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A new perspective on the concept of stability in common winter wheat (*Triticum aestivum* L.) and an indirect approach for integrating genotypic contrast

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Abstract: This study presents a novel concept for stability and adaptability in common winter wheat (*Triticum aestivum* L.), based on a quantitative assessment of the contrast between genotypes. In classical models, stability is often considered within the framework of either dynamic or static concepts, but without accounting for the actual genetic and phenotypic diversity present in the tested populations. The newly developed model integrates this aspect through functional modeling of the relationship between productivity and stability, utilizing a rotated biplot and indirectly integrating genotype contrast through functional modeling in the final evaluation. The model was applied to data from 13 newly developed lines and three standard cultivars, grown under highly contrasting agroecological conditions over three consecutive years. Analyses indicate that the model provides a more objective and precise ranking of the lines, enabling the simultaneous identification of high-yielding and stable genotypes, as well as those with broad or narrow adaptability. The results show a high correlation between the new parameters and classical models, confirming the scientific and practical adequacy of the proposed system. The integration of contrast eliminates distortions caused by extremely divergent genotypes and facilitates the selection of lines with balanced characteristics for practical breeding under variable conditions. The new model is characterized by universality and high efficiency in the comprehensive assessment of wheat genotypes.

Keywords: stability; adaptability; contrast; common winter wheat; breeding; functional modeling

INTRODUCTION

The development of high-yielding varieties of common winter wheat is a complex breeding process that involves not only directly increasing yield, but also ensuring that the high productive potential can be maintained regardless of environmental conditions (Tsenov and Gubatov, 2019; Tsenov et al., 2022a; Tsenov et al., 2022b; Tsenov et al., 2023; Sharma et al., 2025). This necessitates the evaluation of breeding materials not only empirically in terms of productivity, but also through the analysis of results from different growing seasons and various soil-climatic regions (Tahir et al., 2023; Alemayehu et al., 2025).

Such analysis makes it possible to identify parameters related to the stability and adaptability of individual genotypes, as well as to study their complex response to a range of environmental conditions.

In practice, particularly during the development of new varieties, there are often a series of environmental conditions that differ drastically both from each other and from the long-term regional trends (Stoyanov and Baychev, 2018; Stoyanov, 2021; Tahir et al., 2023). This leads to significant differences in yield among a group of genotypes, as well as diverse trends among their values (Mukoyi et al., 2018; Sharma et al., 2025). Such responses are associated with genotype ×

environment interaction and determine the varying stability of each genotype under study (Stoyanov, 2021; Tahir et al., 2023). At the same time, under contrasting environmental conditions, so-called crossover interactions also occur, which are associated with differences in adaptability between genotypes.

The two yield properties - stability and adaptability – have been the subject of various definitions and concepts, and in practice cannot be directly and solely associated with a specific mathematical or statistical method (Stoyanov, 2025a). This raises the extremely important breeding question of the extent to which existing concepts, methods, models, approaches, and parameters enable a realistic assessment of whether a genotype is stable or adaptable. These questions also arise from the fact that the use of two or more methods often yields diverse or even contradictory results for the same genotypes and yield values (Tsenov and Gubатов, 2019). Some researchers use a combination of parameters and combine evaluations from different approaches to obtain maximum information for appropriately ranking their tested lines or varieties (e.g. Tsenov and Gubатов, 2019; Desheva and Deshev, 2021; Uhr et al., 2021; Dimitrov et al., 2022; Tsenov et al., 2022a; Dragov et al., 2024; Stoyanov, 2024; Stoyanov, 2025b). Another common practice is to use one or two different models that have gained popularity and are considered to provide relatively reliable information (e.g., Stoyanov and Baychev, 2018; Stoyanov and Baychev, 2023; Tahir et al., 2023; Khare et al., 2024; Kendal, 2024; Alemayehu et al., 2025; Stoyanov, 2025c).

Although both approaches have their advantages for practical breeding objectives, clarifying whether a genotype is inherently stable and adaptable, rather than only under certain environmental conditions, is not possible for several reasons. Firstly, there are several competing concepts of stability, often with conflicting perspectives. At the same time, most developed models are based on three main statistical approaches – regression analysis, principal component analysis, and analysis of variance – which, due to their mathematical peculiarities, cannot yield identical

results. Such limitations of stability and adaptability with regard to their direct evaluation indicate that what is needed is not a multitude of assessment models, but a quantitative concept forming the basis for developing a unified model for their evaluation.

Furthermore, wheat as a crop is characterized by an extremely broad genetic base, enormous genetic diversity, and geographical differentiation, which distinguishes it from other cultivated species (Bonjean and Angus, 2001; Stoyanov, 2025a). For this reason, in wheat, one can speak not only of contrasting periods of cultivation, but also of contrasting genotypes. The existence of genotypes that differ greatly in their requirements for environmental conditions and in their development under the same environment is a feature that should not be neglected when analyzing yield stability and adaptability.

The aim of the present study is to substantiate a concept for stability and adaptability in common winter wheat; to develop a model for evaluating stability and adaptability based on this concept; and to apply and validate this model in practice, in comparison with accepted models for establishing similar characteristics.

MATERIALS AND METHODS

Plant Material and Growing Conditions

To achieve the stated objective, productivity data were used for 13 newly bred lines of common winter wheat, designated from G1 to G13. The lines were grown in drilled plots, each with an area of 10 m², in four replicates arranged according to the standard randomized block method. Sowing was performed mechanically at the standard time for common winter wheat, at a density of 550 seeds per m². In addition to the studied lines, the standard varieties Lazarka, Dragana, and Pchelina were included as checks. The plots were harvested at full maturity, and yield from each plot was recorded separately. The trial was conducted over three consecutive cropping years – 2019/2020, 2020/2021, and 2021/2022. The genotypes and meteorological characteristics, as well

as the specifics of these cropping years concerning the development of the plant material used, are described in detail in our previous publication (Stoyanov, 2025a).

Conceptual Framework and Model Application

The stability and adaptability of common winter wheat genotypes were evaluated using a newly developed concept that integrates genotypic contrast into the productivity–stability system as proposed by our previous study – Stoyanov (2025a). Within this framework, a genotype is considered stable and adaptable if, under sufficiently contrasting environments and within a contrasting set of genotypes, it follows a predictable productivity response. A detailed theoretical rationale for this concept is provided in the Discussion section.

Model Development

Based on this framework, a model was constructed to generate parameters for stability and adaptability assessment while accounting for

genotypic contrast. Productivity was calculated using the Environment Adjusted Yield Model (EAYM), and stability was assessed through S_{EAYM} (according to Stoyanov, 2021). The relationship between productivity and stability was then approximated by a quadratic function, and the corresponding biplot was rotated to adjust both parameters according to the observed correlation. This transformation resulted in two new indices: FM_{EAYM} (Function Modeled EAYM) and FM_{SEAYM} (Function Modeled S_{EAYM}), which simultaneously reflect productivity, stability, and genotypic contrast.

