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Adaptive potential of short-stemmed winter bread wheat genotypes in the eastern Forest-Steppe of Ukraine

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Abstract. Among the unresolved issues of breeding short-stemmed winter bread wheat genotypes of different ripeness groups, the problem of obtaining high and stable yields without reducing the adaptive potential in the face of limiting environmental factors that periodically occur in different agroecological conditions of cultivation stays relevant. The preliminary identification of suitable sources with a combination of necessary adaptive properties is a crucial step towards the development of highly promising varieties and improvement of the gene pool of plants in Ukraine. The purpose of this study was to find the level of adaptive potential in short-stemmed winter bread wheat genotypes with different vegetation periods, to investigate the plasticity and stability of yields, and to select highly adaptive source material for the conditions of the eastern part of the Forest-Steppe of Ukraine. To fulfil this purpose, the study employed general scientific, field, and dispersion methods of scientific cognition. It was found that in the eastern part of the Forest-Steppe of Ukraine, among short-stemmed winter bread wheat genotypes, the share of those with the highest genetic potential for adaptability combined with high yields (over 16% of the standard) is highest in the group of mid-ripening varieties and amounts to 53.3%. These include mainly Ukrainian genotypes, namely: Blahodarka Odeska, Zoreslava, Rozdyinka Odeska, Kruhozir, Shpalivka (UKR); Ilona (SVK), Urbanus (AUT), and Evklid (FRA). Among

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the early-ripening samples, the share of such genotypes was 33.3%, and in the group of late-ripening varieties – 13.3%. High yield stability ($S^2_{d_i}=0.0$) was inherent in 66.7% of the samples of the early-ripening group, 60% of the mid-ripening group, and 26.7% of the late-ripening group. The identified sources are valuable starting material for the development of new and highly promising winter soft wheat varieties adapted to the growing conditions in the eastern part of the Forest-Steppe of Ukraine

Keywords: yield; plasticity; stability; limiting factors; reaction rate; source; variety

INTRODUCTION

Identification of new short-stemmed winter bread wheat genotypes with high adaptability to changing agroecological conditions is an urgent task on the path to successful intensification of agricultural product diversity and food security. For a long time, the development of high-intensity, short-stemmed winter soft wheat varieties has been the main focus of breeding to increase yield potential. As a result, a considerable number of varieties in the State Register of Plant Varieties of Ukraine (n.d.) have a genetic potential of more than 10 t/ha. However, there is a substantial decrease in its stability and, accordingly, a loss of adaptive potential, which is a considerable obstacle to the successful introduction of varieties into production, which requires the early identification of short-stemmed sources of winter soft wheat with the necessary adaptive properties for the selection improvement of the created gene pool.

In many countries of the world, there is an urgent need to address the impact of various stress factors that can limit the yield and adaptability of various food crops, including winter wheat. A. Raza *et al.* (2019) note that abiotic stresses are the main limiting factors that affect soft winter wheat plants in the environment. According to the scientists, genomic selection (GS) with phenotyping of high-yielding samples is a prominent area in identifying drought resistance genes. D. Soto-Gómez and P. Pérez-Rodríguez (2022) emphasise the significance of perennial wheat as a donor of water scarcity resilience, which can help reduce soil erosion and prevent carbon waste in agriculture. Ukrainian scientists M. Ilchuk *et al.* (2019) note that due to its nutritional value and the existing variety of technological uses, soft winter wheat (*Triticum aestivum* L.) plays a major role in ensuring food security of Ukraine, which is the basis for its economic development.

To ensure the effective introduction of new and promising varieties into production, significant breeding work is being carried out to increase yields and adaptability in certain agro-ecological zones. When investigating the adaptability parameters of modern winter wheat varieties in six agro-ecological regions of Poland, M. Studnicki *et al.* (2019) found that yield variability was determined mainly by the influence of the agro-ecological region of cultivation on the studied varieties, and to a lesser extent by the genotype. Researchers have identified the Sailor and Linus varieties, which are highly adaptable to all the agro-ecological

regions under study at different cultivation intensities. Ukrainian scientists N. Zamlila *et al.* (2019) identified breeding lines of soft winter wheat characterised by the necessary parameters of adaptability and a combination of high yield in the central Forest-Steppe of Ukraine – Lutescens 54360 and Lutescens 35232. A lot of research is being done to improve cultivation technologies to increase gross grain yields. Thus, Ukrainian scientists S. Poltoretskyi *et al.* (2020) argue that the choice of sowing dates was accompanied by changes in other elements of winter wheat cultivation technology – selection of varieties according to ripeness groups, determination of seeding rates, and sowing methods. Chinese scientists W-G. Li *et al.* (2022) emphasise the significance of nitrogen application and irrigation as the principal factors in the formation of high yields of soft winter wheat. According to the findings of the study, the highest yields without substantial lodging of crops were obtained with nitrogen application of 240 kg/ha and irrigation of 600 m³/ha. Indian scientists N. Suresh *et al.* (2020) note that to maximise the yield potential of a genotype, it is necessary to sow at the optimum time.

Ukrainian scientists S. Lyfenko *et al.* (2021) note that in the Steppe zone, early-ripening varieties have greater yield advantages over varieties of other ripeness groups, which almost always fall under the influence of fires and summer drought. The findings also suggest that varieties of high-intensity, short-stemmed type considerably outperform varieties of semi-intensive, medium-stemmed type in terms of potential yield, but the stability of medium-stemmed genotypes is often higher than that of short-stemmed ones.

