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Evaluation of genetic parameters of winter barley varieties under water deficit conditions

Оценка на генетичните параметри на сортове зимен ечемик в условия на воден дефицит

Boryana DYULGEROVA (✉), Nikolay DYULGEROV

Institute of Agriculture – Karnobat, Agricultural Academy, Industrialna 1 Str., 8400 Karnobat, Bulgaria

✉ Corresponding author: bdyulgerova@abv.bg

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ABSTRACT

The aim of the present study was to use REML/BLUP-based procedures in order to estimate variance components and genetic parameters and to determine correlations between grain yield and yield-related traits of winter barley varieties. Studied genotypes were grown in two seasons characterized by different levels of water deficit (precipitation sum was less by 15% in the first growing year and 36% in the second growing year than the long-term precipitation sum). A reduction was observed in all studied yield-related traits, with grain yield in the second year being more than 70% lower than that measured in the first growing year. Lower values of broad-sense heritability in the second growing year for the traits number of spikelets and grains per spike, grain weight per spike, and grain yield were found suggesting that the direct selection of these traits under drought stress conditions will be less effective. Varieties ranking based on the FAI-BLUP index strongly varied across growing seasons, but in both years variety Bojin was selected as a high-performing variety for multiple traits. Considerable differences were observed in the magnitude and directions of correlations between grain yield and yield-related traits between two growing seasons. These findings, in the context of the increasing frequency and duration of drought stress in the region, suggest a longer period of multi-year testing and complicate the process of selection in breeding programs of winter barley.

Keywords: barley, REML/BLUP methodology, FAI-BLUP index, correlation analysis, drought stress

РЕЗЮМЕ

Целта на настоящото изследване е да се оценят компонентите на варианса и генетичните параметри като се използват процедури, базирани на REML/BLUP и да се определят корелациите между добива на зърно и свързаните с добива признаци при сортове зимен ечемик. Изследваните генотипове се отгледани в два сезона, характеризиращи се с различни нива на воден дефицит (сумата на валежите е по-малка с 15% през първата година и с 36% през втората година в сравнение с дългосрочната сума на валежите). Отчетено е понижение на стойностите на всички проучвани признаци свързани с добива, като добивът на зърно е с над 70% по-нисък от този, отчетен през първата година. Установени са по-ниски стойности на наследяемост в широк смисъл през втората реколтна година за признаците брой класчета и зърна в клас, тегло на зърното от клас и добив на зърно, което предполага, че директния отбор на тези признаци при условия на воден стрес ще бъде по-малко ефективна. Класирането на сортовете въз основа на FAI-BLUP индекса варира силно между годините на отглеждане, но и през двете години сортът Божин е избран като сорт, отличаващ се с много добро съчетание на проучваните признаци. Отчетени са значителни разлики в величината и посоката на корелациите между добива на зърно и свързаните с добива признаци в двете реколтни години. Тези данни, в контекста на нарастващата честота и продължителност на периодите със засушаване в региона, предполагат по-дълъг период на многогодишно тестване и усложняват отбора в селекционните програми на зимния ечемик.

Ключови думи: ечемик, REML/BLUP методология, FAI-BLUP индекс, корелационен анализ, воден стрес

INTRODUCTION

Barley is one of the major cereal crops cultivated in Bulgaria. It is primarily used for animal feed and serves as an essential ingredient in the brewing industry. Breeding efforts have focused on improving yield potential, disease resistance, drought tolerance, and quality traits such as protein content, grain size, and malting characteristics (Mihova et al., 2018).

Currently, in most barley breeding programs, parent and advanced lines are selected based on phenotype. The phenotype expression is determined by the combined effects of genotype, environment, and their interaction. The genotype by environmental interaction across location, growing seasons and crop management has often complicated testing and selection of superior genotypes, reducing genetic progress in breeding programs.

The climatic variables that most affect barley yields are temperature and rainfall. These two factors also play a primary role in the occurrence of genotype by environment interaction (Voltas et al., 2002). In Bulgaria, because barley is cultivated exclusively in rain-fed conditions, irregular water supply, and high temperatures often occur during its vegetation. The combination of drought and heat stress negatively affects barley grain yield, and it is a major production constraint for barley production in the country. Frequent and unpredictable periods of water deficit complicate and reduce the efficiency of selection conducted under these conditions. Generally, direct selection for grain yield under stress was considered to be inefficient because it was thought that the heritability of grain yield under drought stress was low relative to yield in non-stress environments (Blum, 1988).

The need for robust and accurate approaches for the prediction of genotypic values and improvement of selection efficiency is making mixed models more and more popular in plant breeding programs (Balzarini, 2002). One of the most used selection procedures includes estimating variance components (i.e., restricted maximum likelihood - REML) and predicting genotypic values (i.e., best linear unbiased prediction - BLUP) (Piepho et al., 2008; Bernardo, 2020). REML/BLUP-based approaches are the better choice in case of the non-additive nature of traits and unbalanced data, both often occurring in plant breeding experiments as compared to ANOVA-based procedures (Hu, 2015).

In barley, these methods were effective in assessing the genetic value of traits of 492 accession at Gatersleben genebank (Hartung at al., 2006). The BLUP techniques were used for the evaluation of the genotype-by-environment interactions under multi-environment trials and the selection of stable barley genotypes (Ahakpaz et al., 2021; Verma et al., 2022). Statistical methods based on BLUP also has applied for the analysis of the data for genomic selection (Zhong et al., 2009).

The aim of this study was to use REML/BLUP-based procedures in order to estimate variance components and genetic parameters, and to determine correlations between grain yield and yield-related traits of winter barley varieties grown in two growing seasons characterized by different levels of drought stress.

MATERIAL AND METHODS

Seventeen six-rowed varieties of winter barley were used in this study. Varieties Bojin, IZ Bori, Izgrev, Vaslets, and Zemela are developed at the Institute of Agriculture – Karnobat, Bulgaria. Varieties Casino (“KWS”), Giga (“KWS”), and Paso (“Limagrain”) were grown commercially in Bulgaria. The rest 9 varieties originate from different European countries: Attiki and Banteng – France; Colonia, Monika, and Dea – Germany; Noveta and Videt – Netherlands; Hampus – Sweden; Brucker Vielzeilige - Austria.