The integration of contrast into the productivity–stability system was achieved through a functional transformation of productivity values (x_i) and stability parameter values (r_i). For n genotypes, a quadratic function of the type $y_i = f(x_i) = ax_i^2 + b$ was approximated (Figure 1). The values of y_i represent the modeled stability response. From each point with coordinates (x_i, r_i), a perpendicular (d) was dropped to the function, and an angle (α) was formed between the ordinate and the function (Figure 2).

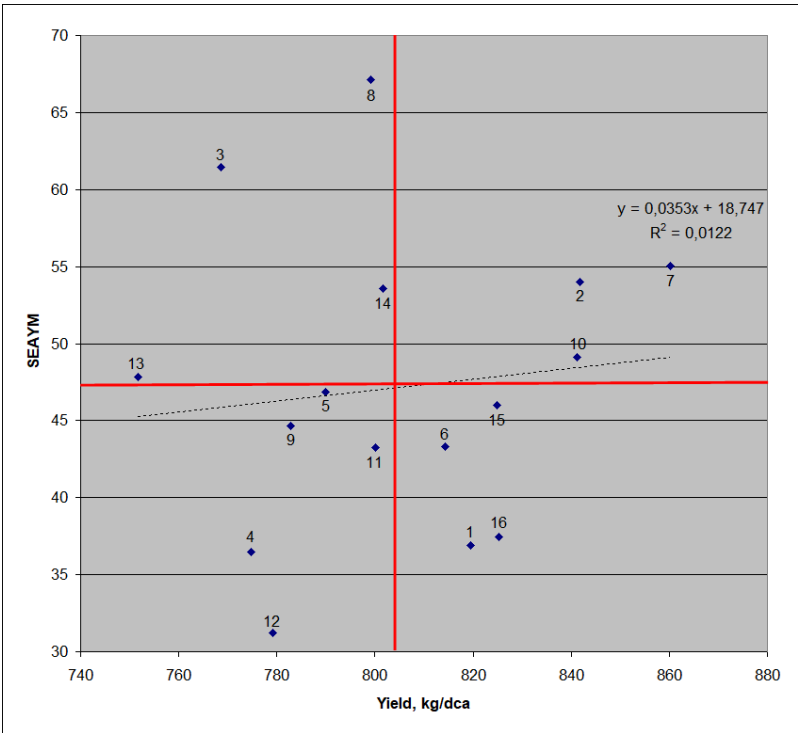


Figure 1. Biplot combining data for yield and the stability parameter, and the function between them

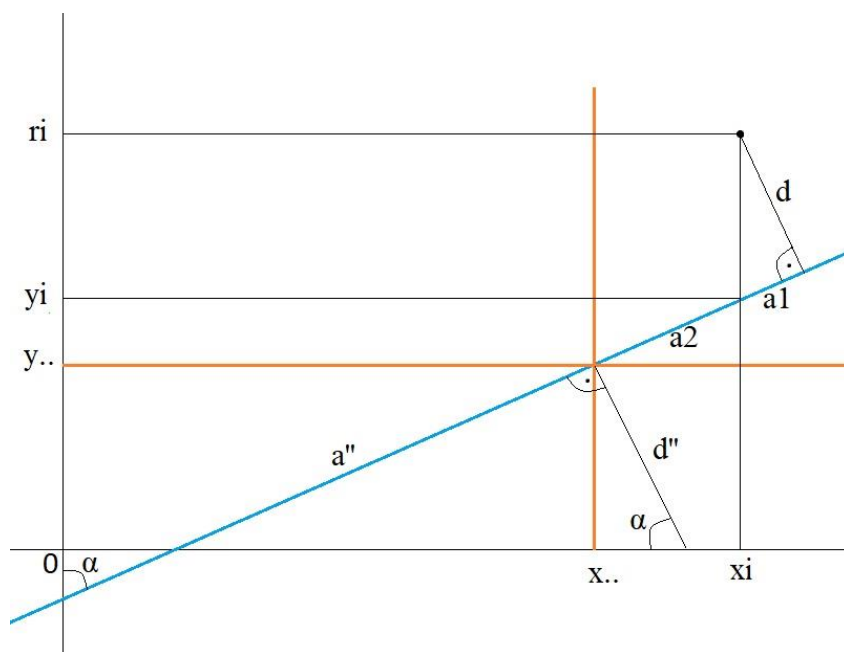


Figure 2. Graph of the parameters calculated during the functional integration of contrast into the stability assessment parameter

Rotation of the coordinate system by $(90^\circ - \alpha)$ yielded transformed values of productivity (a') and stability (d'), thereby indirectly integrating genotypic contrast (Figure 2).

The mathematical transformations underlying the recalculation of a' and d' are presented in formulas (1)-(10), while the procedure is illustrated in Figures 1 and 2.

$$a' = a + a'' \quad (1)$$

$$a = a_1 + a_2 \quad (2)$$

$$a'' = \sqrt{(\bar{x} + x_m)^2 + (f(\bar{x} + x_m) - f(0))^2} \quad (3)$$

$$x_m = \sqrt{|\bar{r} - f(\bar{x})|^2 - |(\bar{r} - f(\bar{x})) \cdot \sin \alpha|^2} \cdot \sin \alpha \quad (4)$$

$$\sin \alpha = \frac{\bar{x}}{\sqrt{\bar{x}^2 + (f(\bar{x}) - f(0))^2}} \quad (5)$$

$$a_1 = \sqrt{|r_i - f(x_i)|^2 - |(r_i - f(x_i)) \cdot \sin \alpha|^2} \quad (6)$$

$$a_2 = \frac{x_i - (x_m + \bar{x})}{\sin \alpha} \quad (7)$$

$$d' = d + d'' \quad (8)$$

$$d = (r_i - f(x_i)) \cdot \sin \alpha \quad (9)$$

$$d'' = \frac{f(\bar{x} + x_m)}{\sin \alpha} \quad (10)$$

a' – the rotated value of x_i

a_1 – the segment enclosed between the point (x_i, y_i) and the point where the perpendicular d intersects the function

a_2 – the segment enclosed between the points $(\bar{x}, \bar{y})$ and (x_i, y_i)

a – the segment formed by a_1 and a_2

a'' – the segment from the point where the function intersects the ordinate to $(\bar{x}, \bar{y})$

$f(0)$ – the value of the function at $x = 0$

x_m – deviation of the mean stability from the functional relationship

d' – the rotated value of r_i

d – the perpendicular segment between (x_i, r_i) and the function

d'' – the segment from the point $(\bar{x}, \bar{y})$ to the abscissa, perpendicular to the function

For each genotype, the rotated values a' and d' represent their coordinates in the transformed system. The value of a' corresponds to modeled

yield adjusted for genotypic contrast, while the value of d' corresponds to the selected stability parameter with contrast indirectly integrated. In the present study, the adjusted values a' and d' are denoted as FM_{EAYM} and FM_{SEAYM} , respectively.

