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Multi-trait selection of wheat lines under drought-stress condition

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ABSTRACT: The immediate need for the increase in wheat production to meet the future world demand, associated with the occurrence of drastic climatic events, such as drought, makes it necessary to develop drought-resilient genotypes. The aims of this work were to evaluate the use of drought-tolerance indices for the selection of wheat genotypes, to compare the genetic gains in grain yield using different selection strategies by means of a multi-trait index, and to select superior drought-tolerant wheat genotypes. The total of 31 tropical wheat lines was evaluated in two experiments. Five agronomic traits were accessed. The grain yield data from the stress and nonstress experiments were used to obtain five drought-tolerance indices. The data were subjected to mixed model analysis, and four selection scenarios were designed. There was a significant effect of genotype for all traits. The inclusion of drought-tolerance indices in the selection index provided superior genetic gains in drought condition. Seven lines were selected due the high frequency of favorable alleles for drought-tolerance and other important agronomic traits. Drought-tolerance indices are appropriate for characterizing the response of wheat genotypes to drought-stress. The inclusion of drought-tolerance indices along with agronomic traits in multi-trait selection strategies provides for superior gains in grain yield compared to the non-inclusion of the indices.

Key words: drought-tolerance, genetic gain, mixed models, selection index, *Triticum aestivum* L.

INTRODUCTION

Wheat (*Triticum aestivum* L.) has a high nutritional value, is able to provide significant amounts of energy in the human diet and, therefore, is a staple food for many populations around the world (Hazard et al. 2020). With the increase in world population and the changes in eating habits, it is estimated that there will be an increase in world demand for wheat by approximately 60% by 2050, which reflects the need for an increase in annual production by 1.6% (Wang et al. 2018). This scenario may be aggravated by recent climate changes causing drastic events such as drought, which in turn affects agricultural systems through unpredictable rainfall patterns, disease, and pest dynamics, leading to a reduction in potential yield gains (Bapela et al. 2022).

Drought-tolerance of wheat genotypes is a complex trait, being affected by several factors, including growth conditions, physiology, genotype, developmental stage, severity, and duration of drought, which implies diverse gene expression patterns and complex signaling pathways (Budak et al. 2015). Understanding the genetic, physiological, and biochemical mechanisms involved in the response of wheat genotypes to drought is useful to design breeding strategies for the selection of superior and drought-resilient genotypes (Nardino et al. 2022). However, understanding such mechanisms often requires genome wide association studies (Ballesta et al. 2020), in addition to physiological assessments and biochemical analyses (Abid et al. 2018), which are often difficult and time-consuming. Alternatively, the response of wheat genotypes to drought can be easily assessed under field conditions by observing the impacts of the stress on agronomic traits (Sallam et al. 2018) and by using drought-tolerance indices (Anwaar et al. 2020).

Several drought-tolerance indices, based on mathematical relationships between grain yield under water-stressed conditions and control (irrigated) conditions, have been proposed to characterize the behavior of genotypes in stress and nonstress environments in order to select drought-tolerant genotypes (Rosielle and Hambling 1981, Fernández 1992, Gavuzzi et al. 1997, Schneider et al. 1997, Jafari et al. 2009, Mohammadi 2016).

The selection of superior wheat genotypes through multivariate strategies can be designed using the multi-trait genotype ideotype distance index (MGIDI) (Olivoto and Nardino 2020), since this index is accurate, easy to interpret, and free of weighting coefficients and multicollinearity problems.

Although some studies have reported the use of drought-tolerance indices for the selection of wheat genotypes resilient to drought stress (Mohammadi 2016, Sallam et al. 2018, Sedri et al. 2019, Anwaare et al. 2020), there are few studies comparing the gains obtained with the inclusion or not of drought-tolerance indices in multi-trait selection strategies for the selection of superior genotypes. Moreover, most existing studies use phenotypic data to make inferences about the genotypes, which may not represent the true genetic value of individuals. Alternatively, the estimation of variance components by restricted maximum likelihood (REML) and prediction of genetic values by the best linear unbiased prediction (BLUP) allow the inference about best genotypes efficiently and accurately.

The objectives of this work were to evaluate the use of drought-tolerance indices for the selection of wheat genotypes, to compare the genetic gains in grain yield using different selection strategies by means of a multi-trait index, and to select superior and drought-tolerant genotypes based on their genotypic values.