The study was conducted during the period of two concessive years 2018/2019 and 2019/2020 in the experimental field of the Institute of Agriculture - Karnobat, Southeastern Bulgaria (42°39' N, 26°59' E). The soil of the experimental field was slightly acidic (pH is 6.2) Pellic Vertisol. The experiments were organized in a Complete Block Design with 4 replications on plots of 10 m^2 with a sowing rate of 450 seeds/m^2. During the growing seasons, standard plant protection practices were used.

The climate of the region is transitional continental characterized by mild winter and dry and hot summer. Meteorological data were recorded during the experimental period (Tables 1 and 2). The average temperatures for most of the months during both growing seasons were higher than those for the long-term period. In both years, there were no extremely low winter temperatures that could cause damage to barley (Table 1).

The weather data was collected at the meteorological station of the National Institute of Meteorology and Hydrology located at the Institute of Agriculture - Karnobat. The sum of precipitation for the 2018/2019 growing season was 73.0 mm lower than the long-term sum (Table 2). During barley vegetation in 2019/2020, the precipitations were exceptionally low (64% from the long-term sum) and plant development took place under drought stress most of the time.

The traits plant height (PH, cm), spike length (SL, cm), number of spikelets per spike (NSS), number of grains per spike (NGS), and grain weight per spike (SW, g) were measured on 20 randomly selected plants in each replication of each variety. The number of spikes per m^2 (SPM) was determined by courting of spikes before harvest in 0.25 m^2 area from the middle of plots and converted to 1 m^2. Grain yield (GY, t/ha) and 1000-grain weight (TGW, g) were determined on a plot basis.

All statistical analyses were carried out using the R package “metan” (Olivoto and Lúcio, 2020). The function for analyzing single experiments (one-way experiments) using a mixed-effect model based on the following equation was used:

$$y_{ij}=\mu+\alpha_i+\tau_j+\varepsilon_{ij}$$

where y_{ij} is the value observed for the ith genotype in the jth replicate (i = 1, 2, ... g; j = 1, 2, ... r); being g and r the number of genotypes and replicates, respectively; α_i is the random effect of the ith genotype; τ_j is the fixed effect of the jth replicate; and ε_{ij} is the random error associated to y_{ij}.

A likelihood ratio test for the genotype effect was performed. Variance components and genetic parameters of studied traits were calculated. Pearson’s correlation coefficients were used to study the relationships between grain yield and yield-related traits in each growing season.

Table 1. Average monthly temperature, absolute maximum and minimum temperatures during winter barley cultivation period in 2018/2019 and 2019/2020 growing years

Months	2018/2019			2019/2020			LTT, °C
	T, °C	T min, °C	T max, °C	T, °C	T min, °C	T max, °C	
X	14.0	1.5	23.6	14.5	4.0	30.0	12.5
XI	7.4	-6.5	21.0	12.4	2.0	24.5	7.1
XII	2.4	-9.5	13.0	4.7	-5.0	18.6	2.6
I	2.5	-11.0	14.8	2.5	-8.2	14.5	0.6
II	4.3	-7.0	19.5	5.7	-7.0	19.0	2.2
III	8.6	-5.0	23.5	8.2	-4.6	22.4	5.3
IV	10.3	0.2	25.4	10.4	-1.0	27.0	10.5
V	17.1	5.5	30.5	16.2	4.5	34.2	15.6
VI	22.6	11.5	34.0	20.7	8.0	34.5	19.6
VII	22.9	15.5	36.6	24.0	12.0	37.5	22.0

T – average monthly air temperature; T min and T max – absolute minimum and maximum air temperature; LTT – long-term average monthly air temperature (1931-2020)

Table 2. Monthly sum of precipitation during the winter barley cultivation period in 2018/2019 and 2019/2020 growing years

Months	2018/2019		2019/2020		LTP, mm
	P, mm	± LTP, mm	P, mm	± LTP, mm	
X	15.4	-28.9	21.6	-22.7	44.3
XI	68.3	14.6	53.4	0.3	53.7
XII	27.3	-23.9	8.0	-43.2	51.2
I	38.9	2.4	13.1	-23.4	36.5
II	15.6	-20.2	33.0	-2.8	35.8
III	8.9	-25.2	29.6	-4.5	34.1
IV	52.9	7.6	19.5	-25.8	45.3
V	44.9	-13.6	54.3	-4.2	58.5
VI	95.6	30.4	71.9	6.7	65.2
VII	33.7	-16.2	0.1	-49.8	49.9
Sum	401.5	-73.0	304.5	-170.0	474.5

P – the monthly sum of precipitation; LTP– the long-term monthly sum of precipitation (1931-2020)

The factor analysis and ideotype-design (FAI-BLUP) index were calculated for the ranking of the genotypes based on multi-trait (Rocha et al., 2018). A selection intensity of 15 % was considered. The FAI-BLUP index was established based on GY and the following grain yield components: SPM, SW, and TGW. The ideotype used in the FAI-BLUP index for included traits was defined as the highest value among the predicted genetic values in both growing seasons.

RESULTS AND DISCUSSION

Variance components and genetic parameters

The estimates of the variance components, genetic parameters, and mean values for the 2018/2019 growing year are shown in Table 3 and for the 2019/2020 growing year in Table 4. A considerable decrease in mean values of all studied traits as a result of drought stress in the second year was observed. The highest reduction was found for grain yield (70.33%), followed by plant height (58.45%) and grain weight per spike (47.99%).