E. Filip *et al.* (2021) notes that the genetic yield potential of a variety is limited by various biotic and abiotic factors, which, accordingly, negatively affects its stability. Polish scientists M. Różewicz *et al.* (2021) note that among biotic factors, fungal diseases cause the most damage, with yields decreasing mainly by 15–20%, and in epiphytotic losses can reach 60%. The main factors that determine the emergence and spread of epiphytotic include the level of genetic protection against pathogens (Kang *et al.*, 2020), weather conditions during the growing season, crop rotation, and soil cultivation system (Iwańska *et al.*, 2019).

The purpose of this study was to determine the adaptive potential of short-stemmed winter wheat genotypes of different ripeness groups in terms of yield

plasticity and stability, to identify sources of high yield potential adapted to the conditions of the eastern part of the Forest-Steppe of Ukraine.

MATERIALS AND METHODS

The research material included 45 short-stemmed samples of soft winter wheat (*Triticum aestivum* L.) of different ripeness groups: early-, mid-, and late-ripening varieties from nine countries, including 11 samples from Ukraine, 10 from Germany, 8 from France, 5 each from Romania and China, 2 each from Austria and the United States of America, and 1 each from Slovakia and Hungary. The early-ripening group included Manera Odeska, Orzhysia Nova, Soborna (Ukraine); MV Sed (Hungary), Centurion, Rezetat, F11208G2, F10222G5-11, F 08034G1-01 (Romania); CA 13014, KN 41, KN 40, T 51 (China); OK 10126, Bentley (United States of America); mid-ripening – Blahodarka Odeska, Svitohliad, Zoloto Ukrainy, Zoreslava, Rodzynka Odeska, Kruhozir, Shpalivka, MIP Feieriiia (Ukraine); Ilona (Slovakia); Aspekt (Germany); Urbanus, Tacitus (Austria); Evklid, Bardotka (France); Flourish (Canada), and late-ripening – Fagus, Achim, Dromos, Bonanza, Nordkap, Rotax, KWS Malibu, Akrotos, Mattus (Germany); RGT Reform, Matchball, Praktik, Sailor, Boomer, Memory (France). Each ripeness group consisted of 15 samples. The study of samples of different ecological and geographical origin is necessary to determine the adapted genotypes of different ripeness groups to the conditions of the eastern part of the Forest-Steppe of Ukraine.

The study was conducted in 2018-2021 in the laboratory of cereal genetic resources of the National Centre for Plant Genetic Resources of Ukraine (NCPGRU) of the V.Y. Yuriev Plant Production Institute of the National Academy of Agrarian Sciences of Ukraine. The experiments were designed following the requirements of selection field experiments (Dospekhov, 1985). Sowing was carried out in pairs at the optimum time with a seeding rate of 4.5 million grains per 1 ha using a Klen-1.5SP seeder (a selection seeder with a portioned sowing unit, made in Ukraine) on plots of 5 m² in threefold replication. In spring, the crops were fertilised with ammonium nitrate (N₄₀). The standard for the short-stemmed samples was the Bunchuk variety, which was sown through 20 numbers. The samples were studied according to the methodology (Merezhko *et al.*, 1999) and the classifier of the genus *Triticum* L. (CMEA's extended harmonised classifier of the genus *Triticum* L., 1989). The study of plasticity and stability of plant genotypes was carried out according to the method of S.A. Eberhart and

W.A. Russel (1966). The linear regression coefficient (b_i) characterises the average response of the genotype to changes in growing conditions, indicates the level of its plasticity and allows predicting changes in a particular trait within the conditions under study. The fluctuation of the factual yield in relation to the regression line is determined by the standard deviation from the regression line. The variance of the stability of the trait (S^2d_i) indicates how reliably the variety corresponds to the plasticity estimated by the regression coefficient. The smaller the quadratic deviation, at which S^2d_i accordingly approaches zero, the more stable the genotype. Parameters and combinations of these traits indicate the level of adaptability of the genotypes under study to growing conditions. Statistical processing of the results was carried out according to the methodology (Dospekhov, 1985).

To fulfil the purpose of this study, the research methods were employed as follows: general scientific (analysis and synthesis) – to differentiate and generalise the results, field – to determine yield, and dispersion – to determine the levels of plasticity and stability of yield, as well as to assess the reliability of experimental data. Experimental studies of plants (both cultivated and wild), including the collection of plant material, were following the institutional, national, or international guidelines. The authors adhered to the standards of the Convention on Biological Diversity (1992) and the Convention on Trade in Endangered Species of Wild Fauna and Flora (1979).

RESULTS

Analysing the weather conditions of the study in 2018-2021 by the growing season, it was found that different values of the hydrothermal coefficient (HTC) contributed to the differentiation of winter bread wheat samples by plasticity and yield stability, as well as by the duration of the growing season. The autumn period was very dry in 2018 (HTC=0.49) and 2020 (HTC=0.46), and quite wet in 2019 (HTC=1.46). The meteorological conditions of the vegetative spring and summer periods of the study differed significantly in terms of moisture availability and temperature: the spring periods of 2019 (HTC=1.26) and 2021 (HTC=1.46) were sufficiently moist, and the spring period of 2020 (HTC=2.05) was excessively moist. In addition, the summer months of 2020 were characterised by sufficient moisture (HTC=1.27), while in 2019 (HTC=0.62) and 2021 (HTC=0.64) they were dry (Fig. 1).