MATERIAL AND METHODS

Plant material and field experiment

The genotypes consisted of 31 lines developed by the Universidade Federal de Viçosa (UFV) Wheat Breeding Program and five commercial cultivars developed by public and private companies, recommended for cultivation in the Center-South region of Brazil:

- BRS 264 (Empresa Brasileira de Pesquisa Agropecuária – EMBRAPA);
- CD 151 (Agrigenetics, Inc.);
- ORS 1403 (Or Melhoramento de Sementes LTDA);
- Tbio Aton (Biotrigo Genética LTDA);
- Tbio Duque (Biotrigo Genética LTDA).

Two field experiments were conducted in the winter of 2020 in the experimental area of Professor Diogo Alves de Mello (20º45’14”S; 42º52’55”W; 648 m altitude) of the Department of Agronomy, at UFV, in Viçosa, Minas Gerais, Brazil. The experiments were conducted in a randomized block design with three replications. The plots consisted of five lines of 5 m each, spaced at 0.2 m, with a population density of 350 seeds m-2. Agronomical practices were performed according to the technical recommendations for wheat cultivation.

Drought-stress and nonstress conditions

Initially, soil samples were collected at depths of 0-10 and 0-20 cm. The samples were homogenized and sent to laboratory analysis to obtain the soil water retention curve. For soil moisture monitoring, samples were collected every two days at ten random points in each experiment, at depths of 0-10 and 0-20 cm. The samples were then weighted and placed in an oven with circulating air at 60 °C for 48 hours. Finally, the samples were weighted again to estimate the amount of water in the soil (Fig. 1).

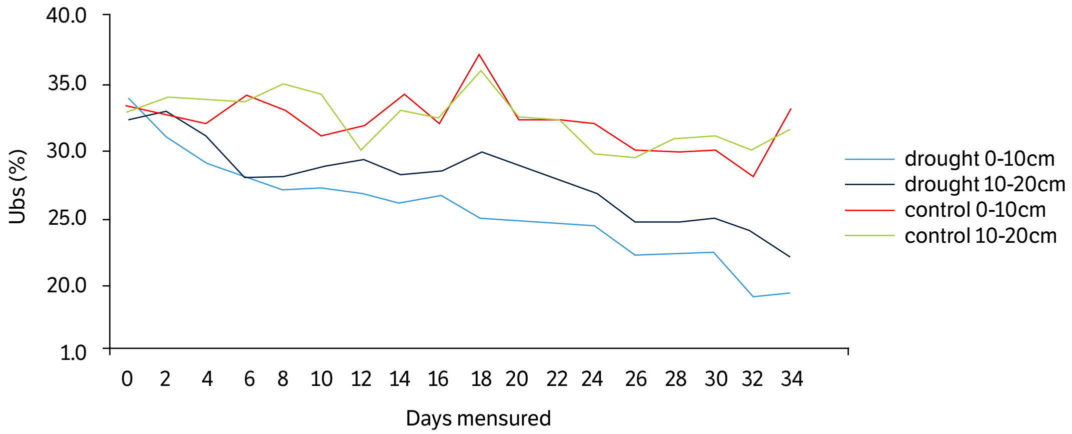


Figure 1. Results of the soil moisture gradient in the environments for two sampled depths, in which 0th corresponds to the onset of drought stress and the 34th the end of stress.

The control experiment was conducted with sprinkler irrigation to meet the water needs of the crop throughout its development. The stress experiment was conducted with sprinkler irrigation until the flowering phase. After this period, irrigation was restricted, and the genotypes were subjected to water stress for 30 days until the beginning of physiological maturity, after which irrigation was reestablished.

Traits evaluated and drought-stress tolerance indices

The number of days for heading (DH, days) was evaluated when at least 50% of the plants in each plot had fully exposed spikes. Five representative plants from each plot were used to measure the average plant height (PH, cm) with the aid of a ruler graduated in centimeters. The evaluations for disease were performed during the grain filling phase: for the evaluation of Tan Spot (TS, notes), notes from 1 to 5 were attributed according to the scale proposed by Lamari and Bernier (1989). For the evaluation of Leaf Rust (LR, notes), notes ranging from 0 to 4 according to the scale proposed by McIntosh et al. (1995) were attributed. After physiological maturity, the plots were manually harvested for yield determination (GY, kg·ha^{-1}), adjusting the moisture content for 13% in all plots. The yield data from the stress and non-stressed experiments were used to calculate the drought-tolerance indices (Table 1).