Nevertheless, barley is regarded as one of the most tolerant cereal crops to drought, water deficit is the primary limitation to barley growth, development, and productivity in many parts of the world, including Bulgaria. Usually, drought stress is combined with high temperatures. Simultaneous heat and drought stress initiate various processes like a decreased rate of photosynthesis coupled with abnormal respiration, closed stomata, and high leaf temperature all these events result in reduced crop yield (Mittler, 2006). The distribution of precipitation during the vegetation period is another major factor that affects grain yields. Drought stress during tillering or stem elongation reduces the number of grains per spike (Ferrante et al., 2008) while water deficit during the grain-filling period decreases grain weight (Rajala et al., 2011). Heat and drought stress at anthesis can reduce grain number per unit area due to lower fertilization caused by pollen sterility and/or ovule abortion (Barnabas et al., 2008).

The amount of precipitation for the period October - February was considerably lower in the second growing year (about 42% lower than the long-term sum) compared to the first year (about 25% lower than the long-term sum). Those conditions strongly affected the tillering and the number of spikes per 1 m^2 in 2019/2020 was almost twice as low as the number of spikes per m^2 in 2018/2019 (620 spikes per 1 m^2 in 2018/2019 and 387 spikes per 1 m^2 in 2019/2020). Bento et al. (2021) also concluded that winter precipitation proves to be an important factor for barley grain yield. In the present study, the number of spikes per m^2 was presented at harvest and most probably water scarcity affected not only the maximum number of tillers produced but also the proportion that survive to maturity. In drought-stress environments, tiller mortality is a common response to water-limited conditions in barley (Hoyle et al., 2020).

The two growing seasons differed also in the pattern of distribution of spring precipitation. In 2018/2019, the water deficit in April was partly compensated by rainfalls in May, while in 2019/2020, there was a water deficit in both months, and in April the amount of rainfalls was over two times lower than typical for the region.

Table 3. Variance components and genetic parameters of grain yield and yield-related traits of winter barley varieties for the 2018/2019 crop season

Parameters	PH	SPM	SL	NSS	NGS	SW	TGW	GY
Vg	54.50	14153.00	1.06	15.40	18.20	0.06	6.93	0.92
Gen (%)	76.10	62.90	95.00	94.60	92.9	76.10	96.40	78.7
Vr	17.10	8344.00	0.06	0.89	1.39	0.02	0.26	0.25
Res (%)	23.90	37.10	5.02	5.42	7.09	23.90	3.63	21.3
Vph	71.50	22497.00	1.11	16.30	19.60	0.07	7.19	1.17
H^2	0.76	0.63	0.95	0.95	0.93	0.76	0.96	0.79
Accuracy	0.92	0.93	0.99	0.99	0.99	0.96	0.99	0.97
CVg	7.40	19.5	13.60	6.05	7.28	8.57	5.98	18.4
CVr	4.15	3.13	3.13	1.45	4.81	4.81	1.16	9.59
CV ratio	1.78	4.35	4.35	4.18	1.78	1.78	5.15	1.92
LRT	49.7*	30.6*	122.0*	118.0*	106.0*	49.6*	137.0*	54.9*
Average	99.60	620.35	7.55	64.98	58.61	2.73	44.00	5.19

Vg- genotypic variance; Vr- residual variance; Gen (%) and Res (%) - the respective % of variance components to the phenotypic variance; H^2 - broad-sense heritability; Accuracy - accuracy of selection; CVg - genotypic coefficient of variation; CVr - residual coefficient of variation; CV ratio - ratio between genotypic and residual coefficient of variation; LRT- Likelihood Ratio Test

Table 4. Variance components and genetic parameters of yield-related traits of winter barley varieties for the 2019/2020 crop season

Parameters	PH	SPM	SL	NSS	NGS	SW	TGW	GY
Vg	40.30	4077.00	0.89	18.50	22.80	0.03	2.79	0.11
Gen (%)	87.30	85.20	94.40	76.00	83.00	61.20	92.20	40.50
Vr	5.87	708.00	0.05	5.83	4.65	0.02	0.24	0.61
Res (%)	12.70	14.80	5.58	24.00	38.8	38.80	7.78	59.50
Vph	46.20	4786.00	0.94	24.3	27.4	0.05	3.02	0.27
H^2	0.87	0.85	0.94	0.76	0.83	0.61	0.92	0.41
Accuracy	0.98	0.98	0.99	0.93	0.98	0.93	0.99	0.86
CVg	15.30	16.50	16.4	8.63	12.80	12.90	5.19	21.30
CVr	5.86	6.87	4.48	4.84	5.78	10.30	1.51	25.80
CV ratio	2.62	2.40	4.11	1.78	2.21	1.26	3.44	0.83
LRT χ^2	78.4*	71.4*	117.0*	49.6*	65.2*	28.8*	101.0*	12.2*
Mean	41.38	387.28	5.76	49.83	37.10	1.42	32.19	1.54

Vg- genotypic variance; Vr- residual variance; Gen (%) and Res (%) - the respective % of variance components to the phenotypic variance; H^2 - broad-sense heritability; Accuracy - accuracy of selection; CVg - genotypic coefficient of variation; CVr - residual coefficient of variation; CV ratio - ratio between genotypic and residual coefficient of variation; LRT χ^2- χ^2 Likelihood Ratio Test

This had a particularly strong influence on the number of grains per spike and in the second year, a significant reduction in the mean value of the trait was found.

The obtained results confirmed a huge impact of pre-anthesis water deficit on barley productivity reported previously (Al-Ajlouni et al., 2016).

The likelihood-ratio test revealed that all variables had a significant ($P < 0.05$) genotype effect, indicating the existence of genetic variability among the barley varieties for studied traits. The genotypic coefficient of variation (CVg) as a percentage of the general average, represents the amount of genetic variation that exists (Sahu, 2013). The CVg allows the comparison of the genetic variability of the different traits analyzed. The highest genotypic coefficients of variation were observed for GY, SPM and SL in both growing years. These values can be considered of moderate magnitude and indicated that the traits showed greater variability, allowing the achievement of gain by selection. Among all the traits studied, TGW had the lowest coefficient of genotypic variation - 5.98% in 2018/2019 and 5.19% in 2019/2020.