A detailed theoretical justification for the choice of models and the integration of genotypic contrast is presented in the Discussion section. In practical terms, these transformations allow the simultaneous evaluation of yield performance and stability while correcting for genotypic contrast, thus aligning the model more closely with breeding objectives.

Statistical Analysis

The developed model was applied to the yield data for the studied common winter wheat genotypes. FM_{EAYM} and FM_{SEAYM} were included in a biplot, and genotypes combining high productivity and stability were identified. To evaluate the adequacy of the model, a comparison was made between the developed method and the most widely used practical models for stability assessment: the regression model of Eberhart and Russell (1966), variance by Shukla (1972), ecovalence by Wricke (1962), relative stability (s_{gi}), general adaptive ability (OAC), and specific adaptive ability (CAC) by Kilchevskii and Khotyleva (1989), as well as AMMI analysis according to the methodology described by Gauch (1992). A Pearson correlation analysis was conducted between the values obtained from the studied models. For data processing and for calculating modeled values and parameters according to Kilchevskii and Khotyleva (1989), MS Office Excel 2003 was used; for analyses according to Eberhart and Russell, Shukla, and Wricke, the StabilitySoft software package (Pour-Aboughadareh et al., 2019) was used; for AMMI analysis, the AMMISOFT software was used; and for the correlation analysis – IBM SPSS Statistics, v.19.

RESULTS

The highly contrasting environmental conditions observed during the study periods resulted

in average yield values for the individual genotypes that do not provide a good basis for accurate ranking. This is due to the complex genotype $\times$ environment interaction, which, although relatively weak compared to the effect of the environment itself, leads to very different yield rankings among the studied lines. For this reason, a more reliable picture of mean productivity is given by the modeled values obtained through the application of EAYM (Table 1).

For the 2019/2020 season, the highest EAYM values were recorded for genotypes G4, G9, and G12, while the lowest were observed for G5, G11, and G8. In the following growing season (2020/2021), the best results for the same modeled parameter were seen in lines G13, G7, and G8, with the lowest in G6, G9, and G10. In both periods, the standard varieties were ranked identically in terms of their values – Lazarka showed the highest EAYM values, followed by Dragana, with Pchelina exhibiting the lowest. It is notable that, compared to the other genotypes included in the study, Pchelina has a very low modeled productivity. During the third cropping period, the highest modeled values were recorded for G4, G5, and G12, and the lowest for G1, G8, and G9. The standard varieties were ranked differently compared to the previous two periods, with Dragana achieving the highest EAYM value, followed by Pchelina, and Lazarka with the lowest results.

On average, over the entire study period, the highest modeled productivity according to EAYM was observed in G4, G7, and G12, and the lowest in G1, G9, and G10. These genotypes have significantly higher values than the mean for the entire study period. Nevertheless, their ranking differs from that based on actual yield values, with line G13 exhibiting higher productivity than G12 (according to Stoyanov (2025a)). This indicates that environmental conditions mask certain effects and prevent some genotypes from being correctly ranked according to their productive potential. A particularly illustrative example is genotype G5, for which the difference between the rankings based on actual and modeled values is five positions, indicating that this genotype is highly influenced by contrasting growing con-

Table 1. Results for EAYM and S_{EAYM} of the studied common winter wheat lines

Genotype	2019/2020	2020/2021	2021/2022	Average	S_{EAYM}
Lazarka	460,7	***937,4	1171,5	856,5	36,93
Dragana	450,2	*872,5	***1364,9	***895,8	54,00
Pchelina	400,0	748,3	**1341,8	830,0	61,48
G1	457,4	801,0	1175,4	811,3	36,46
G2	432,3	822,3	1256,0	836,8	46,87
G3	456,1	861,6	1255,3	857,7	43,29
G4	***493,1	820,8	***1431,9	***915,3	55,05
G5	380,0	843,2	***1375,7	866,3	67,12
G6	**474,4	730,5	1277,8	827,6	44,66
G7	451,4	***905,7	1313,7	***890,3	49,10
G8	421,9	***924,3	1183,9	843,4	43,25
G9	***490,6	782,2	1158,7	810,5	31,22
G10	450,8	683,5	1264,4	799,5	47,81
G11	413,5	854,4	1297,8	855,3	53,56
G12	***487,7	798,6	*1326,2	*870,8	45,98
G13	*466,0	***930,9	1191,2	862,7	37,48
Average	449,1	832,3	1274,1	851,9	-
<i>LSD0.05</i>	<i>15,91</i>	<i>36,25</i>	<i>40,46</i>	<i>15,82</i>	-
<i>LSD0.01</i>	<i>20,91</i>	<i>47,64</i>	<i>53,17</i>	<i>20,80</i>	-
<i>LSD0.001</i>	<i>26,71</i>	<i>60,86</i>	<i>67,92</i>	<i>26,57</i>	-

ditions. This is further confirmed by the S_{EAYM} value for the same genotype, which is the highest under the current conditions.

At the same time, the S_{EAYM} parameter allows the stability of all genotypes to be determined under the same contrasting conditions. Figure 3 presents the effects of EAYM and S_{EAYM} and the combinations of productivity and stability for the individual studied lines of common winter wheat. Unlike Figure 1, where the biplot combines yield and SEAYM values, when combined with EAYM, it is found that, in practice, two lines – G5 and G11 – are characterized by higher mean productivity based on modeled values than the mean for actual yield. This indicates that the contrasting environmental conditions mask the real productive potential of these two genotypes, due to the accumulation of certain effects in the arithmetic means. The graph allows the identification of those genotypes that are both

highly productive and stable. The best combination of productivity and stability is observed in lines G3, G12, and G13, as well as the standard variety Dragana. Good and very good productivity, but with above-average stability under contrasting conditions, is found in lines G4, G5, G7, and G11, as well as the standard Lazarka. Below-average productivity combined with high stability is observed in lines G1, G2, G6, G8, and G9, while low productivity and low stability under contrasting conditions are combined in G10 and the standard Pchelina. Despite these results, the graph does not allow for the simultaneous comparison of data with the contrast between genotypes and for the evaluation of their adaptability.