Table 1. Drought-tolerance indices.

Drought-tolerance indices	Code	Equation	Reference
Stress tolerance index	STI	$\frac{Y_S * Y_C}{(Y_C)^2}$	Fernández (1992)
Yield index	YI	$\frac{Y_S}{\bar{Y}_S}$	Gavuzzi et al. (1997)
Geometric mean productivity	GMP	$\sqrt{Y_S * Y_C}$	Schneider et al. (1997)
Mean productivity	MP	$\frac{Y_S * Y_C}{2}$	Rosielle and Hambling (1981)
Harmonic mean	HM	$\frac{2(Y_C - Y_S)}{Y_C + Y_S}$	Jafari et al. (2009)

Y_S and Y_C: drought-stress and nonstress grain yeld of a given genotype, respectively; $\bar{Y}_S$ and $\bar{Y}_C$: average yield of a all genotypes under drought-stress and nonstress conditions, respectively.

Statistical analysis

Mixed model analysis

The agronomic data were subjected to mixed model analysis for the estimation of genetic parameters by the REML method, and prediction of genotypic values by BLUP according to Eq. 1:

$$y = Xb + Zu + e \tag{1}$$

in which: y = a vector $\eta[\Sigma_{j=1}^{r}(gr)]\times 1$ of observations, that is, the response of the ith genotype in the jth block (i = 1, 2, ..., g; j = 1, 2, ..., r; $y = [y_{11}, y_{12}, ..., y_{gr}]'$); b = a vector 1 × r of block fixed effects, $b\ [\gamma_1, \gamma_2, ..., \gamma_r]'$; g = a vector m [1 × g] of the random effects of genotype, $g\ [\alpha_1, \alpha_2, ..., \alpha_g]'$, $g \sim N(0; I\ \sigma_g^2)$; e = a vector n × 1 of the random error effects, $e = [y_{11}, y_{12}, ..., y_{gr}]'$, $e \sim N(0; I\ \sigma_g^2)$; X, and Z = the incidence matrices of the effects.

Genetic correlation analysis

The genotypic values of the drought-tolerance indices and the agronomic traits evaluated in the nonstress and stress experiments were subjected to genetic correlation analysis, as Eq. 2:

$$\hat{r}_{g_{xy}} = \frac{Cov_g\ (x, y)}{\sqrt{\sigma_g^2(x)\sigma_g^2(y)}} \tag{2}$$

in which: $\hat{r}_{g_{xy}}$ = the genetic correlation coefficient between two random variables; Cov_g = the genotypic covariance; σ_g^2 = the genotypic variance; x and y = two random variables.

Multi-trait genotype ideotype distance index

The selection of the best genotypes in the stress experiment was performed using the MGIDI (Olivoto and Nardino 2020).

For the selection strategies, four scenarios were considered: selection in the stress experiment considering only agronomic traits (first scenario); selection in the stress experiment considering both agronomic traits and drought-tolerance indices (second scenario); selection in the nonstress experiment considering only agronomic traits (third scenario); and selection in the nonstress experiment considering both agronomic traits and drought-tolerance indices (fourth scenario). MGIDI requires the planning of an ideotype for the analyzed traits. In this work, positive desired gains were assumed for the traits GY, GMP, HM, MP, STI, and YI, and negative desired gains were assumed for DH, PH, LR, and TS.

The MGIDI was applied based on a two-way table, as Eq. 3:

$$MGIDI_i = [\Sigma_{j=1}^{f}(\gamma_{ij} - \gamma_j)^2]^{0.5} \tag{3}$$

in which: $MGIDI_i$ = the MGIDI for the ith genotype; γ_{ij} = the score of the ith genotype in the jth factor (i = 1, 2, …, g; j = 1, 2, …, f), being *g* and *f* the numbers of genotypes and factors, respectively; γ_j = the jth ideotype score.