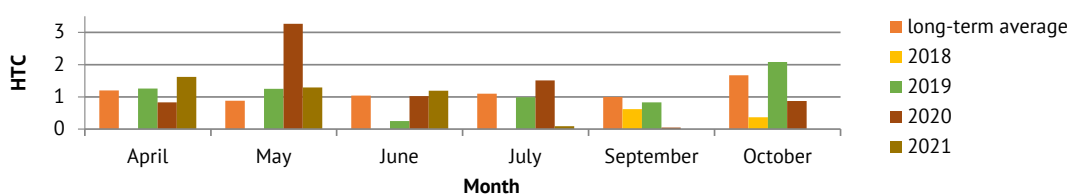


Figure 1. Hydrothermal coefficient of the vegetation periods of the study, 2018-2021

Source: compiled by the authors of this study

The length of the growing season was shortest in 2021 and longest in 2020 was the most favourable year for high yields. In 2019 and 2021, its levels were mostly lower. Notably, moisture deficit and high temperature in July 2021 ($HTC=0.09$) caused grain inflammation, which had a more negative impact on yield formation compared to previous years of the study, which was caused by a decrease in the breeding value of the structural elements of ear productivity. Thus, the contrast of weather conditions in the growing seasons of 2018-2021 contributed to the identification of sources of high yields adapted to the growing conditions in the eastern part of the Forest-Steppe of Ukraine.

During 2018-2020, the duration of the vegetation period (germination-ripening) in short-stemmed winter wheat samples ranged from 275 to 290 days, which made it possible to distinguish sources according to three ripeness groups: early-, mid-, and late-ripening. The group of early-ripening genotypes with a vegetation period ranging from 276 to 279 days included Manera Odeska, Orzhytsia Nova, Soborna (UKR); MV Sed (HUN); Centurion,

Retezat, F 11208G2, F 10222G5-11, F 08034G1-01 (ROU); CA 13014, KN 41, KN 40, T 51 (CHN); OK 10126, Bentley (USA). The vegetation period of the Bunchuk standard was 282 days, and that of the early-ripening standard Aurora Myronivska was 279 days.

In the early maturing group, six sources of high yields (over 16% of the standard) were identified, namely: Manera Odeska (UKR), Centurion (ROU), Retezat (ROU), CA 13014 (CHN), OK 10126 (USA), and Bentley (USA), with a share of 40%; the standard is Bunchuk (UKR) – 5.38 t/ha. As a result of the research, the linear regression coefficient (b_i) determined that the plasticity of the samples under study ranged within 0.50-1.71 in terms of yield in the group of early-ripening samples. High plasticity ($b_i > 1.0$), i.e., a wide ecological norm of reaction, was characterised by six genotypes, which accounted for 40.0% of the total number of samples under study, including Orzhytsia Nova ($b_i=1.71$), Soborna ($b_i=1.69$), Manera Odeska ($b_i=1.32$) (UKR); F11208G2 ($b_i=1.08$) (ROU); CA 13014 ($b_i=1.22$), KN 40 ($b_i=1.07$) (CHN); standard – Bunchuk ($b_i=1.41$) (UKR) (Table 1).

Table 1. Parameters of plasticity and stability of the best early-ripening and short-stemmed samples of soft winter wheat by yield, 2018-2021

Sample name	Country of origin	Vegetation period, days	Yield, t/ha			Regression coefficient, b_i	Stability variance, S^2d_i
			X_{max}	X_{min}	X_{med}		
Bunchuk, standard	UKR	282	7.20	4.30	5.38	1.41	0.73
Manera Odeska	UKR	279	7.80	5.50	6.68	1.32	0.01
Orzhytsia Nova	UKR	278	7.35	4.45	6.18	1.71	0.26
Soborna	UKR	277	6.53	3.65	5.34	1.69	0.16
MV Sed	HUN	278	6.80	5.40	6.22	0.82	0.05
Centurion	ROU	279	6.70	5.82	6.58	0.50	0.00
Retezat	ROU	278	7.15	5.85	6.45	0.73	0.04
F11208G2	ROU	279	6.50	4.62	5.59	1.08	0.00
F10222G5-11	ROU	278	6.24	4.85	5.53	0.79	0.02
F 08034G1-01	ROU	278	5.83	4.55	5.23	0.72	0.00
CA 13014	CHN	276	7.22	5.20	6.59	1.22	0.64
KN 41	CHN	277	6.85	5.65	6.21	0.68	0.03
KN 40	CHN	277	6.85	4.95	5.80	1.07	0.13
T 51	CHN	276	6.45	4.80	5.62	0.94	0.02
OK 10126	USA	278	7.80	6.87	7.37	0.58	0.01
Bentley	USA	278	6.61	5.71	6.26	0.53	0.03
LSD _{0.05}		–	–	–	0.34	–	–
min		276	5.83	3.65	5.23	0.50	0.00
max		279	7.80	6.87	7.37	1.71	0.64
Average in the experiment		278	6.87	5.13	6.06	1.00	0.00

Source: compiled by the authors of this study

Genotypes with best response to changes in growing conditions ($b_i=1.0$) were not observed in the group of early-ripening samples. Low plasticity ($b_i < 1.0$), i.e., a weak response to changes in growing conditions,

was inherent in nine genotypes, which accounted for 60%. The following samples were included: Centurion ($b_i=0.50$), F 08034G1-01 ($b_i=0.72$), Retezat ($b_i=0.73$) (ROU); MV Sed ($b_i=0.82$) (HUN); KN 41 ($b_i=0.68$), T 51

($b_i=0.94$) (CHN); Bentley ($b_i=0.53$) and OK 10126 ($b_i=0.58$).