When a linear function is constructed between EAYM and S_{EAYM} (Figure 4), it is found that the distance from the function line to each point, for each specific genotype, is different. The closer a genotype is to this line, the more valid

is the statement that, in this specific case, more productive genotypes are characterized by lower stability. If the regression line has a negative slope, then the higher the productivity, the more stable the genotype located closer to the line will be. Regardless of the slope, the lower a genotype is located from the line, the more stable it is; the higher it is, the less stable. It should be noted that the more positive the slope of the function line, the more genotypes there are that are high-yielding but with low stability, or low-yielding and highly stable. This trend is widely observed in practice and has been repeatedly reported in studies with various genotypes (e.g. Calderini and Slafer, 1999; Mustăţea et al., 2009; Abd El-Shafi et al., 2014; Gomaa et al., 2018; Curin et al., 2021). If the slope of the function line is negative, this means that the predominant genotypes are both highly productive and highly stable, or low-yielding and unstable. This type of genotype $\times$ environment interaction is more of an exception than a feature of a real population of genotypes. Therefore, the slope of the function line can be considered a measure of contrast between genotypes. This is due to the fact that the smaller the slope, the lower the contrast between genotypes, as their productivity will be formed completely independently of their stability. Conversely, the greater the slope, the more the formation of productivity is associated with genotype stability. The more productivity is linked to stability, the greater the contrast between genotypes, as such a set will show genotypes whose productivity has responded to different environmental conditions to varying degrees.

In this context, if a genotype is located on the line and is both highly productive and highly stable, this means that it has responded favorably to all environmental conditions. This means that such a genotype is also broadly adaptable. In the opposite case, the less productive a genotype is, the more stable it is with a positive slope, and less stable with a negative slope. In this situation, if a genotype is on the line, regardless of stability, it has not responded favorably to any of the environmental conditions studied; i.e., there are no conditions in the studied set that would pro-

vide for its high productivity. In this case, such a genotype can again be considered broadly adaptable, because it comes closest to the reaction of a genotype that, when conditions change, would respond with high productivity. Thus, adaptability is determined not only by a specific response, but also by the potential for response under certain environmental conditions. Any deviation from the line and a specific hypothetical reaction in this case means that a genotype has responded to the environment differently from the ideal hypothetical case.

Our results show a positive slope of the function line between EAYM and S_{EAYM} . This indicates that, in this case, the closer a genotype is to the function line, the more it conforms to the main observed trend between productivity and stability and fits the correlation between them. Conversely, the more distant genotypes are, the more they deviate from the established trend. Of particular interest in this study is the fact that the b_i indicator correlates with the values of the distances to the line – d_{FM} . This shows that d_{FM} is directly related to adaptability and, accordingly, to productivity, which is also supported by the connection with EAYM, grain yield, and the indicators OAC and CAC. In addition, there is a high correlation with S_{EAYM} , indicating that productivity is connected in a specific way with stability, i.e., the trend observed in Figures 3 and 4 is not random, but is the result of relationships within the productivity-stability system.

The distances formed from the point of each real combination of productivity and stability, perpendicularly to the function line, are different for each of the studied genotypes, as shown in Figures 3 and 4. Nonetheless, a tendency is observed for the more productive genotypes to have lower values for these distances to the line, which, together with the correlation with b_i , indicates that more productive genotypes are more broadly adaptable but less stable. At the same time, as productivity approaches the mean, more genotypes are found to have higher stability. At the same time, the lowest-yielding genotypes are characterized by higher values of the distances to the regression line, indicating that low-yielding