The proportion of the MGIDI of the ith genotype explained by the jth factor (ω_ij) was given by Eq. 4:

$$\omega_{ij} = \frac{\sqrt{D_{ij}^2}}{\sum_{j=1}^{f}\sqrt{D_{ij}^2}} \tag{4}$$

in which: D_{ij} = the distance between the *i*th genotype and ideotype for the *j*th factor.

The smaller the contribution of a factor is, the closer the traits of that factor are to the ideotype (Olivoto and Nardino 2020). The predicted genetic gains using MGIDI were calculated for each trait considering selection intensity of 20%.

RESULTS

Mixed-model analysis

Table 2 presents the mixed-model analyses for the agronomic traits evaluated in the stress and nonstress experiments, as well as for the drought-tolerance indices. Mean heritability values ranged from 0.63 (GY) to 0.91 (LR) in the nonstress experiment, and from 0.56 (TS) to 0.90 (PH) in the stress experiment. The heritability values of drought-tolerance indices ranged from 0.64 (YI) to 0.79 (GMP, MP, and HM). Selective accuracies ranged from 0.79 (GY) to 0.96 (LR) in the nonstress experiment and from 0.75 (TS) to 0.95 (DH) in the stress experiment. The accuracy values of the drought-tolerance indices ranged from 0.80 (YI) to 0.89 (GMP, MP, and HM).

Table 2. Mixed-model analysis, estimated variance components, and genetic parameters of 36 wheat genotypes.

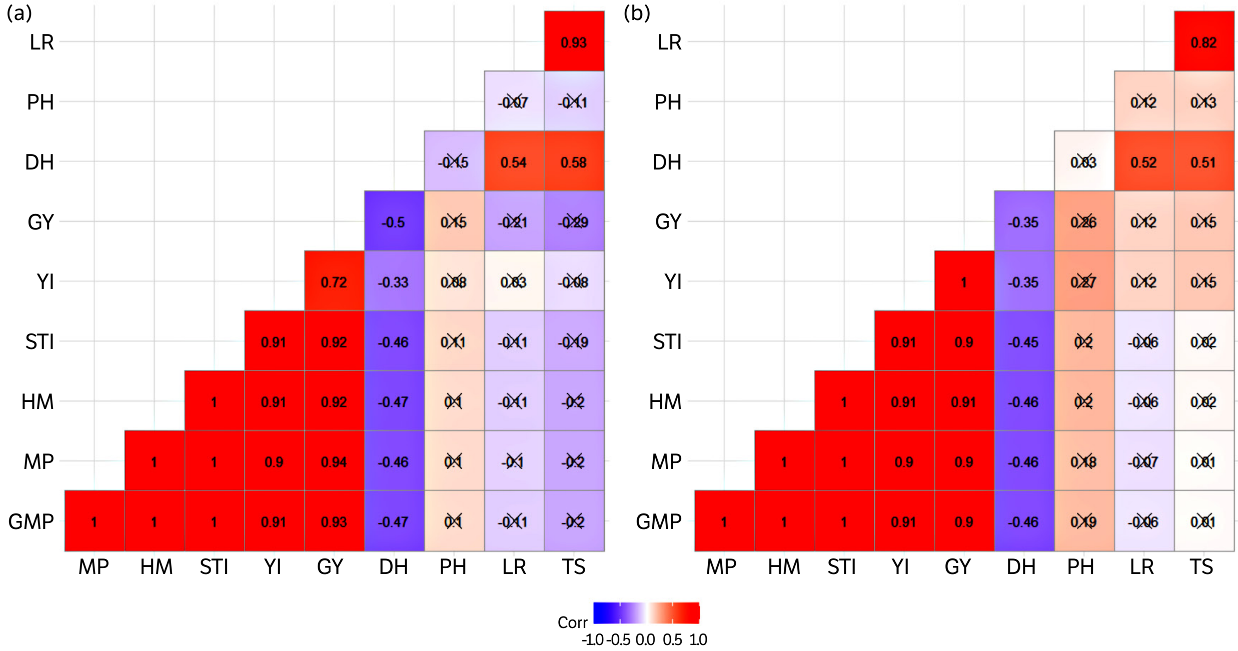
Parameters	**Traits[1]**				
	GY	**DH**	**PH**	**LR**	**TS**
$\hat{\sigma}^2_g$	193,721.00*	4.20*	13.50*	0.54*	0.26*
$\hat{\sigma}^2_r$	342,300.00	2.39	18.10	0.15	0.19
$\hat{\sigma}^2_p$	536,021.00	6.59	31.70	0.69	0.45
h^2_m	0.63	0.88	0.69	0.91	0.80
Accuracy	0.79	0.92	0.83	0.96	0.89
CV_g (%)	10.50	3.53	4.13	31.50	25.90
CV_r (%)	14.00	2.66	4.78	16.80	22.40
p-value	5.62E-04	8.28E-11	2.95E-05	1.32E-17	1.13E-08
Parameters	**Traits[2]**				
	GY	**DH**	**PH**	**LR**	**TS**
$\hat{\sigma}^2_g$	130,146.00*	3.75*	12.10*	0.18*	0.10*
$\hat{\sigma}^2_r$	198,311.00	1.20	16.00	0.25	0.24
$\hat{\sigma}^2_p$	328,457.00	4.95	28.10	0.42	0.34
h^2_m	0.66	0.90	0.69	0.68	0.56
Accuracy	0.81	0.95	0.83	0.82	0.75
CV_g (%)	9.85	3.41	4.14	18.00	15.00
CV_r (%)	12.20	1.93	4.76	21.40	22.80
p-value	3.71E-04	3.07E-16	2.69E-05	5.34E-05	3.53E-03
Parameters	**Traits[3]**				
	GMP	**MP**	**HM**	**STI**	**YI**
$\hat{\sigma}^2_g$	169,244.00*	168,354.00*	17,139.00*	0.03*	0.01*
$\hat{\sigma}^2_r$	134,502.00	137,723.00	132,421.00	0.03	0.02
$\hat{\sigma}^2_p$	303,745.00	306,077.00	302,560.00	0.06	0.03
h^2_m	0.79	0.79	0.79	0.78	0.64
Accuracy	0.89	0.89	0.89	0.88	0.80
CV_g (%)	10.60	10.50	10.70	20.60	9.64
CV_r (%)	9.41	9.47	9.40	19.20	12.40
p-value	3.56E-07	5.05E-07	2.79E-07	1.05E-0.6	1.18E-03