Ten genotypes (66.7%) were characterised by high productivity stability with the lowest numerical value of the stability variance ($S^2d_i=0.0$). These include the following varieties and lines: Manera Odeska ($S^2d_i=0.01$) (UKR); Centurion ($S^2d_i=0.00$), F11208G2 ($S^2d_i=0.00$), F10222G5-11 ($S^2d_i=0.00$), F 08034G1-01 ($S^2d_i=0.00$), Retezat ($S^2d_i=0.04$) (ROU); T 51 ($S^2d_i=0.02$), KH 41 ($S^2d_i=0.03$) (CHN); OK 10126 ($S^2d_i=0.01$), Bentley ($S^2d_i=0.03$) (USA); the standard is Bunchuk ($S^2d_i=0.73$) (UKR). The most unstable samples were Orzhytsia Nova ($S^2d_i=0.26$), Soborna ($S^2d_i=0.16$) (UKR); MV Sed ($S^2d_i=0.05$) (HUN); CA 13014 ($S^2d_i=0.64$), KN 40 ($S^2d_i=0.13$) (CHN).

Thus, in the group of early-ripening and short-stemmed samples, genotypes that combine a low level of plasticity and high yield stability ($b_i<1.0$) and ($S^2d_i=0.0$) prevail, the share of which is 53.3%. These include Centurion, Retezat, F10222G5-11, F 08034G1-01 (ROU); KN 41, T 51 (CHN); OK 10126, Bentley (USA). A prominent level of plasticity and unstable productivity ($b_i>1.0$) and ($S^2d_i>0.0$) were inherent in four samples (26.7%) – Orzhytsia Nova, Soborna (UKR); CA 13014, KN 40 (CHN). In addition, two genotypes were selected that combine high plasticity with a stable manifestation of yield ($b_i>1.0$) and ($S^2d_i=0.0$) – Manera Odeska (UKR) and F11208G2 (ROU), the share of which is 13.3%. According to the calculation model by S.A. Eberhart and W.A. Russell (1966), such genotypes are the most valuable because they effectively use favourable factors of growing conditions and are characterised by stable yields. The variety MV Sed (HUN) combined low plasticity and unstable yield ($b_i<1.0$) and ($S^2d_i>0.0$).

As a result of the study of plasticity and stability parameters of the best early-ripening and short-stemmed winter wheat genotypes, it was found that in the eastern

part of the Forest-Steppe of Ukraine, five varieties (33.3%) have the highest adaptive potential in combination with high yield (more than 16% above the standard): Manera Odeska (UKR), Centurion, Retezat (ROU), OK 10126, and Bentley (USA). The group of mid-ripening genotypes with a growing season varying from 283 to 286 days included the following varieties: Blahodarka Odeska, Svitohliad, Zoloto Ukrainy, Zoreslava, Rodzynka Odeska, Kruhozir, Shpalivka, MIP Feieriia (UKR); Ilona (SVK); Aspekt (DEU); Urbanus, Tacitus (AUT); Evklid, Bardotka (FRA); Flourish (CAN). The growing season of the Podoliianka mid-ripening standard was 284 days.

In the mid-ripening group, 12 sources of high yields (more than 16% above the standard) were found, including the following samples: Blahodarka Odeska, Svitohliad, Zoloto Ukrainy, Zoreslava, Rodzynka Odeska, Kruhozir, Shpalivka (UKR); Ilona (SVK); Urbanus (AUT); Evklid, Bardotka (FRA); Flourish (CAN), with a share of 80%. It was found that in the mid-ripening group of short-stemmed samples, plasticity (b_i) ranged within 0.27-2.07. The proportion of genotypes with high plasticity ($b_i>1.0$) was 40.0% of the total number of samples. These include the varieties Kruhozir ($b_i=1.52$), Rodzynka Odeska ($b_i=1.18$), Shpalivka ($b_i=1.10$) (UKR); Aspekt ($b_i=1.54$) (DEU); Tacitus ($b_i=2.07$) (AUT); Flourish ($b_i=1.83$) (CAN).

The mid-ripening samples Zoloto Ukrainy ($b_i=0.97$) (UKR) and Evklid ($b_i=0.98$) (FRA) were distinguished by the best response to changes in growing conditions ($b_i=1.0$), with a share of 13.3%. A weak response to changes in growing conditions and, accordingly, a low level of plasticity ($b_i<1.0$) was inherent in seven samples, the share of which was 46.7%. These include the following varieties: Blahodarka Odeska ($b_i=0.36$), Svitohliad ($b_i=0.59$), Zoreslava ($b_i=0.59$), MIP Feieriia ($b_i=0.72$) (UKR); Ilona ($b_i=0.43$) (SVK); Urbanus ($b_i=0.27$) (AUT); Bardotka ($b_i=0.35$) (FRA) (Table 2).