The CVg of most of the studied traits, including GY, was higher in 2019/2020. This may be due to genotype by environment interaction, in which some varieties can be more greatly affected by drought stress than others, resulting in a high variance in these traits. El-Hashash et al. (2018) also noted higher genetic variability of yield-related traits under drought than under irrigation. The CVg/CVr ratio determined the coefficient of relative variation. This parameter allows for assessing the possibilities for improvement in the evaluated population for the studied trait. Ribeiro et al. (2009) stated that the higher the relative variation, the greater the chance of selecting genotypes with superior performance. High relative variation was observed for the traits TGW (5.15), SPM (4.35), SL (4.35), and NSS (4.18) in 2018/2019 and for SL (4.11) in 2019/2020. Considerably lower values of relative variation for SPM, NSS, TGW, and GY in the second growing year in comparison with the first year were found, suggesting that unfavorable conditions reduce the possibilities of successful selection for the particular traits.

Accuracy is associated with the precision of selection and is the major element of genetic progress that can be altered to maximize genetic gain. Values for accuracy can vary from 0 to 1 and can be classified as very high - greater than or equal to 0.90, high - from 0.70 to 0.89, moderate - from 0.50 to 0.69, and low - below 0.50 (Resende and Duarte, 2007). Results obtained for accuracy varied from 0.92 to 0.99 in 2018/2019 and from 0.86 to 0.99 in 2019/2020. This indicated that the number of replications was sufficient to obtain high selective accuracy in studied traits.

The broad-sense heritability (H^2) expresses the amount of genetic variation in relation to the total phenotypic variation (Sahu, 2013). This is one of the most important genetic parameters that breeders use to evaluate quantitative traits and assess potential genetic gains. Heritability is classified as high when it has a value higher than 80%, moderate when it ranges between 40-80%, and low when it is less than 40% (Singh, 2001). High heritability suggests that direct selection can be successful under particular experimental conditions. Results show that TGW had the highest heritability in both growing years (0.96 in 2018/2019 and 0.92 in 2019/2020).

Other researchers also reported high values of broad-sense heritability for TKW in barley (Chand et al., 2008; Amabile et al., 2016). According to Tinker et al. (1996), the heritability for TKW was different depending on the environment, suggesting that the variation among heritability values might be explained by the considerable heteroscedasticity among the environments. The high level of heritability observed in the present study indicates that the expression of this trait is less affected by the environment and the selection based on phenotypic performance could be effective.

SL, NSS, and NGS were other traits that demonstrated very high (over 0.90) heritability in 2018/2019. While the heritability of SL was at the same level in 2019/2020, values for NSS and NGS were significantly lower than in 2018/2019. Lower heritability in 2019/2020 than in 2018/2019 also was found for SW.

Heritability estimates of SPM and PH were moderate (0.63 and 0.76, respectively) in 2018/2019 and high (0.85 and 0.87) in 2019/2020. Heritability of GY had a value of 0.79 in 2018/2019 and 0.41 in 2019/2020. Estimates of broad-sense heritability for barley grain yield, varied considerably in the literature, probably due to differences in the type of genetic material and the environments where the studies were performed. Some authors reported high or moderate values (Addisu et al., 2015; Akgün, 2016; Sunil and Khan, 2017) while others found low estimates (Ahmadi et al., 2016) for this trait. Studies of the same genotypes in different environments also found a significant effect of environment on the broad-sense heritability of barley GY (Bouzerzour and Dekhili, 1995; Tinker et al.,1996; Chand et al., 2008).

These results imply that selection for NSS, NGS, SW, and GY under drought stress will be less effective. According to Ceccarelli et al. (1992), the heritability of barley grain yield under low-yielding conditions is expected to be low. The superior lines can only be identified by repeated testing in the target environment, as they will be tolerant to variable types, intensity, duration, and timing of stresses.

Recently, years of extreme weather events (usually a combination of drought and high temperatures) as well the periods of several consecutive years of stressful conditions have become more common. This seriously complicated the process of barley breeding by reducing the selection efficiency and genetic gain and prolonging the breeding process by necessitating more growing seasons for testing. The increasing threats of drought and heat stresses require the complementation of conventional breeding approaches with genomic tools that can accelerate the development of high-yielding and stress-resilient barley varieties.

FAI-BLUP index

Plant breeders commonly make selection decisions based on a number of traits. To facilitate the process of multi-trait selection, the routinely used approach is index selection. One of the recently proposed selection indices is the factor analysis based on ideotype design associated with the best linear unbiased prediction (FAI-BLUP) index based on univariate mixed models (Rocha et al., 2018). The application of this multi-trait index allows the prediction of genetic effects with mixed models, and the calculation of genetic values using REML/BLUP (Resende et al., 2014).

The advantages of the FAI-BLUP index are the possibility of exploiting the covariance between traits, can be used with unbalanced data, and does not require weight assignment to the different traits. The FAI-BLUP index has the potential to improve multiple traits simultaneously since it considers predicted genetic effects (Rocha et al., 2018). The FAI-BLUP index was used for multiple-trait selection in some cereals crops such as sorghum (de Silva et al., 2018; Oliveira et al., 2019; Botelho et al., 2022), wheat (Meier et al., 2021; Casagrande et al., 2022) and maize (Peixoto et al., 2021). To our knowledge, there is no information about the application of this index in barley breeding.

In the 2018/2019 growing season, the selected genotypes according to the FAI-BLUP index were Veslets, Noverta, and Bojin, while in the 2019/2020 growing season - Dea, Colonia, and Bojin (Figure 1). Bojin was selected as a high-performing variety for multiple traits in both growing years, which differ in meteorological conditions. As in the present study, the most important components of barley grain yield - SPM, SW, and TGW, were used for idiotype design, the selected cultivars that are close to the idiotype may be a valuable genetic resource for improving barley yield under drought stress.

There was a considerable difference in the ranking of cultivars over two growing seasons. For example, variety Veslets was ranked first in 2018/2019 and 14th in 2019/2020 and Collonia ranked last in 2018/2019 and second in 2019/2020. Bojin was selected in both growing years, indicating a favorable combination of studied traits and stable performance in conditions of drought stress.