[1]Deviance analysis for agronomic traits in nonstress experiment; [2]deviance analysis for agronomic traits in stress experiment; [3]deviance analysis for drought stress indices; GY: grain yield; DH: days for heading; PH: plant height; LR: leaf rust; TS: tan spot; GMP: geometric mean productivity; MP: mean productivity; HM: harmonic mean; STI: stress tolerance index; YI: yield index; $\hat{\sigma}^2_g$: genotypic variance component; $\hat{\sigma}^2_r$ residual variance component; $\hat{\sigma}^2_p$: phenotypic variance component; h^2m: average heritability; CV_g (%): genotypic coefficient of variation; CV_r (%): residual coefficient of variation; **significant at 5% or 1% error probability by the Chi-square test: $\chi_{1\%} = 6.63$.

The genotypic coefficients of variation ranged from 3.53 (DH) to 31.50% (LR) in the nonstress experiment, and from 3.41 (DH) to 18% (LR) in the stress experiment. The coefficients of genotypic variation of drought-tolerance indices ranged from 9.64 (YI) to 20.60% (STI). The coefficients of residual variation in the nonstress experiment ranged from 2.66 (DH) to 22.40% (TS), while in the stress experiment the values ranged from 1.93 (DH) to 22.80% (TS). The coefficients of residual variation of the drought-tolerance indices ranged from 9.40 (HM) to 19.20% (STI).

Correlation among traits

Figure 2 presents the correlation coefficients of the genotypic values between the agronomic traits evaluated in the nonstress (Fig. 2a) and stress (Fig. 2b) experiments with the drought-tolerance indices. In both experiments, the drought-tolerance indices showed perfect correlations among themselves. GY showed correlations ≥ 0.90 with all drought-tolerance indices. DH showed moderate and negative correlations with drought-tolerance indices and GY, and moderate and positive correlations with LR and TS. LR and TS showed a high and positive correlation with each other. These results suggest that the correlation among those traits may not vary considering normal and low water availability situations.