Table 2. Parameters of plasticity and stability of the best mid-ripening and short-stemmed varieties of soft winter wheat by yield, 2018-2021

Sample name	Country of origin	Vegetation period, days	Yield, t/ha			Regression coefficient, b_i	Stability variance, S^2d_i
			X_{max}	X_{min}	X_{med}		
Bunchuk, standard	UKR	282	7.20	4.30	5.38	1.41	0.73
Blahodarka Odeska	UKR	284	7.85	7.15	7.51	0.36	0.01
Svitohliad	UKR	284	8.70	6.00	7.40	0.59	3.06
Zoloto Ukrainy	UKR	285	7.85	6.14	6.78	0.97	0.10
Zoreslava	UKR	285	7.30	6.24	6.68	0.59	0.01
Rodzynka Odeska	UKR	284	7.82	5.62	6.67	1.18	0.02
Kruhozir	UKR	283	8.10	5.32	6.54	1.52	0.01
Shpalivka	UKR	283	7.40	5.40	6.27	1.10	0.01
MIP Feieriia	UKR	285	6.80	5.45	6.08	0.72	0.00
Ilona	SVK	285	7.18	6.35	6.78	0.43	0.02
Aspekt	DEU	285	7.63	4.90	5.94	1.54	0.20
Urbanus	AUT	286	7.00	6.50	6.67	0.27	0.03

Table 2. Continued

Sample name	Country of origin	Vegetation period, days	Yield, t/ha			Regression coefficient, b_i	Stability variance, S^2d_i
			X_{max}	X_{min}	X_{med}		
Tacitus	AUT	285	7.87	4.26	5.54	2.07	0.69
Evklid	FRA	283	7.73	5.88	6.79	0.98	0.03
Bardotka	FRA	286	7.07	6.15	6.58	0.35	0.21
Flourish	CAN	285	7.58	3.95	6.40	1.83	1.22
LSD _{0.05}		-	-	-	0.31	-	-
min		283	6.80	3.95	5.54	0.27	0.00
max		286	8.70	7.15	7.51	2.07	3.06
Average in the experiment		285	7.57	5.60	6.50	1.00	0.00

Source: compiled by the authors of this study

Nine genotypes (60%) were characterized by high stability with the lowest numerical value of the stability variance ($S^2d_i=0.0$). These included the following varieties: MIP Feieriia ($S^2d_i=0.00$), Blahodarka Odeska ($S^2d_i=0.01$), Zoreslava ($S^2d_i=0.01$), Kruhozir ($S^2d_i=0.01$), Shpalivka ($S^2d_i=0.01$), Rodzynka Odeska ($S^2d_i=0.02$) (UKR); Ilona ($S^2d_i=0.02$) (SVK); Urbanus ($S^2d_i=0.03$) (AUT); Evklid ($S^2d_i=0.03$) (FRA). The most unstable samples ($S^2d_i>0$) included Svitohliad ($S^2d_i=3.06$), Zoloto Ukrainy ($S^2d_i=0.10$) (UKR); Aspect ($S^2d_i=0.20$) (DEU); Tacitus ($S^2d_i=0.69$) (AUT); Bardotka ($S^2d_i=0.21$) (FRA), and Flourish ($S^2d_i=1.21$) (CAN).

Therefore, the group of mid-ripening and short-stemmed samples is dominated by genotypes that combine a low level of plasticity and high yield stability ($b_i<1.0$) and ($S^2d_i=0.0$), the share of which is 33.3%. These include the varieties MIP Feieriia, Blahodarka Odeska, Zoreslava (UKR); Ilona (SVK); Urbanus (AUT). Three genotypes (20%) were identified, which combine high plasticity with a stable manifestation of productivity ($b_i>1.0$) and ($S^2d_i=0.0$), namely: Rodzynka Odeska, Kruhozir, Shpalivka (UKR). Aspekt (DEU), Tacitus (AUT), and Flourish (CAN) varieties were characterised by high sensitivity to growing conditions with unstable productivity ($b_i>1.0$) and ($S^2d_i>0.0$), the share of which is 20%. Less adapted to growing conditions were Svitohliad (UKR) and Bardotka (FRA), which combined a low level of plasticity with unstable productivity ($b_i<1.0$) and ($S^2d_i>0.0$), the share of which was 13.3%. It is worth noting the variety Evklid (FRA), which combined best response to changes in growing conditions with stable productivity ($b_i=1.0$) and ($S^2d_i=0.0$). The sample of Zoloto Ukrainy (UKR) also combined the best response to changes in growing conditions, but the yield was less stable ($b_i=1.0$) and ($S^2d_i>0.0$).

It was found that among the best mid-ripening and short-stemmed winter bread wheat genotypes in the eastern part of the Forest-Steppe of Ukraine, eight varieties (53.3%) have the highest adaptive potential in combination with high yield (more than 16% above the standard): Blahodarka Odeska, Zoreslava, Rodzynka Odeska, Kruhozir, Shpalivka (UKR); Ilona (SVK); Urbanus (AUT); Evklid (FRA). The group of late-ripening genotypes with a vegetation period ranging from 287 to 290 days included Fagus, Achim, Dromos, Bonanza, Nordkap, Rotax, KWS Malibu, Akrotas, Mattus (DEU); RGT Reform, Matchball, Praktik, Sailor, Boomer, Memory (FRA). The growing season of the late-ripening standard Yuivata 60 (UKR) was 288 days. In the late-ripening group of short-stemmed genotypes, five sources of high yields (more than 16% above the standard) were identified, including Fagus, Achim, Dromos, Bonanza (DEU); RGT Reform (FRA), whose share was 33.3%.