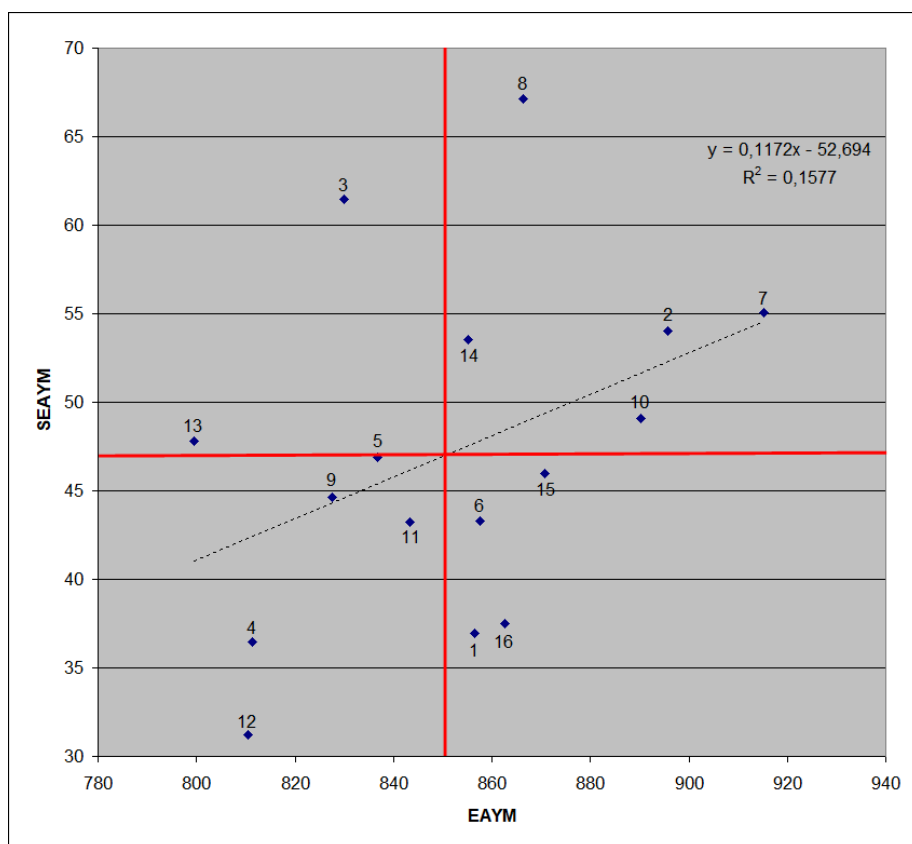


Figure 3. EAYM biplot for the studied common winter wheat lines

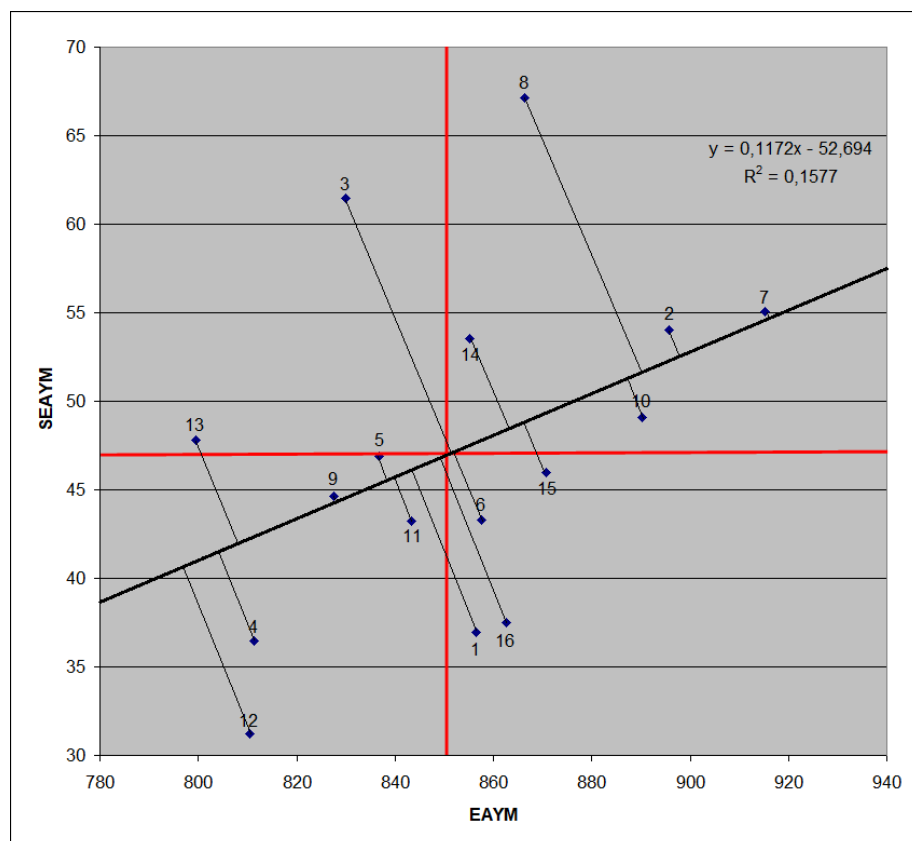


Figure 4. Function between EAYM and S_{EAYM} and deviation from the function for the studied common winter wheat genotypes

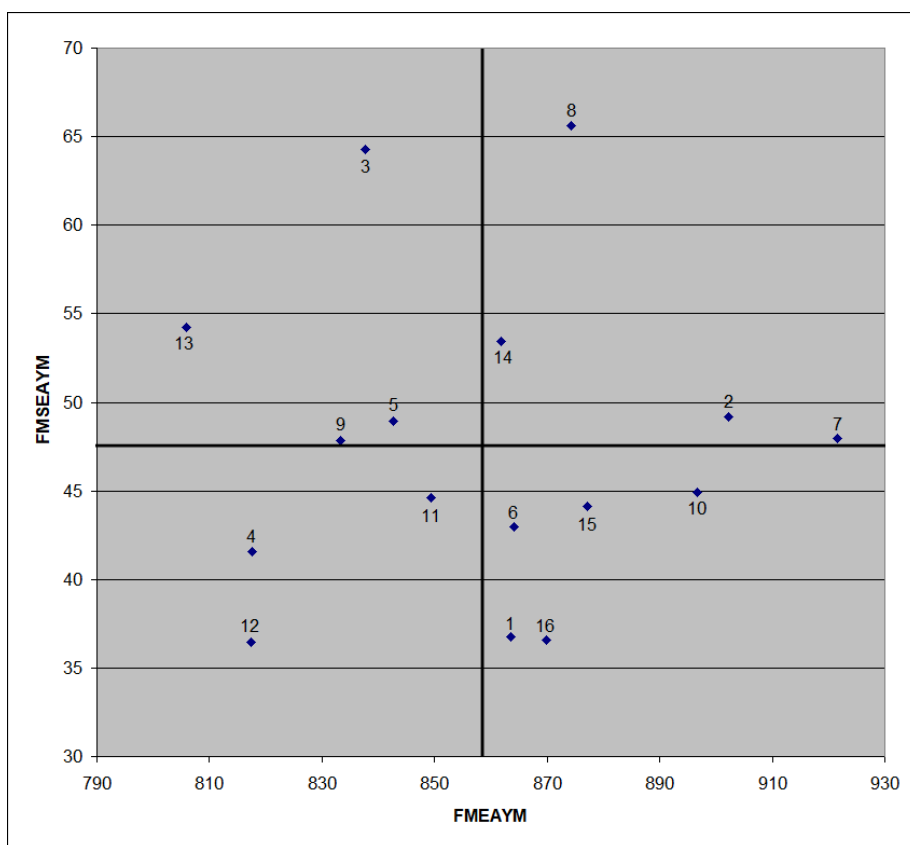


Figure 5. Functionally modeled EAYM biplot

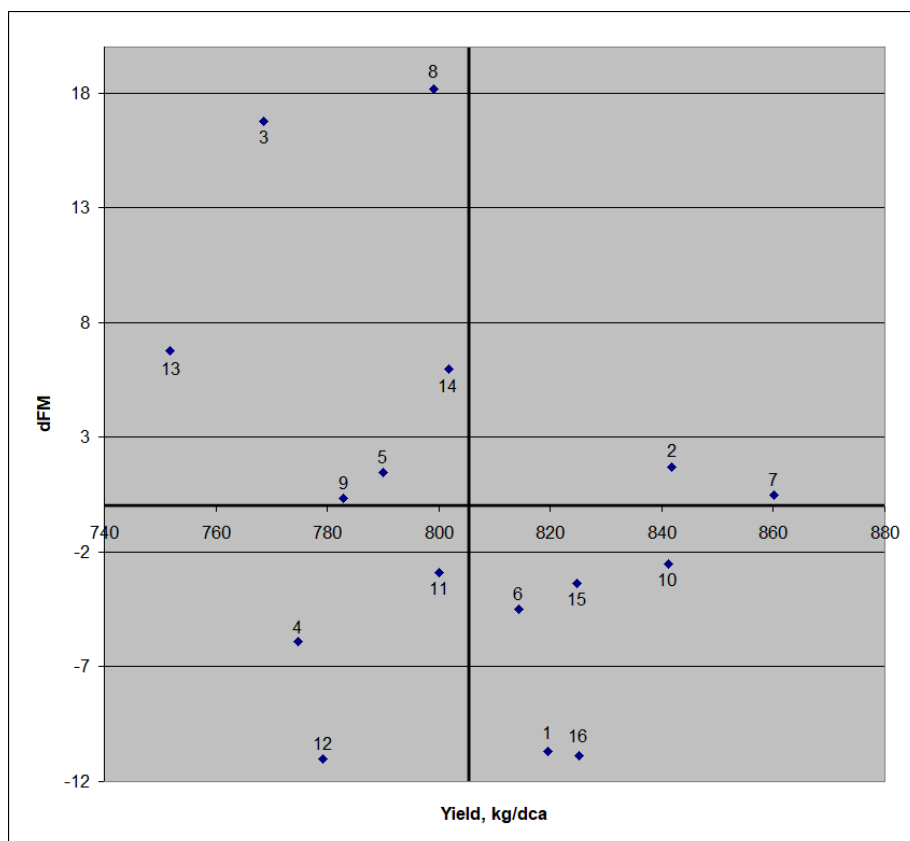


Figure 6. Biplot combining the results for productivity and stability as expressed by the d_{FM} parameter

genotypes are narrowly adaptable, but to unfavorable environmental conditions. Such characteristics are logical, as the studied lines are highly productive advanced and improved generations of common winter wheat.