GY: grain yield; DH: days for heading; PH: plant height; LR: leaf rust; TS: tan spot; GMP: geometric mean productivity; MP: mean productivity; HM: harmonic mean; STI: stress tolerance index; YI: yield index; *non-cross and cross cells indicate non-significant and significant correlations, respectively, at 5 or 1% error probability.

Figure 2. (a) Genetic correlation among agronomic traits and drought-tolerance indices in the nonstress experiment; (b) genetic correlation among agronomic traits and drought-tolerance indices in the stress experiment*.

Factor analysis

Table 3 presents the results of the factor analysis considering the four scenarios of selection. In the first scenario, the traits were grouped in two factors, with the average communality equal to 0.73. The traits DH, LR, and TS constituted the first factor, while GY and PH constituted the second factor. In the second scenario, the traits were grouped in two factors, with the average communality equal to 0.82. GY, PH, GMP, MP, HM, STI, and YI constituted the first factor, while DH, LR, and TS constituted the second factor.

In the third scenario, the traits were grouped just as occurred in the first scenario, i.e., DH, LR, and TS constituted the first factor, while GY and PH constituted the second factor, and the average communality was also 0.73. In the fourt scenario, average communality was 0.75, and the drought-tolerance indices were grouped in the same factor, while GY, DH, PH, LR and TS were grouped in the second factor. GY and PH had low factorial loading values in this scenario. The average communalities obtained in the four selection scenarios revealed that the factors explained a high proportion of the total variation observed.

Table 3. Explained variance, factorial loadings after varimax rotation, and communalities obtained in the factor analysis considering four selection scenarios*.

Trait	1st Scenario		
	FA1	FA2	h
GY	-0.03	**0.88**	0.78
DH	**-0.79**	0.38	0.76
PH	-0.14	**-0.63**	0.42
LR	**-0.90**	-0.18	0.85
TS	**-0.90**	-0.22	0.85
Trait	**2nd Scenario**		
	FA1	**FA2**	**h**
GY	**-0.94**	0.11	0.93
DH	-0.45	**-0.70**	0.69
PH	0.26	-0.25	0.13
LR	0.02	**-0.92**	0.85
TS	0.08	**-0.92**	0.85
GMP	**-0.99**	-0.08	0.98
MP	**-0.98**	-0.09	0.97
HM	**-0.99**	-0.07	0.98
STI	**-0.98**	-0.07	0.97
YI	**-0.96**	0.11	0.93
Trait	**3rd Scenario**		
	FA1	**FA2**	**h**
GY	-0.31	**-0.69**	0.57
DH	**-0.69**	**-0.45**	0.68
PH	-0.08	0.78	0.61
LR	**-0.95**	0.00	0.90
TS	**-0.95**	-0.08	0.91
Trait	**4th Scenario**		
	FA1	**FA2**	**h**
GY	-0.40	**0.48**	0.38
DH	-0.28	**0.77**	0.67
PH	0.14	**-0.19**	0.06
LR	0.12	**0.92**	0.85
TS	0.08	**0.94**	0.89
GMP	**-0.98**	0.12	0.98
MP	**-0.98**	0.12	0.98
HM	**-0.99**	0.12	0.99
STI	**-0.98**	0.11	0.97
YI	**-0.90**	0.07	0.81

1st Scenario: factor analysis considering only agronomic traits in the stress experiment; 2nd Scenario: factor analysis considering both agronomic traits and drought-tolerance indices in the stress experiment; 3rd Scenario: factor analysis considering only agronomic traits in the nonstress experiment; 4th Scenario: factor analysis considering both agronomic traits and drought-tolerance indices in the nonstress experiment; GY: grain yield; DH: days for heading; PH: plant height; LR: leaf rust; TS: tan spot; GMP: geometric mean productivity; MP: mean productivity; HM: harmonic mean; STI: stress tolerance index; YI: yield index; h: Communality; *bold values indicate the variables grouped within each factor.

Predicted selection gains

Table 4 presents the predicted mean genotypic values and the gains from selection considering the four selection scenarios. In the first scenario, DH, LR, TS, and PH showed negative gains, and GY showed a positive gain, with a value equal to 1.24%. In the second scenario, we also observed negative gains for the traits DH, LR, and TS. The gains for GY and for drought-tolerance indices were positive, being the percent gain for GY equal to 5.48%, approximately five times higher than the gain provided for in this trait in the first scenario. Among the drought-tolerance indices, the largest gain observed was for STI, being 16.30%.