It was found that in this group of the varieties under study, plasticity (b_i) ranged from 0.13 to 2.18. The proportion of genotypes with high plasticity ($b_i>1.0$) was 53.3% of the total number of samples. These include Akrotas ($b_i=2.18$), Mattus ($b_i=1.38$), KWS Malibu ($b_i=1.21$), Achim ($b_i=1.15$), Dromos ($b_i=1.15$), Nordkap ($b_i=1.11$) (DEU); Sailor ($b_i=1.17$), RGT Reform ($b_i=1.12$) (FRA). Medium plastic genotypes with the best response to changes in growing conditions ($b_i=1.0$) were not observed in the group of late-ripening and short-stemmed samples. A low level of plasticity ($b_i<1.0$) was inherent in seven varieties, which accounted for 46.7% of the total number of samples under study. These included the following varieties: Rotax ($b_i=0.58$), Bonanza ($b_i=0.64$), Fagus ($b_i=0.66$) (DEU); Praktik ($b_i=0.13$), Memory ($b_i=0.73$), Boomer ($b_i=0.78$), Matchball ($b_i=0.91$) (FRA) (Table 3).

Table 3. Parameters of plasticity and stability of the best late-ripening and short-stemmed varieties of soft winter wheat by yield, 2018-2021

Sample name	Country of origin	Vegetation period, days	Yield, t/ha			Regression coefficient, b_i	Stability variance, S^2d_i
			X_{max}	X_{min}	X_{med}		
Bunchuk, standard	UKR	282	7.20	4.30	5.38	1.41	0.73
Fagus	DEU	288	8.33	6.30	7.30	0.66	0.35

Table 3. Continued

Sample name	Country of origin	Vegetation period, days	Yield, t/ha			Regression coefficient, b_i	Stability variance, S^2d_i
			X_{max}	X_{min}	X_{med}		
Achim	DEU	287	8.70	5.80	6.83	1.15	0.00
Dromos	DEU	287	8.33	4.11	6.56	1.15	4.36
Bonanza	DEU	287	7.53	5.00	6.43	0.64	1.73
Nordkap	DEU	288	7.80	5.00	6.00	1.11	0.00
Rotax	DEU	290	6.53	4.63	5.55	0.58	0.47
KWS Malibu	DEU	290	7.47	4.32	5.48	1.21	0.14
Akratos	DEU	287	8.40	4.92	5.84	2.18	3.59
Mattus	DEU	288	6.58	2.13	4.40	1.38	2.29
RGT Reform	FRA	288	8.80	6.00	6.97	1.12	0.04
Matchball	FRA	287	7.73	4.75	6.19	0.91	1.15
Praktik	FRA	288	6.05	5.67	5.84	0.13	0.01
Sailor	FRA	290	7.62	3.45	5.81	1.17	3.67
Boomer	FRA	288	7.05	4.37	5.73	0.78	1.19
Memory	FRA	290	6.50	3.76	5.25	0.73	1.74
LSD _{0.05}		-	-	-	0.40	-	-
min		287	6.05	2.13	4.40	0.13	0.00
max		290	8.80	6.30	7.30	2.18	4.36
Average in the experiment		288	7.54	4.53	5.91	1.00	0.00

Source: compiled by the authors of this study

A low level of plasticity ($b_i < 1.0$) was inherent in seven varieties, which accounted for 46.7% of the total number of samples under study. These include the following varieties: Rotax ($b_i = 0.58$), Bonanza ($b_i = 0.64$), Fagus ($b_i = 0.66$) (DEU); Praktik ($b_i = 0.13$), Memory ($b_i = 0.73$), Boomer ($b_i = 0.78$), Matchball ($b_i = 0.91$) (FRA). Four genotypes (26.7%) were characterised by high productivity stability ($S^2d_i = 0.0$). These included the following varieties: Achim ($S^2d_i = 0.00$), Nordkap ($S^2d_i = 0.00$) (DEU); Praktik ($S^2d_i = 0.01$), RGT Reform ($S^2d_i = 0.04$) (FRA). In the sample of late-ripening samples, the share of the most unstable samples ($S^2d_i > 0.0$) was 73.3%, which included Dromos ($S^2d_i = 4.36$), Akkratos ($S^2d_i = 3.59$), Mattus ($S^2d_i = 2.29$), Bonanza ($S^2d_i = 1.73$), Rotax ($S^2d_i = 0.47$), Fagus ($S^2d_i = 0.35$), KWS Malibu ($S^2d_i = 0.14$) (DEU); Sailor ($S^2d_i = 3.67$), Memory ($S^2d_i = 1.74$), Boomer ($S^2d_i = 1.19$), Matchball ($S^2d_i = 1.15$) (FRA).

Thus, the group of late-ripening and short-stemmed samples is dominated by genotypes that combine a low level of plasticity with yield instability ($b_i < 1.0$) and ($S^2d_i > 0.0$), the share of which is 40%. These include the Fagus, Bonanza, Rotax (DEU); Matchball, Boomer, Memory (FRA) varieties. Varieties Achim, Nordkap (DEU) and RGT Reform (FRA) were distinguished by a combination of high plasticity and yield stability ($b_i > 1.0$) and ($S^2d_i = 0.0$), their share is 20% of the total number of the late-ripening varieties under study. Varieties Dromos, KWS Malibu, Akkratos, Mattus (DEU); Sailor (FRA) were characterised by high sensitivity to growing conditions with unstable productivity ($b_i > 1.0$) and ($S^2d_i > 0.0$), the share of which is also 33.3%. Variety Praktik (FRA) was characterised by low sensitivity to growing conditions

with stable productivity ($b_i > 1.0$) and ($S^2d_i = 0.0$). Based on the conducted study, it was found that among the best late-ripening and short-stemmed winter bread wheat genotypes, the highest adaptive potential in combination with high yields (more than 16% above the standard) was achieved by Achim (DEU) and RGT Reform (FRA), with a share of 13.3%.