The lack of consistency of cultivar rankings between growing years confirms the need for multi-year testing, especially for highly variable rain-fed environments.

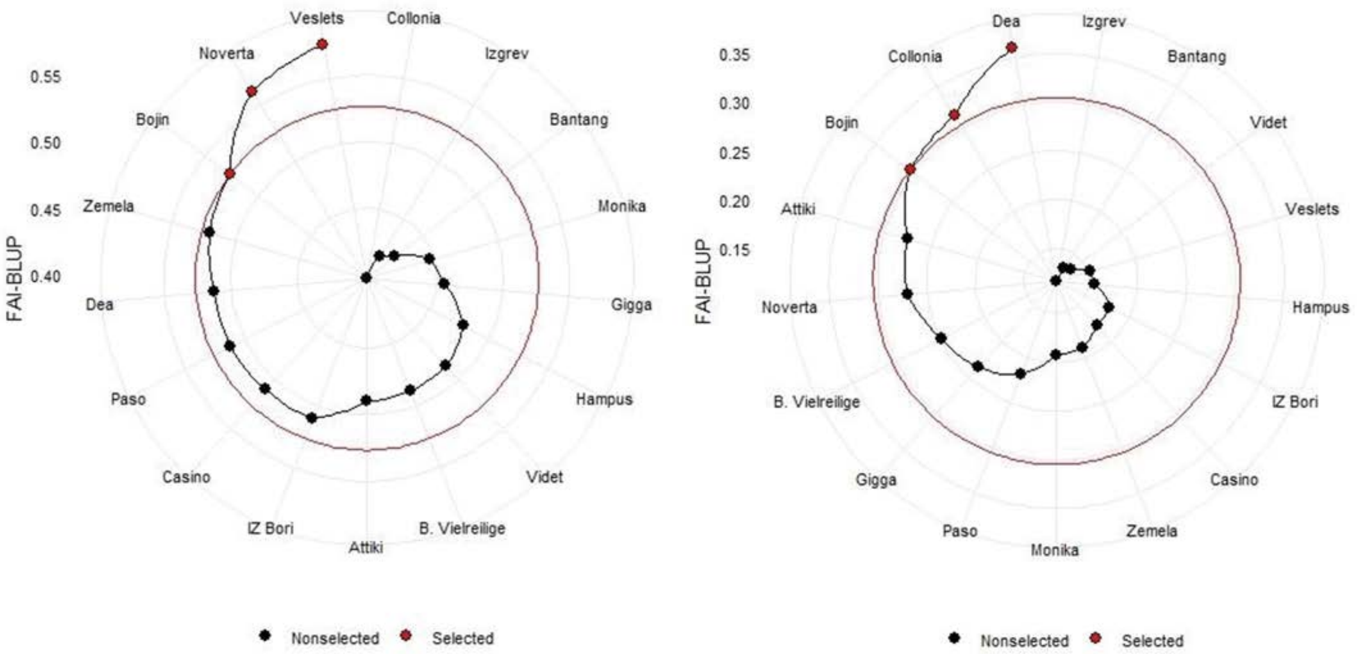

Figure 1. Genotype ranking and selected genotypes for the FAI-BLUP index considering a selection intensity of 15% (red circle) in 2018/2019 growing season (left) and 2019/2020 growing season (right)

Correlations

Knowledge of the direction and magnitude of correlations between traits is extremely important for the breeder to formulate simultaneous selection strategies in multiple traits. This is especially important when a trait of high economic value has low heritability or is difficult to evaluate compared to another associated trait.

Considerable differences were observed in the magnitude and directions of correlations between traits in two growing seasons (Figure 2). There were significant positive correlations between SW and NGS, NSS, SL and PH in both growing years. The association between SW and TGW was positive in 2018/2019 and negative in 2019/2020. In the 2019/2020 growing year, negative correlations between TGW and NSS, NGS, and SW were observed, while in 2018/2019 we found no correlations between TGW and these traits.

GY was positively correlated with SPM (r = 0.48) and negatively correlated with SW (r = -0.5), TGW (r = -0.48), PH (r = -0.41), and NSS (r = -0.39) in 2018/2019. While in the 2019/2020 growing year, significant positive correlations were found between GY and PH (r = 0.32) and SW (r = 0.25). Mekonnon (2014) reported that PH, SL, and NGS were the most important traits that affect the grain yield performance of barley in low rainfall environments.

Sefatgol and Ganjali (2017) studied the effect of late-season drought stress and found that GY had a positive correlation with harvest index, SPM, NGS, and SL and a negative correlation with TGW. In our previous study on spring hulless barley, positive correlations of GY with the NSS, PH, NGS, and SW under drought conditions were observed (Dyulgerov and Dyulgerova, 2020).

Differences in the strength and direction of associations between yield-related traits in non-stress and drought environments were also reported previously (Dyulgerov and Dyulgerova, 2020; Thabet et al., 2020; Mahdy et al., 2022). A possible explanation is that the alleles controlling high grain yield in low-yielding conditions are probably at least partially different from those controlling high grain yield in high-yielding conditions (Ceccarelli et al. 1992).