Figures 5 and 6 present the data from the modeled EAYM biplot and a comparison of d_{FM} with yield. In practice, both biplots display identical data, but they provide different information. While the first biplot shows the transformed

EAYM model from a functional perspective, the second offers a direct comparison between the model and grain yield. The first graphical interpretation represents not only the integration of contrast between genotypes in the productivity–stability system but is also influenced by the contrast between the different growing seasons. This allows for the identification of those genotypes that, under highly contrasting conditions, achieve lower results than they would under uni-

Table 2. Correlations between yield and the parameters for stability and adaptability, and among the individual studied parameters

	Yield	b_i	s^2d_i	σ^2_i	W_i^2	IPCA1	OAC
Yield	1,000	0,382	-0,093	-0,231	-0,231	0,232	1,000**
b_i	0,382	1,000	-0,319	-0,231	-0,231	-0,237	0,382
s^2d_i	-0,093	-0,319	1,000	0,690**	0,690**	0,089	-0,093
σ^2_i	-0,231	-0,231	0,690**	1,000	1,000**	0,040	-0,231
W_i^2	-0,231	-0,231	0,690**	1,000**	1,000	0,040	-0,231
IPCA1	0,232	-0,237	0,089	0,040	0,040	1,000	0,232
OAC	1,000**	0,382	-0,093	-0,231	-0,231	0,232	1,000
CAC	1,000**	0,382	-0,093	-0,231	-0,231	0,232	1,000**
S_{gi}	0,015	,924**	-0,222	-0,079	-0,079	-0,326	0,015
EAYM	,956**	,632**	-0,154	-0,241	-0,241	0,083	0,956**
S_{EAYM}	0,110	,946**	-0,229	-0,096	-0,096	-0,444	0,110
d_{FM}	-0,293	,758**	-0,183	0,000	0,000	-0,519*	-0,293
FM_{EAYM}	,954**	,638**	-0,156	-0,234	-0,234	0,086	0,954**
FM_{SEAYM}	-0,294	,758**	-0,183	0,000	0,000	-0,520*	-0,294
	CAC	S_{gi}	EAYM	S_{EAYM}	d_{FM}	FM_{EAYM}	FM_{SEAYM}
Yield	1,000**	0,015	0,956**	0,110	-0,293	0,954**	-0,294
b_i	0,382	0,924**	0,632**	0,946**	0,758**	0,638**	0,758**
s^2d_i	-0,093	-0,222	-0,154	-0,229	-0,183	-0,156	-0,183
σ^2_i	-0,231	-0,079	-0,241	-0,096	0,000	-0,234	0,000
W_i^2	-0,231	-0,079	-0,241	-0,096	0,000	-0,234	0,000
IPCA1	0,232	-0,326	0,083	-0,444	-0,519*	0,086	-0,520*
OAC	1,000**	0,015	0,956**	0,110	-0,293	0,954**	-0,294
CAC	1,000	0,015	0,956**	0,110	-0,293	0,954**	-0,293
S_{gi}	0,015	1,000	0,304	0,982**	0,939**	0,312	0,939**
EAYM	0,956**	0,304	1,000	0,397	0,000	1,000**	0,000
S_{EAYM}	0,110	0,982**	0,397	1,000	0,918**	0,404	0,918**
d_{FM}	-0,293	0,939**	0,000	0,918**	1,000	0,007	1,000**
FM_{EAYM}	0,954**	0,312	1,000**	0,404	0,007	1,000	0,007
FM_{SEAYM}	-0,293	0,939**	0,000	0,918**	1,000**	0,007	1,000

form and favorable conditions. The direct combination of yield with d_{FM} makes it easier to identify genotypes that combine high productivity, stability, and adaptability, without the values being additionally influenced by contrast between environmental conditions. In both graphs, genotypes located at the bottom are more stable than the others. Genotypes with d_{FM} values close to 0 (or to the mean FM_{SEAYM} value) are characterized as broadly adaptable, while those with higher or lower values have, respectively, narrower adaptability to favorable or unfavorable environmental conditions.

According to these modeled criteria, the standard variety Dragana and lines G2, G3, G4, G6, G7, G8, and G12 exhibit the broadest adaptability. Narrow adaptability to favorable conditions is observed in the standard variety Pchelina and lines G5, G10, and G11. Narrow adaptability to unfavorable conditions is found in the standard variety Lazarka and lines G1, G9, and G13. Applying the stability characteristics from the same model, the most stable are the standard variety Lazarka and lines G1, G3, G7, G8, G9, G12, and G13, while less stable are the standard varieties Dragana and Pchelina and lines G2, G4, G5, G6, G10, and G11.

When comparing the results with those from classical methods for adaptability and stability, there is a very strong similarity with the adaptability index b_i by Eberhart and Russell (1966) and with OAC and CAC calculated according to Kilchevskiy and Khotyileva (1989). The data for the correlation coefficients (Table 2) show that the d_{FM} parameter is, in fact, highly and significantly correlated with b_i , but weakly and insignificantly with OAC and CAC. On the other hand, FM_{SEAYM} is very highly and significantly correlated with OAC and CAC. These data show, on the one hand, that d_{FM} is indeed related to adaptability, and on the other, that the contrast between individual genotypes regarding their productivity is definitively related to the adaptive ability of a genotype under diverse and contrasting environmental conditions. In terms of stability indicators, d_{FM} (and FM_{SEAYM}) correlates highly with the s_g parameter by Kilchevskiy and Khotyileva

(1989), as well as with the IPCA1 values from the AMMI model. This is partly due to the specifics of S_{EAYM} , as d_{FM} is calculated based on these values. The correlation with s_g indicates that the stability of contrasting genotypes under contrasting environmental conditions is primarily based on deviations caused by both forms of contrast. The correlation with the AMMI model, on the other hand, shows that the contrast between genotypes and its integration through functional modeling makes it possible for stability, as expressed by d_{FM} (and FM_{SEAYM}), to be represented as the interaction of a genotype with environmental conditions. These features provide sufficient grounds to consider that the d_{FM} parameter (or FM_{SEAYM}) could be successfully applied as a criterion for the simultaneous determination of both stability and adaptability.

The obtained results demonstrate both the expected variability among genotypes and the potential of the proposed model to capture stability in contrasting environments. To place these findings in a broader breeding context, they must be interpreted in relation to existing concepts of stability and adaptability.

DISCUSSION

Concept development

According to the classical definitions of stability proposed by Becker and Leon (1988), two main concepts are distinguished: static and dynamic. The static concept, also referred to as biological stability (Becker, 1981), assumes that a genotype is stable if its productivity at the phenotypic level remains at a similar level regardless of environmental conditions. In contrast, the dynamic concept defines stability as the minimal deviation of a genotype from a predictable response under changing environmental conditions. According to Yan and Kang (2002), for a genotype to be considered stable within this framework, such predictability must be consistent across all tested environments. This type of stability, often called agronomic stability (Becker and Leon, 1988), is generally preferred, as it al-

lows the monitoring of stability across modifications in cultivation technology.