Proceeding from the above findings, it can be argued that among short-stemmed winter bread wheat genotypes there are sources characterised by a combination of high levels of adaptive potential and yield in the eastern part of the Forest-Steppe of Ukraine, which are mostly represented in the group of mid-ripening samples. The in-depth search for such genotypes allows thoroughly differentiating the genetic diversity of winter soft wheat by adaptive properties and to identify the best varieties and breeding lines of the Ukrainian plant gene pool to meet the needs of humanity.

DISCUSSION

Due to the abnormally high air temperatures and droughts observed in Ukraine in recent decades, as noted by Yu. Kolupaev *et al.* (2023), there are prerequisites for an in-depth investigation of the adaptive properties of plants and the selection of the best gene pool for breeding. Varieties of different ecological and geographical origins are being introduced into production, which differ in their physiological and morphological-biological characteristics, specifically: winter hardiness, length of the growing season, height, structural elements of yield, etc., and therefore it is quite significant and relevant, especially with climate change, to differentiate the

source material by yield and adaptive properties in relation to the region of their cultivation (Bondarenko & Nazarenko, 2020). Generally, the level of genotype-environment interaction (Studnicki *et al.*, 2019), weather conditions (Harkness *et al.*, 2020), and sowing dates (Petrychenko *et al.*, 2021) have the greatest influence on the formation of a variety's yield.

According to many scientists, namely J. Laugerotte *et al.* (2022), the stress resistance of winter wheat varieties to biotic and abiotic factors is crucial for the stabilisation and development of agriculture. Ukrainian researchers M. Sydorenko and S. Chebotar (2020) note that among abiotic factors, as environmental stressors affecting plant homeostasis, the problems of water deficit caused by drought, usually accompanied by hot temperatures, which is widely predicted with climate change, are becoming increasingly important. Chinese scientists W-G. Li *et al.* (2022) note that under conditions of dehydration, there are considerable disruptions in metabolic processes, protein breakdown, changes in the chemical state of the cytoplasm, and a decrease in the amount of organic matter accumulated by plants, which often leads to a significant decrease in gross grain yields and yield instability.

The problem of high and stable yields by a genotype, due to the intensification of cultivation technologies and the creation of high-intensity short-stemmed varieties, does not cause consensus among scientists on the possibility of solving this problem. Ukrainian scientists S. Lyfenko *et al.* (2021) note that semi-intensive, medium-sized varieties mostly have horizontal leaves, which better protects the soil surface from drying out and overheating, and yield formation becomes more stable compared to high-intensive varieties. During the formation of a productive stem stand of 600-800 pcs./m², high-intensity, short-stem varieties are quite significant for them to have an erectoid leaf position, which contributes to better illumination of the leaves of different tiers. A. Zviahin *et al.* (2008) argue that there are no soft winter wheat varieties that can combine high resistance to stress factors, including drought, and high yield stability. However, T. Yurchenko *et al.* (2020), researchers at the the V.M. Remeslo Myronivka Institute of Wheat under the National Academy of Agrarian Sciences of Ukraine, note that the negative correlation between stress resistance and yield is not absolute, and therefore there are prospects for the best combination of these traits in one genotype. It was found that the variety Oberih Myronivskiy combines a high level of yield and is characterised by high drought tolerance according to a range of drought tolerance indices (DSI – drought susceptibility index; TOL – drought tolerance index; MP – mean productivity; YSI – yield stability index; YI – yield index; STI – stress tolerance index; GMP – geometric mean productivity).

A range of scientists, including K. Dhiwar *et al.* (2020), N. Suresh *et al.* (2020) note that highly plastic plant genotypes, characterised by high yields under

improved growing conditions, but with their deterioration or reduction of the agrophysical background, are most often characterised by a considerable decrease in yield levels. Samples with low plasticity show less variability in yield under different growing conditions and are characterised by the formation of low, but mostly stable yields even under stressful growing conditions. UK scientists J. Pennacchi *et al.* (2019) identified four modern British soft winter wheat varieties – Gladiator, Humber, Mercato, and Zebedee – which combine relatively high yield potential with stable yields over three years of contrasting growing conditions in the UK.

According to Yu. Lavrynenko *et al.* (2020), a necessary step towards the development of highly promising and adaptive winter wheat varieties is to assess not only the potential yield, but also the parameters of its plasticity and stability, which reflect the adaptive properties of genotypes. In a breeding process aimed only at increasing yields, the adaptive potential of varieties decreases over time. Thus, the findings of the study on the adaptability of high-yielding varieties and breeding lines of winter bread wheat in the eastern part of the Forest-Steppe of Ukraine are unique, and the identified sources require further research, including biochemical studies. Summarising the above, it is believed that with a targeted search for the necessary highly adaptive and productive winter bread wheat genotypes among different ripeness groups, according to the parameters of plasticity and yield stability, it is quite possible to identify varieties that are the most adapted to certain growing conditions.