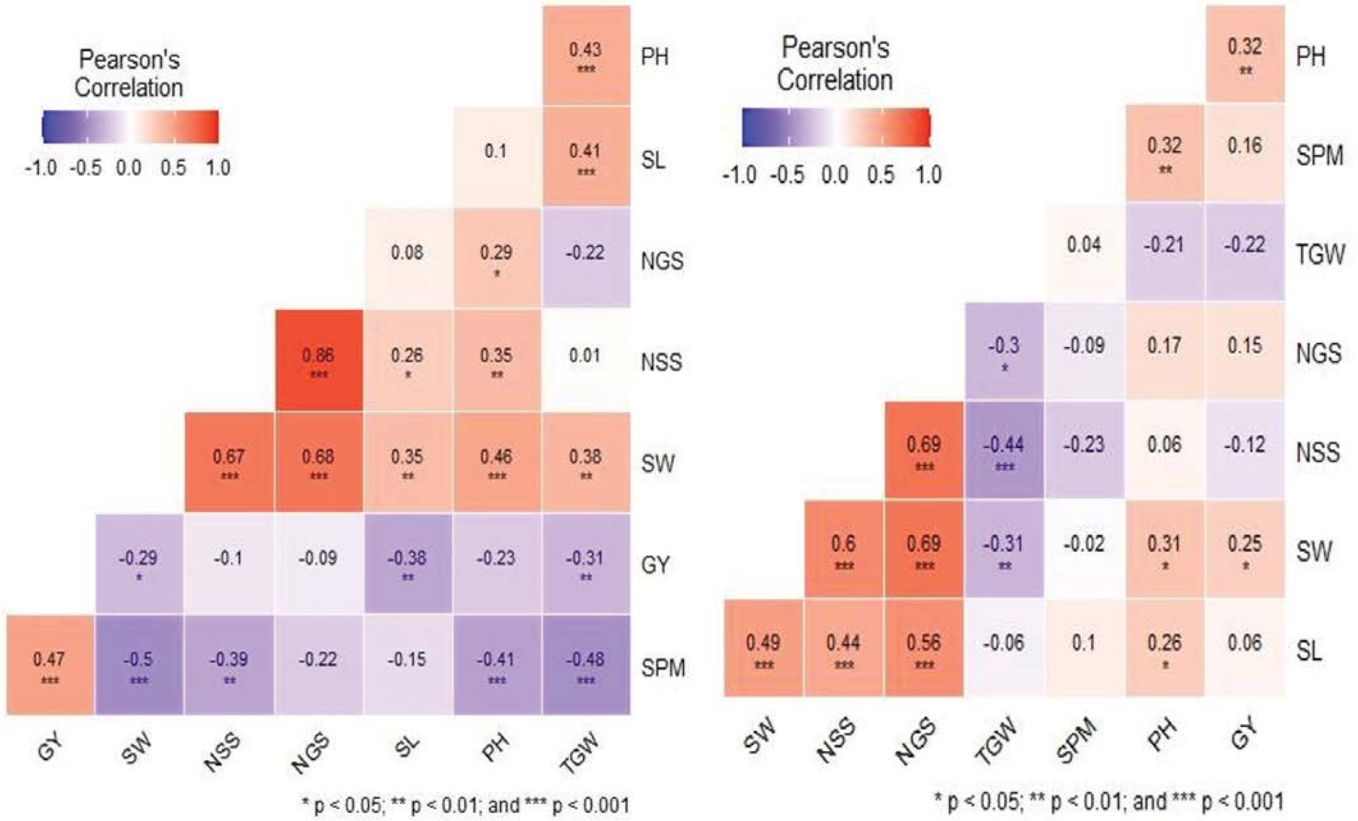

Figure 2. Correlation coefficients among grain yield and yield-related traits in the 2018/2019 growing season (left) and 2019/2020 growing season (right)

CONCLUSION

Grain yield and yield-related traits of winter barley varieties were compared in two growing years characterized by conditions of mild and severe drought stress (precipitation sum was less by 15% in the first growing year and 36% in the second growing year than the long-term precipitation sum). A reduction was observed in all studied yield-related traits, with grain yield in the second year being more than 70% lower than that measured in the first growing year.

Lower values of broad-sense heritability in the second growing year for NSS, NGS, SW, and GY were found suggesting that the direct selection of these traits under drought stress will be less effective.

Varieties ranking based on the FAI-BLUP index strongly varied across growing seasons, but in both years variety Bojin was selected as a high-performing variety for multiple traits. Therefore, this variety could be recommended as a variety with high grain yield potential and low susceptibility to water deficit stress.

Considerable differences were observed in the magnitude and directions of correlations between GY and yield-related traits between two growing seasons.

These findings, in the context of the increasing frequency and duration of drought stress in the region, suggest a longer period of multi-year testing and a complicated process of selection in breeding programs of winter barley.

REFERENCES

Addisu, F., Shumet, T. (2015) Variability, heritability and genetic advance for some yield and yield related traits in barley (*Hordeum vulgare* L.) landraces in Ethiopia. International Journal of Plant Breeding and Genetics, 9 (2), 68-76.
DOI: http://dx.doi.org/10.3923/ijpbg.2015.68.76

Ahakpaz, F., Abdi, H., Neyestani, E., Hesami, A., Mohammadi, B., Nader Mahmoudi, K., Abedi-Asl, G., Jazayeri Noshabadi, M. R., Ahakpaz, F., Alipour, H. (2021) Genotype-by-environment interaction analysis for grain yield of barley genotypes under dryland conditions and the role of monthly rainfall. Agricultural Water Management, 245.
DOI: http://dx.doi.org/10.1016/j.agwat.2020.106665

Ahmadi, J., Vaezi, B., Pour-Aboughadareh, A. (2016) Analysis of variability, heritability, and interrelationships among grain yield and related characters in barley advanced lines. Genetika, 48 (1), 73-85.
DOI: http://dx.doi.org/10.2298/GENSR1601073A

Akgün, N. (2016) Genetic variability and correlation studies in yield and yield related characters of barley (*Hordeum vulgare* L.) genotypes. Selcuk Journal of Agriculture and Food Sciences, 30 (2), 88-95.

Al-Ajlouni, Z. I., Al-Abdallat, A. M., Al-Ghzawi, A. L. A., Ayad, J. Y., Abu Elenein, J. M., Al-Quraan, N. A., Baenziger, P. S. (2016) Impact of pre-anthesis water deficit on yield and yield components in barley (*Hordeum vulgare* L.) plants grown under controlled conditions. Agronomy, 6 (2), 33.
DOI: http://dx.doi.org/10.3390/agronomy6020033

Amabile, R. F., Faleiro, F. G., Capettini, F., Sayd, R. (2015) Estimation of genetic parameters, phenotypic, genotypic and environmental correlations on barley (*Hordeum vulgare* L.) grown under irrigation conditions in the Brazilian Savannah. Interciencia, 40 (4), 255-262.