Table 4. Predicted genetic gains of the selected genotypes through multi-trait genotype-ideotype distance index considering four selection scenarios.

Trait	1st Scenario		
	OB	**SB**	**SG (%)**
DH	56.80	55.20	-2.49
LR	2.33	1.99	-9.90
TS	2.12	1.95	-4.64
GY	3664.00	3732.00	1.24
PH	84.10	83.80	-0.19
Trait	**2nd Scenario**		
	OB	**SB**	**SG (%)**
GY	3,664.00	3,967.00	5.48
PH	84.10	84.70	0.50
GMP	3,896.00	4,307.00	8.35
MP	3,919.00	4,329.00	8.23
HM	3,873.00	4,285.00	8.44
STI	0.89	1.08	16.30
YI	1.00	1.08	5.04
DH	56.80	54.90	-3.03
LR	2.33	2.17	-4.71
TS	2.12	2.05	-1.80
Trait	**3rd Scenario**		
	OB	**SB**	**SG (%)**
DH	58.10	57.30	-1.09
LR	2.33	2.59	10.2
TS	1.96	2.13	6.64
GY	4,174.00	4,271.00	1.47
PH	89.01	90.2	0.88
Trait	**4th Scenario**		
	OB	**SB**	**SG (%)**
GY	4,174.00	4,394.00	3.32
PH	89.01	90.90	1.48
GMP	3,896.00	3,948.00	0.17
MP	3,919.00	3,976.00	0.20
HM	3,873.00	3,920.00	0.14
STI	0.89	9,131.00	0.37
YI	1.00	1.03	0.43
DH	56.80	54.90	-2.18
LR	2.33	2.09	-11.93
TS	1.96	1.68	-11.21

1st Scenario: selection gains considering only agronomic traits in the stress experiment; 2nd Scenario: selection gains considering both agronomic traits and drought-tolerance indices in the stress experiment; 3rd Scenario: selection gains considering only agronomic traits in the nonstress experiment; 4th Scenario: selection gains considering both agronomic traits and drought-tolerance indices in the nonstress experiment; GY: grain yield; DH: days for heading; PH: plant height; LR: leaf rust; TS: tan spot; GMP: geometric mean productivity; MP: mean productivity; HM: harmonic mean; STI: stress tolerance index; YI: yield index; OB: original best linear unbiased prediction (BLUP) means; SB: best linear unbiased prediction (BLUP) means of the selected genotypes; SG (%): predicted selection gains.

In the third scenario, GY presented positive and DH negative desired gains, while LR, TS, and PH had positive undesired gains. In the fourth scenario, GY presented positive desired gain, while the drought-tolerance indices presented positive and low magnitude gains. DH, LR and TS showed negative desired gains.

Selected genotypes and their strength and weaknesses

In the first scenario, the genotypes VI 14088, VI 14001, VI 9007, VI 14668, VI 14327, VI 9037, and VI 9004 were selected (Fig. 3a). The FA1 factor provided for the lowest contributions to genotype VI 14088 (Fig. 4a). The smallest contributions provided for the factor FA2 were to genotypes VI 14327 and VI 9007 (Fig. 4a). In the second scenario, the genotypes VI 14001, VI 9004, VI 131313, VI 14327, BRS 264, VI 14668, and VI 14118 were selected (Fig. 3b). In this strategy, the lowest observed contribution of the FA1 factor was for BRS 264 (Fig. 4b). The FA2 factor provided for the lowest contributions to genotypes VI 14327 and VI 14668 (Fig. 4b).