Despite the widespread use of these concepts, consensus is lacking as to whether a given parameter for stability assessment should be assigned to one or the other. Tsenov et al. (2022a) emphasize that the same indicator is often interpreted as belonging to different concepts, or even simultaneously to both. From a breeding perspective, such classifications are of limited practical value, as they can lead to the interpretation of data in unsuitable directions. Nevertheless, the development of models for stability assessment should be grounded in the fundamental principles of the employed concept.

Most theoretical formulations of the dynamic concept of stability in genotype $\times$ environment interaction implicitly rely on three principles: (1) the predictability of yield under changing environmental conditions, (2) the variation of yield across environments, and (3) the existence of differences in phenotypic expression among genotypes within a set. The first principle assumes that if a genotype does not deviate from the mean model productivity of the set, it can be considered stable across the studied environments. The second principle emphasizes the inevitability of yield variation with changing environmental conditions, while the third highlights that genotypes within any set differ in their phenotypic expression. In practice, however, such principles cannot be categorically fulfilled, particularly in crops such as common winter wheat, due to species-specific characteristics.

Within the dynamic framework, the set of genotypes tested under given environments is treated as a single population. The mean-model productivity and the trends derived from it are often identified with the performance of the entire set, while the individual genotypes are positioned relative to it. In real-world conditions, however, the studied sets of winter wheat genotypes are typically highly heterogeneous, especially when breeding material of diverse geographic origin is included. As a result, the mean-model productivity can be significantly skewed depending on the prevailing type of response. This has been ob-

served even in crops with a narrower genetic base, such as triticale (Stoyanov, 2024). For example, if the majority of genotypes are high yielding, the mean will be elevated; if most are low yielding, the mean will decrease; and if the set consists of equal proportions of high- and low-yielding genotypes, the mean will shift again. Consequently, the characterization of stability becomes highly conditional, as the composition of the set may determine whether a genotype is classified as stable or unstable. Thus, the same genotype may appear highly unstable in one set and extremely stable in another.

Two general approaches can be applied to address these contradictions. The first is to preselect genotypes that differ in productivity, i.e., contrasting genotypes. Although such contrasting sets may produce more consistent responses, this approach is more a matter of model construction than true stability assessment. The second approach relies on the empirical evaluation of each genotype relative to the others in the set, thereby quantifying genotypic contrast directly. Previous work has shown that such contrast can be measured quantitatively (Stoyanov, 2025a). This approach allows the stability of a genotype to be assessed independently of the particular set in which it is included, since the measure of contrast itself serves as a stable criterion.

The second and third principles of the dynamic concept further highlight the complexity of stability assessment in wheat. Productivity inevitably changes with the environment, and genotypes inevitably differ even under identical conditions. Productivity in cereals is determined by a complex of traits, variably influenced by both genotype and environment (Mihova, 2020). For example, one genotype may respond to an environment with higher 1000-grain weight and fewer grains per spike, while another may show the reverse trend. Under different conditions, the same genotypes may reverse their responses, resulting in similar yields despite distinct underlying mechanisms. Although two genotypes may produce similar yields, their stability cannot be regarded as equivalent from an agronomic perspective. Differentiating them on the basis of

yield alone is therefore insufficient. Solutions to this problem include the simultaneous evaluation of yield-related traits alongside yield stability (Stoyanov, 2023), or the development of composite model values that integrate yield and yield-related traits. While effective, these approaches are not always feasible due to data limitations. An alternative solution is to maximize the number of contrasting environments, thereby reducing the likelihood of yield convergence due to compensatory mechanisms.

On this basis, a refined concept of stability for common winter wheat can be formulated: a stable genotype is one that, under sufficiently contrasting environmental conditions and within a set of contrasting genotypes, follows a predictable productivity response across all conditions. Accordingly, methods for stability assessment should meet three criteria: they must (1) be based on a sufficient number of environments, (2) include contrasting genotypes, and (3) provide a measure of genotypic contrast. Any dynamic concept-based model can thus be applied if it satisfies the first two conditions, with the third criterion introduced through additional modification.

The concept of adaptability is closely linked to stability. Mariotti et al. (1976) define adaptability as the ability of a genotype to respond favorably to environmental change, while Sedghi-Azar et al. (2008) describe broad adaptability as the capacity to maintain stable performance across multiple environments. From this perspective, stability and adaptability are interconnected, sharing common principles of evaluation. Moreover, the parameters used to assess adaptability often overlap with those applied in stability models. In this study, adaptability is defined in line with the specificities of common winter wheat: an adaptable genotype is one that, when environments change, performs favorably relative to other contrasting genotypes grown under the same conditions. A broadly adaptable genotype is one that, across contrasting environments, maintains favorable performance relative to contrasting genotypes, regardless of the direction of environmental change. Thus, any method or model formulated to evaluate adaptability should likewise

meet the three criteria identified for stability assessment: sufficient environmental coverage, inclusion of contrasting genotypes, and quantification of genotypic contrast.

These criteria not only refine the theoretical understanding of stability and adaptability but also establish the basis for constructing a model that operationalizes them. Building on this framework, the model was designed to integrate genotypic contrast directly into stability assessment.

Model Development

The adopted concept provides a framework for constructing models that incorporate genotypic contrast into the assessment of stability and adaptability. In developing such a model, several critical considerations arise, reflecting both the mathematical nature of the chosen methodology and its suitability for capturing the complexity of genotype $\times$ environment interactions.

A central requirement of any model for stability assessment is its capacity to generate quantitative indicators that are not confounded with yield magnitude. As emphasized by Tsenov et al. (2022a), when stability parameters exhibit a strong correlation with yield, the ability to assess stability independently is compromised. Conversely, weaker correlations make it possible to evaluate productivity and stability as distinct attributes. This challenge necessitates the use of approaches that incorporate environmental variability explicitly. In this respect, the Environment Adjusted Yield Model (EAYM) offers a notable advantage, as it combines yield values with a stability component while simultaneously accounting for the influence of contrasting environments (Stoyanov, 2021). Such a framework inevitably produces a correlation between productivity and stability, yet this correlation is not detrimental; rather, it reflects the biological reality of wheat cultivation, in which genuine combinations of high yield and high stability can be identified. The present study builds on this premise, adopting EAYM and its stability-related derivative S_{EAYM} as the basis for modeling.

The integration of genotypic contrast into stability assessment relies on the recognition that

yield itself embodies a measure of contrast. Previous work (Stoyanov, 2025a) has demonstrated that dynamic contrast values (YC_i) are strongly correlated with yield. This relationship implies that yield can be used as a numerical proxy for contrast, while stability parameters, by construction, already incorporate yield to varying extents (Tsenov and Gubatov, 2019). Establishing a functional relationship between some productivity parameter (e.g. yield, EYAM) and a given stability parameter thus creates an avenue for indirect integration of genotypic contrast into stability indices.