CONCLUSIONS

The highest genetic potential for adaptability among short-stemmed soft winter wheat genotypes in the conditions of the eastern part of the Forest-Steppe of Ukraine in combination with high yield are mid-ripening varieties, namely: Blahodarka Odeska ($b_i=0.36$; $S^2d_i=0.01$), Zoreslava ($b_i=0.59$; $S^2d_i=0.01$), Rodzynka Odeska ($b_i=1.18$; $S^2d_i=0.02$), Kruhozir ($b_i=1.52$; $S^2d_i=0.01$), Shpalivka ($b_i=1.10$; $S^2d_i=0.01$) (UKR); Ilona ($b_i=0.43$; $S^2d_i=0.02$) (SVK), Urbanus ($b_i=0.27$; $S^2d_i=0.03$) (AUT), and Evklid ($b_i=0.98$; $S^2d_i=0.03$) (FRA), the share of which is 53.3%. Early-ripening varieties were slightly inferior to them in quantitative composition – Manera Odeska ($b_i=1.32$; $S^2d_i=0.01$) (UKR), Centurion ($b_i=0.50$; $S^2d_i=0.00$), Retezat ($b_i=0.73$; $S^2d_i=0.04$) (ROU), OK 10126 ($b_i=0.58$; $S^2d_i=0.01$), and Bentley ($b_i=0.53$; $S^2d_i=0.03$) (USA), which made up 33.3% of the total sample of the group of samples under study. The smallest share of well-adapted and high-yielding varieties (13.3%) was in the group of late-ripening varieties, which included Achim ($b_i=1.15$; $S^2d_i=0.00$) (DEU) and RGT Reform ($b_i=1.12$; $S^2d_i=0.04$) (FRA).

It was found that plasticity (b_i) with increasing duration of the vegetation period increased from 1.71 – the maximum level of its manifestation in the early-ripening group to 2.18 in the late-ripening group.

Therewith, the stability parameters had the opposite nature, which according to the variance of stability (S^2d_i) in the early-ripening group within 0.00-0.64, in the mid-ripening group – within 0.00-3.06, and in the late-ripening group – within 0.00-4.36. The proportion of samples with high plasticity ($b_i > 1.0$) in the early- and mid-ripening groups was 40.0% each, and 53.3% in the late-season group. Genotypes with the best response to changes in growing conditions ($b_i = 1.0$) were observed only in the group of mid-ripening samples, which included Zoloto Ukrainy ($b_i = 0.97$) (UKR) and Evklid ($b_i = 0.98$) (FRA), with a share of 13.3%. High stability ($S^2d_i = 0.0$) was observed in 66.7% of the samples in the early-ripening group, 60% in the medium-ripening group, and 26.7% in the late-ripening group.

The identified high-yielding and short-stemmed sources of different ripeness groups with high adaptive

potential are valuable source material for the development of new and highly promising winter bread wheat varieties adapted to stressful growing conditions in the eastern part of the Forest-Steppe of Ukraine. The prospect of further research is to investigate the morphological, physiological, and anatomical features of the architectonics of plants with different adaptive properties of the material. The study of the anatomical structure of the stem and ear, the structure of the leaf apparatus will open more opportunities for systematising the research findings.

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CONFLICT OF INTEREST

The authors of this study declare no conflict of interest.

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Адаптивний потенціал короткостеблих генотипів пшениці м'якої озимої в умовах східного Лісостепу України

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Анотація. Серед невирішених питань селекції короткостеблих генотипів пшениці м'якої озимої різних груп стиглості залишається актуальною проблема отримання високих та стабільних врожаїв, без зниження адаптивного потенціалу в умовах прояву лімітуючих факторів зовнішнього середовища, які періодично виникають у різних агроекологічних умовах вирощування. Попереднє виділення відповідних джерел з поєднанням необхідних адаптивних властивостей є досить важливим етапом на шляху створення високоперспективних сортів та покращення генофонду рослин України. Мета досліджень – визначення рівня адаптивного потенціалу в короткостеблих генотипів пшениці м'якої озимої різних за тривалістю вегетаційного періоду, вивчення пластичності та стабільності врожайності, а також виділення високоадаптивного вихідного матеріалу для умов східної частини Лісостепу України. Для досягнення поставленої мети використовували загальнонауковий, польовий та дисперсійний методи досліджень. Визначено, що в умовах східної частини Лісостепу України, серед короткостеблих генотипів пшениці м'якої озимої, частка з найвищим генетичним потенціалом адаптивності у поєднанні з високою врожайністю (понад 16 % до стандарту) найбільшою є у групі середньостиглих сортів і складає 53,3 %. До них відносяться переважно вітчизняні генотипи, а саме: Благодарка одеська, Зореслава, Родзинка одеська, Кругозір, Шпалівка (UKR); Ilona (SVK) Urbanus (AUT) та Evklid (FRA). Серед ранньостиглих зразків частка таких генотипів складала 33,3 %, а у групі пізньостиглих сортів – 13,3 %. Висока стабільність урожайності ($S^2d_i=0,0$) була характерною для 66,7 % зразків ранньостиглої групи, 60 % – середньостиглої та 26,7 % – пізньостиглої. Виділені джерела є цінним вихідним матеріалом для створення нових та високоперспективних сортів пшениці м'якої озимої, адаптованих до умов вирощування у східній частині Лісостепу України

Ключові слова: урожайність; пластичність; стабільність; лімітуючі чинники; норма реакції; джерело; сорт