Balzarini, M. (2002). Applications of mixed models in plant breeding. In: Kang, M. S., ed. Quantitative genetics, genomics and plant breeding. Wallingford UK: CABI Publishing, pp. 353-363.
DOI: http://dx.doi.org/10.1079/9780851996011.0353

Barnabas, B., Jäger, K., Fehér, A. (2008) The effect of drought and heat stress on reproductive processes in cereals. Plant, cell & environment, 31 (1), 11-38.
DOI: http://dx.doi.org/10.1111/j.1365-3040.2007.01727.x

Bento, V. A., Ribeiro, A. F., Russo, A., Gouveia, C. M., Cardoso, R. M., Soares, P. M. (2021) The impact of climate change in wheat and barley yields in the Iberian Peninsula. Scientific Reports, 11 (1), 1-12. DOI: http://dx.doi.org/10.1038/s41598-021-95014-6

Bernardo, R. (2020). Reinventing quantitative genetics for plant breeding: something old, something new, something borrowed, something BLUE. Heredity, 125 (6), 375-385.
DOI: http://dx.doi.org/10.1038/s41437-020-0312-1

Blum, A., (1988) Plant Breeding for Stress Environments. Boca Raton: CRC press. DOI: https://doi.org/10.1201/9781351075718

Botelho, T. T., Leite, P. S. D. S., Parrella, R. A. D. C., Nunes, J. A. R. (2022) Strategies for multi-trait selection of sweet sorghum progenies. Crop Breeding and Applied Biotechnology, 21.
DOI: http://dx.doi.org/10.1590/1984-70332021v21n4a59

Bouzerzour, H., Dekhili, M. (1995) Heritabilities, gains from selection and genetic correlations for grain yield of barley grown in two contrasting environments. Field Crops Research, 41 (3), 173-178.
DOI: http://dx.doi.org/10.1016/0378-4290(95)00005-B

Casagrande, C. R., Mezzomo, H. C., Silva, C. M., Lima, G. W., Souza, D. J. P., Borém, A., Nardino, M. (2022) Selection indexes based on genotypic values applied to Brazilian tropical wheat breeding. Agronomy Science and Biotechnology, 8, 1-16.
DOI: http://dx.doi.org/10.33158/ASB.r171.v8.2022

Ceccarelli, S., Grando, S., Hamblin, J. (1992) Relationship between barley grain yield measured in low-and high-yielding environments. Euphytica, 64 (1-2), 49-58.
DOI: http://dx.doi.org/10.1007/BF00023537

Chand, N., Vishwakarma, S. R., Verma, O. P., Kumar, M. (2008) Worth of genetic parameters to sort out new elite barley lines over heterogeneous environments. Barley Genetics Newsletter, 38, 10-13.

da Silva, M. J., Carneiro, P. C. S., de Souza Carneiro, J. E., Damasceno, C. M. B., Parrella, N. N. L. D., Pastina, M. M., Simeone M. L. F., Eugene Schaffert R. E., da Costa Parrella, R. A. (2018) Evaluation of the potential of lines and hybrids of biomass sorghum. Industrial Crops and Products, 125, 379-385.
DOI: http://dx.doi.org/10.1016/j.indcrop.2018.08.022

Dyulgerov, N., Dyulgerova, B. (2020) Variability, heritability, and correlations among grain yield and related traits in hulless barley accessions. Trakia Journal of Sciences, 18 (4), 285-293.
DOI: http://dx.doi.org/10.15547/tjs.2020.04.002

El-Hashash, E. F., Agwa, A. M. (2018) Genetic parameters and stress tolerance index for quantitative traits in barley under different drought stress severities. Asian Journal of Research in Crop Science, 1 (1), 1-16. DOI: http://dx.doi.org/10.9734/AJRCS/2018/38702

Ferrante, A., Savin, A., Slafer, G. A. (2008) Wheat and barley floret development in response to nitrogen and water availability. Italian Journal of Agronomy/Rivista di Agronomia, 3 suppl., 205-206.

Hartung, K., Papa, H. P., Knüpffer, H. (2006). Analysis of genebank evaluation data by using geostatistical methods. Genetic resources and crop evolution, 53 (4), 737-751.
DOI: http://dx.doi.org/10.1007/s10722-004-4716-1

Hoyle, A., Brennan, M., Rees, L., Jackson, G. E., Hoad, S. P. (2020) Post-anthesis water-stressed barley maintains grain specific weight through altered grain composition and plant architecture. Plants, 9 (11), 1564. DOI: http://dx.doi.org/10.3390/plants9111564

Hu, X. (2015) A comprehensive comparison between ANOVA and BLUP to valuate location-specific genotype effects for rape cultivar trials with random locations. Field Crops Research, 179, 144-149.
DOI: http://dx.doi.org/10.1016/j.fcr.2015.04.023

Mahdy, R. E., Ashehri, D., Alatawi, H. A., Al-Amrah, H., Mahdy, E. E. (2022) Direct and indirect selection for grain yield and grain weight in late generations of bread wheat under drought stress and normal irrigation environments. Plants, 11 (12), 1604.
DOI: http://dx.doi.org/10.3390/plants11121604

Meier, C., Marchioro, V. S., Meira, D., Olivoto, T., Klein, L. A. (2021) Genetic parameters and multiple-trait selection in wheat genotypes. Pesquisa Agropecuária Tropical, 51.
DOI: http://dx.doi.org/10.1590/1983-40632021v5167996

Mekonnon, B. (2014) Selection of barley varieties for their yield potential at low rain fall area based on both quantitative and qualitative characters North West Tigray, Shire, Ethiopia. International Journal of Plant breeding and Genetics, 8 (4), 205-213.
DOI: http://dx.doi.org/10.3923/ijpbg.2014.205.213