This approach rests on the observation that any stability parameter exhibits a linear or nonlinear dependency on yield, and therefore can be modeled accordingly. By incorporating the contrast embedded in yield into the stability calculation, the resulting parameters more accurately reflect the joint effects of productivity, stability, and genotypic differentiation. Such modeling not only adjusts the stability estimates for differences among genotypes but also mitigates the risk that extreme genotypes dominate the interpretation of stability.

It is important to note that the integration of contrast can be achieved through alternative mathematical strategies. One possible approach is the direct comparison of YC_i values with stability and adaptability parameters. Another, applied in the present study, leverages the strong correlation between YC_i and yield, using functional modeling to accumulate yield effects within the stability parameter. Both approaches are theoretically valid, but the latter provides a more seamless incorporation of contrast into the established productivity-stability framework.

The resulting model, therefore, allows for stability and adaptability assessments that remain robust even in sets of highly diverse genotypes. It ensures that differences in productivity exert a minimized and controlled influence on stability estimation. In practice, this enhances the ability to identify genotypes that combine high yield potential with consistent performance across environments, thus providing a valuable tool for breeding programs targeting both productivity and resilience.

Practical significance of the model

One of the most important criteria when choosing a method for stability assessment is its effectiveness in guiding breeding decisions. Numerous studies across various crops (Zeleeke Ashango et al., 2016; Mare et al., 2017; Kosev and Georgieva, 2018; Kumar et al., 2021; Laghari et al., 2021; Nataraj et al., 2021; Bakheit et al., 2022; Mossie et al., 2024; Tsenov et al., 2022c; Stoyanov, 2022; Parfenova and Psareva, 2024; John et al., 2025; Meena et al., 2025) have tested different indicators, yet the conclusions are often inconsistent. Such issues frequently result in conflicting outcomes that obscure rather than facilitate genotype selection.

From a breeding standpoint, it is therefore sufficient to rely on a limited set of fundamentally different models to validate new approaches. In our study, such comparisons clearly demonstrated the strengths of the newly developed model. The functionally modeled parameter with integrated genotypic contrast (d_{FM}) showed high and significant correlation with the adaptability index b_i and consistent associations with other classical stability measures (Table 2). This confirms that the model captures the essential features of genotype performance while neutralizing the disproportionate influence of extreme responses.

The key practical advantage of the model lies in its ability to identify genotypes that maintain both productivity and stability across contrasting environments. This is particularly relevant for breeding under conditions of increasing climatic variability. For instance, the model highlighted G4, G7, G12, and the standard variety Dragana as lines combining high yield with broad adaptability. Such information provides breeders with a more objective basis for advancing lines that will perform reliably beyond the environments of initial testing. Moreover, the differentiation between FM_{EAYM} and FM_{SEAYM} values offers a direct criterion for targeted breeding: lines with high FM_{EAYM} can be prioritized as donors of yield stability, while those with favorable FM_{SEAYM} values are candidates for cultivation in regions facing unpredictable climatic stresses.

Thus, by integrating genotypic contrast into stability assessment, the proposed model not only

refines theoretical evaluation but also provides breeders with a practical decision-making tool. It reduces the risk of advancing lines that appear promising in specific trials but fail under broader adaptation, thereby improving the efficiency of selection and supporting the development of varieties resilient to changing environments.

Model Adequacy

There are various studies highlighting that the adequacy of a given model can be successfully validated by comparison with classical approaches. Kilchevskii and Khotyleva (1989) developed a stability parameter (s_{gi}), which is based on the ratio between the variance of the specific adaptive ability (CAC) of a studied genotype and its general adaptive ability (OAC). This indicator is highly associated with yield and is mathematically quite different from classical approaches. The authors compared it with the Eberhart and Russell model, noting that s_{gi} is associated with b_i , which enables simultaneous selection for productivity, stability, and adaptability based on a single parameter.

Our results (the values of d_{FM} and FM_{SEAYM}) also show a high and significant correlation with s_{gi} , further confirming that functional modeling allows for the simultaneous assessment of both stability and adaptability. This is due to the fact that the contrast between genotypes is integrated into the stability parameter, and the contrast itself is, by nature, a measure of the genotype's ability to produce variable yields (Stoyanov, 2025a). At the same time, the Environment Adjusted Yield Model (EAYM) applied in this study allows the introduction of additional contrast between genotypes based on their mean performance across all growing periods. The specific stability parameter (S_{EAYM}), based on the difference between EAYM and actual yield, makes it possible to adequately measure genotype stability even under contrasting environmental conditions.

Thus, combining the concept of genotype contrast, EAYM, and actual yield (by indirectly integrating contrast into a specific stability parameter) results in a multiple approach that encompasses both the environmental and genotypic specifics, in terms of both productivity and stabil-

ity. Furthermore, $FM_{SEAYM}(d_{FM})$ incorporates the idea of adaptability in addition to stability, which, similar to s_{gi} , allows for the identification of genotypes valuable from a breeding perspective when combined with productivity values. These indicators are fully capable of fulfilling the task of determining stability and adaptability based on an integrated multiple approach, as required in modern crop breeding.

Our results are consistent with both our previous studies (Stoyanov, 2025b) and those of other researchers mentioned above. In practice, the thesis that yield stability in common winter wheat remains a subject for breeding improvement is confirmed. Nevertheless, genotypes such as G4 and G7 show a favorable combination of broad adaptability, good stability, and high productivity, making them suitable for further testing under diverse agroecological conditions in the country.

CONCLUSION

Based on the results and discussion presented, the following conclusions can be drawn:

The newly developed model combines the analysis of stability and adaptability with a quantitative assessment of genotypic contrast, allowing for a more realistic evaluation in heterogeneous populations.

1. The application of a rotated biplot and functional modeling of the relationship between productivity and stability ensures the indirect integration of contrast, adjusting stability assessments according to differences among genotypes.

2. The model is applicable to various methods for the assessment of stability and adaptability and demonstrates a high correlation with established classical parameters, confirming its scientific validity and universality.

3. Application of the new concept and model to advanced lines of common winter wheat enables clear distinction between highly productive and stable lines (e.g., G4, G7, G12, Dragana) as well as genotypes with narrow adaptability.

4. The integration of contrast eliminates distortions caused by extremely divergent geno-

types, facilitating the selection of lines with balanced characteristics for practical breeding.

5. The new model shows statistically significant correlation with leading classical methods and successfully integrates parameters for stability, adaptability, and contrast, ensuring its applicability and reliability in breeding practice. The model thus provides breeders with a reliable tool for identifying high-yielding, stable, and broadly adaptable lines under variable environments.

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