
G8	5.37-9	22.20-8	1.41-7	8.61-9	0.85-2	0.26-3	4.10-3	0.87-8	0.22-1	6.01-4
G9	5.70-3	23.41-9	0.33-9	8.24-8	0.69-6	0.70-8	9.91-9	0.40-2	0.29-3	7.82-7

***Note:** $\bar{X}$, average yield, t/ha; CV, coefficient of variation, %; bi, regression coefficient; S2di, mean square deviation from regression; R2, coefficient of determination; σi2, stability variance; Wi, ecovalence; Pi, indicator of the superiority of variety; Si(1) and Si(2), non-parametric indicators of stability; R, rank (genotype ranking)*
***Source:** compiled by the authors of this study*

According to the mean square deviation (S^2_{di}), the lines G2 and G7 were the most stable (rank 1 and 2). According to the regression coefficient (b_i), the line G5 (1.02) was characterised by the optimal response to changes in environmental conditions. The response of the line G4 (0.91) was close to optimal. The least response to change in environmental conditions was observed in the line G9 (0.33), the most response was in the line G3 (1.49). Ecovalence stability (W_i) was the highest in the lines G6 and G4 (ranks 1 and 2) and the lowest in G9 (rank 9), as for the parameter b_i. According to the indicator of the superiority of variety (P_i), the lines G2 and G9 prevailed (rank 1 and 2). The best value (rank 1) of the first non-parametric indicator of stability ($S_i^{(1)}$) was obtained by the lines G1, G3, and G8; the second non-parametric indicator of stability ($S_i^{(2)}$) was obtained by the lines G7 and G6.

Correlation analysis was used to determine the relationship between the given parameters of adaptive ability, stability, and average yield (Table 6). The indicators $\sigma^2(SAA)_{gi}$, $S_{gi,}$ $K_{gi,}$ b_i) had no significant relationship with the average yield. Selection for them can help identify stable genotypes without taking into account their yield. Above-average and average correlation was noted in the indicators S^2_{di} (r = 0.70) and BVG_i (r = 0.54), which are the most balanced for the combination of yield and stability.

***Table 6**. Correlation coefficients between the average yield of winter wheat lines and adaptability indicators, 2018-2021*

Indicator	**$\bar{X}$**	**GAA_{gi}**	**$\sigma^2(SAA)_{gi}$**	**S_{gi}**	**BVG_i**	**C_{gi}**	**b_i**
GAA_{gi}	**1.00**	–	–	–	–	–	–
$\sigma^2(SAA)_{gi}$	0.08	0.08	–	–	–	–	–
SAA_{gi}	0.07	0.07	**1.00**	–	–	–	–
S_{gi}	-0.28	-0.28	**0.93**	–	–	–	–
BVG_i	**0.54**	**0.54**	**-0.79**	**-0.96**	–	–	–
C_{gi}	0.08	0.08	**1.00**	**0.93**	**-0.79**	–	–
b_i	-0.13	-0.13	**0.96**	**0.97**	**-0.89**	**0.96**	–
S^2_{di}	**0.70**	**0.70**	0.19	-0.07	0.28	0.19	-0.09

***Source:** compiled by the authors of this study*

Direct correlation (+1.0) was noted between $\sigma^2(SAA)_{gi}$ and K_{gi}, and high positive correlation with S_{gi} (r = 0.93) and b_i (r = 0.96); between indicators S_{gi} and K_{gi} (r = 0.93), between S_{gi} and b_i (r = 0.97), as well as between K_{gi} and b_i (r = 0.96). A significant negative correlation was established between BVG_i and $\sigma^2(SAA)_{gi}$ (r = -0.79), S_{gi} (r = -0.96), K_{gi} (r = -0.79), and b_i (r = -0.89). All these regularities can be considered when assessing the adaptability of genotypes (breeding lines). Evaluation is an important and final stage of any breeding program before the release of a variety. At this stage, the goal is to identify lines with good results in one or more mega-environments where the lines are recommended to be grown, and to identify where the line is not recommended to be grown. At the evaluation stage, all lines must have an elite level of performance and most, if not all, of the required traits. Differences between lines are often minor compared to selection trials of early generations because phenotype and GS have improved only consistently better lines. The concept of a mega-environment is a group of environments where lines reveal themselves in the same way. B. Gerrish *et al.* (2019) note that mega-environments are usually identified using some form of cluster analysis to confirm that the environments are similar. The study by L. Crespo-Herrera *et al.* (2021) confirms that the value of knowing the mega-environment is that the breeder can select evaluation (syn. testing) sites in different mega-environments to obtain the most useful data to confirm the value of the line.