Mihova, G., Baychev, V., Alexandrov, T., Petrova, T., Stanoeva, Y., Ivanova, V. (2018). Breeding of cereal crops at Dobrudzha Agricultural Institute–General Toshevo, Bulgaria. Journal of Agricultural, Food and Environmental Sciences, JAFES, 72 (2), 124-131.
DOI: http://dx.doi.org/10.55302/JAFES18722124m

Mittler, R. (2006) Abiotic stress, the field environment and stress combination. Trends in plant science 11 (1), 15–19.
DOI: http://dx.doi.org/10.1016/j.tplants.2005.11.002

Oliveira, I. C. M., Marçal, T. D. S., Bernardino, K. D. C., Ribeiro, P. C. D. O., Parrella, R. A. D. C., Carneiro, P. C. S., Schaffert, R. E., Carneiro, J. E. D. S. (2019) Combining ability of biomass sorghum lines for agroindustrial characters and multitrait selection of photosensitive hybrids for energy cogeneration. Crop Science, 59 (4), 1554-1566. DOI: http://dx.doi.org/10.2135/cropsci2018.11.0693

Olivoto, T., Lúcio, A. D. C. (2020). metan: An R package for multi-environment trial analysis. Methods in Ecology and Evolution, 11(6), 783-789. DOI: http://dx.doi.org/10.1111/2041-210X.13384

Peixoto, M. A., Coelho, I. F., Evangelista, J. S. P. C., Santos, S. S. D. O., Alves, R. S., Pinto, J. F. N., dos Reis E. F., Bhering, L. L. (2021) Selection of maize hybrids: an approach with multi-trait, multi-environment, and ideotype-design. Crop Breeding and Applied Biotechnology, 21 (2). DOI: http://dx.doi.org/10.1590/1984-70332021v21n2a31

Piepho, H. P., Möhring, J., Melchinger, A. E., Büchse, A. (2008). BLUP for phenotypic selection in plant breeding and variety testing. Euphytica, 161(1-2), 209-228.
DOI: http://dx.doi.org/10.1007/s10681-007-9449-8

Rajala, A., Hakala, K., Mäkelä, P., Peltonen-Sainio, P. (2011). Drought effect on grain number and grain weight at spike and spikelet level in six-row spring barley. Journal of Agronomy and Crop Science, 197 (2), 103-112.
DOI: http://dx.doi.org/10.1111/j.1439-037X.2010.00449.x

Resende, M. D. V., Duarte, J. B. (2007) Precisão e controle de qualidade em experimentos de avaliação de cultivares. Pesquisa Agropecuária Tropical, 37, 182–194 (in Portuguese).

Ribeiro, E. H., Pereira, M. G., de Souza Coelho, K., Júnior, S. D. P. F. (2015) Estimativas de parâmetros genéticos e seleção de linhagens endogâmicas recombinantes de feijoeiro comum (*Phaseolus vulgaris* L.). Ceres, 56 (5), 580-590 (in Portuguese).

Rocha, J. R. A. S. C., Machado, J. C., Carneiro, P. C. S. (2018) Multitrait index based on factor analysis and ideotype-design: Proposal and application on elephant grass breeding for bioenergy. GCB Bioenergy, 10, 52–60. DOI: http://dx.doi.org/10.1111/gcbb.12443

Sahu, P. K. (2013) Research methodology: A guide for researchers in agricultural science, social science and other related fields. New York: Springer.
DOI: http://dx.doi.org/10.1007/978-81-322-1020-7

Sefatgol, F., Ganjali, H. (2017) Evaluation of drought stress tolerance in advanced barley cultivars in Sistan region. Bioscience biotechnology research communications, 10 (2), 276-286.

Singh, B. D. (2001) Plant Breeding: Principles and Methods (6th edition). New Delhi: Kalyani Publishers.

Sunil, K. D., Khan, M. (2017) Investigation of genetic variability for yield and yield related traits in barley (*Hordeum vulgare* L.) genotypes. Indian Journal of Ecology, 4, 869-872.

Thabet, S. G., Moursi, Y. S., Karam, M. A., Börner, A., Alqudah, A. M. (2020) Natural variation uncovers candidate genes for barley spikelet number and grain yield under drought stress. Genes, 11 (5), 533. DOI: http://dx.doi.org/10.3390/genes11050533

Tinker, N. A., Mather, D. E., Rossnagel, B. G., Kasha, K. J., Kleinhofs, A., Hayes, P. M., Falk, D. E., Ferguson, T., Shugar, L. P., Legge, W. G., Irvine, R. B., Choo, T. M., Briggs, K. G., Ullrich, S. E., Franckowiak, J. D., Blake, T. K., Graf, R. J., Dofing, S. M., Saghai Maroof, M. A., Scoles, G. J., Hoffman, D., Dahleen, L. S., Kilian, A., Chen, F., Biyashev, R. M., Kudrna, D. A., Steffenson, B. J. (1996) Regions of the genome that affect agronomic performance in two-row barley. Crop Science 36 (4), 1053-1062. DOI: http://dx.doi.org/10.2135/cropsci1996.0011183X003600040040x

Verma, A., Verma, R. P. S., Singh, J., Kumar, L., Singh, G. P. (2022) Genotype X Environment Interactions of Fodder Barley Genotypes as Estimated by AMMI, BLUP and Non Parametric Measures. Current Agriculture Research Journal, 10 (2), 46-54.
DOI: http://dx.doi.org/10.12944/CARJ.10.2.02

Voltas J., van Eeuwijk F., Igartua E., del Moral L. G., Molina-Cano J. L., Romagosa I. (2002) Genotype by environment interaction and adaptation in barley breeding: basic concepts and methods of analysis. In: Slafer, G., ed. Barley Science: Recent Advances from Molecular Biology to Agronomy of Yield and Quality. Binghamton, NY: Food Products Press, 205–241.

Zhong, S., Dekkers, J. C., Fernando, R. L., Jannink, J. L. (2009) Factors affecting accuracy from genomic selection in populations derived from multiple inbred lines: a barley case study. Genetics, 182 (1), 355-364. DOI: http://dx.doi.org/10.1534/genetics.108.098277