T. Begna (2022). are of the opinion that the interpretation of the performance of new varieties is impaired by genotype-environment interaction. One of the most used methods for identifying genotypes that have high and stable performance in different environments is the analysis of main effects and multiplicative interaction (AMMI). A. Seyoum *et al.* (2020), R. Kachapur *et al.* (2023), and M. Maniruzzaman *et al.* (2019) in their research confirm that variety evaluation and mega-environment identification are one of the most important tasks of environmental trials (multi-environment trial – MET) and are a prerequisite for identifying stable and high-performance genotypes. Although yield is a combined result of genotype (G), environment (E), and genotype × environment (GE) interactions, only G and GE are relevant for variety evaluation and mega-environment identification. The GGE biplot analysis graphically displays G, GE, MET in a way that facilitates visual variety assessment and mega-environment identification.

T. Asres *et al.* (2019) using ANOVA and GGE biplot evaluated twelve barley varieties, considering earliness, malt quality, grain yield and stability indicators in three districts of North Gondar (Ethiopia), which helped them to identify the high-yielding and most adapted in different environments variety IBON-174/ 03. M. Göransson *et al.* (2019) in eight regions of Northern and Central Europe evaluated 169 breeding lines of barley with respect to early maturity, height, lodging resistance under different environmental conditions. The findings showed that there are still considerable variations within the modern gene pool, and therefore the ideal combinations of alleles for regional adaptation that could facilitate the expansion of cereal cultivation further north need to be further identified. K. Van Meerbeek *et al.* (2021) noted the need for constant research on ecological stability, productivity, lodging resistance, and tolerance of created varieties to climate changes. Undoubtedly, the varieties with more consistently prominent level of productivity in combination with resistance to abiotic and biotic factors of the environment will be the most valuable for the producer.

CONCLUSIONS

The use of multi-environment (years, preceding crops, sowing dates) tests at the final stage of breeding process of winter common wheat is a practical and effective way of evaluating and selecting breeding lines (genotypes) that combine yield potential and increased stability in different weather conditions over cultivation years. The absolute yield was noted: minimum – (2.96 t/ha, G7 Lutescens 528/03), for sowing in the medium (E8, 2020-GM-II); maximum – (8.30 t/ha, G3 Lutescens 36756) – (E17, 2014-CR-II). The maximum level of yield by sowing dates after the predecessors was stable over the years: after the predecessor, sideral par (GM) had the maximum level of average yield for sowing in the third season (October 5), after maize for silage (CR) – in the second season (September 25). The inclusion of multi-environment tests in the selection process increases its effectiveness and makes it possible to single out the most promising lines of soft winter wheat based on the combination of yield and stability.

Parametric and non-parametric statistical indicators revealed that the studied genotypes differed significantly in response to the conditions of different years. Ranks (R) confirm the assessment of the studied parameters and allow to differentiate between genotypes. Selection by statistical indicators ($\sigma^2(SAA)_{gi}$, S_{gi}, K_{gi}, b_i) may help to distinguish stable genotypes without taking into account their yield. The most informative is the indicator BVG_i, which is relatively balanced in terms of productivity and stability.

ACKNOWLEDGEMENTS

None

CONFLICT OF INTEREST

The authors of this study declare no conflict of interest.

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Оцінка стабільності селекційних ліній пшениці м'якої озимої в багатосередовищних випробуваннях

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Анотація. Зміна клімату кидає виклик сільськогосподарському виробництву. Щоб уникнути виробничих втрат і використати потенціал, що з'являється, неминуче знадобиться адаптація в управлінні сільським господарством, зокрема шляхом створення високоадаптованих і пластичних сортів. Для отримання сортів пшениці, що поєднують продуктивність і стабільність, у 2018-2021 рр. у Миронівському інституті пшениці імені В. М. Ремесла Національної академії аграрних наук України вивчали вісім перспективних селекційних ліній пшениці м'якої озимої в багатофакторних дослідах за трьох строків сівби після двох попередніх культур. За допомогою ANOVA було встановлено, що умови середовища мали найбільший достовірний внесок у варіацію врожайності (72,09 %), взаємодія генотип-середовище та генотип мали значно менший внесок (25,30 % та 2,61 % відповідно). Строки сівби попередніх культур мали значний вплив на варіювання продуктивності лінії. Вищі врожаї були отримані після сидерату (гірчиця) у 2019 та 2020 роках. Стабільний максимальний рівень продуктивності за строками сівби був після попередника гірчиці на сидерат за сівби 5 жовтня (третій строк) та після кукурудзи на силос за сівби 25 вересня (другий строк). Встановлено, що умови другого строку сівби були аналітичним фоном для добору високоврожайних ліній озимої пшениці. Для практичної селекційної роботи відібрано селекційні лінії Lutescens 36921, Erythrospermum 36866, Erythrospermum 36802 та створено нові сорти Трудівниця миронівська, МІП Вишиванка та Грація миронівська, які характеризуються високою врожайністю та адаптивністю

Ключові слова: пшениця м'яка озима; селекційна лінія; взаємодія генотип-середовище; статистичні параметри