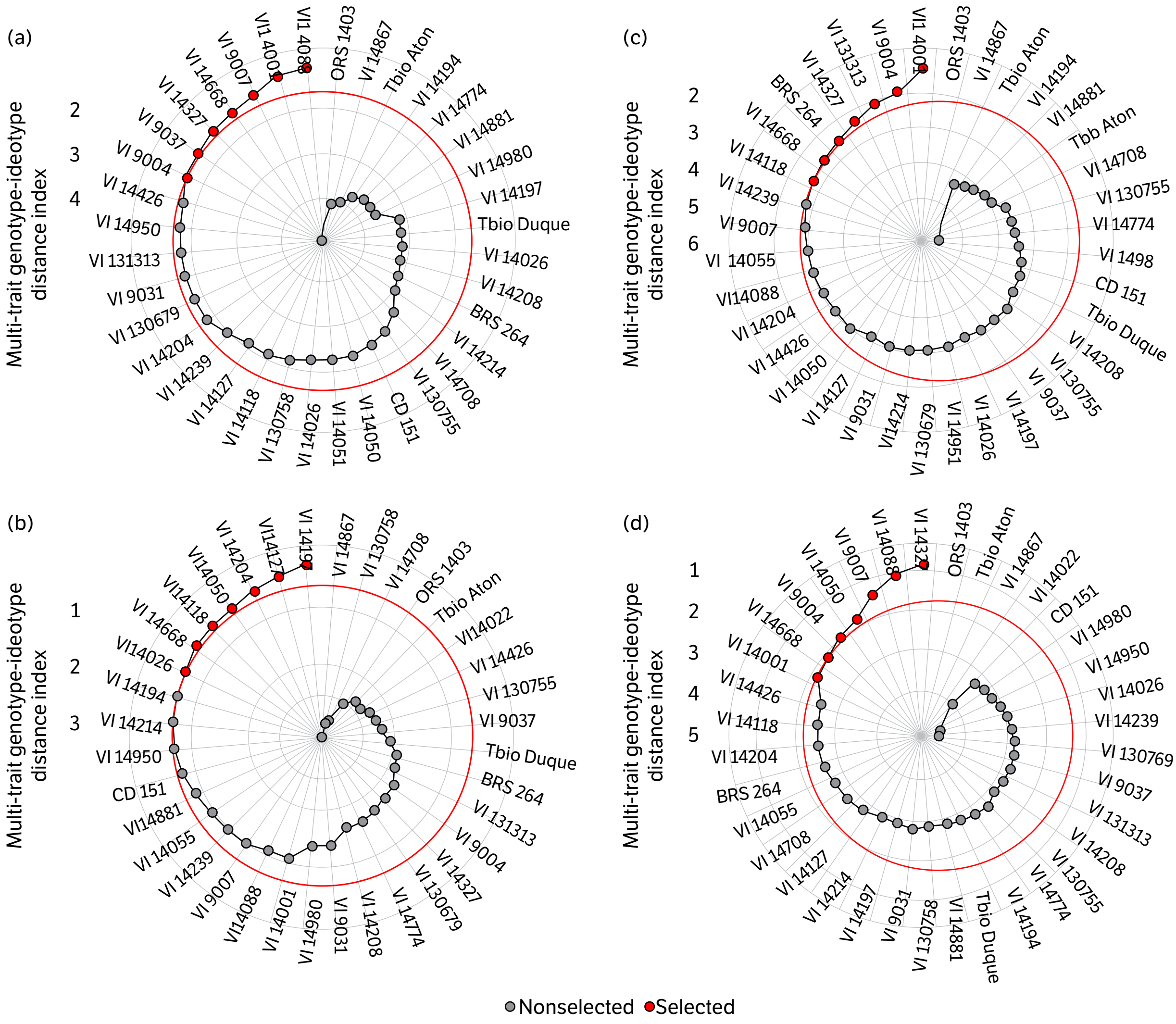


Figure 3. Genotype ranking and selected genotypes (in red) in ascending order for the multi-trait genotype ideotype distance index considering four scenarios: (a) only agronomic traits in the stress experiment; (b) both agronomic traits and drought-tolerance indices in the stress experiment; (c) only agronomic traits in the nonstress experiment; (d) both agronomic traits and drought-tolerance indices in the nonstress experiment. Red circle represents cut point according to the selection pressure.

In the third scenario, the selected genotypes were VI 14197, VI 14127, VI 14204, VI 14050, VI 14118, VI 14668, and VI 14026 (Fig. 3c). The FA1 factor provided for the lowest contribution to the genotype VI 14118, while FA2 factor had the lowest contribution for genotype VI 14127 (Fig. 4c). In the fourth scenario, the selected genotypes were VI 14327, VI 14088, VI 9007, VI 14050, VI 9004, VI 14668 and VI 14001 (Fig. 3d). The FA1 factor provided for the lowest contributions to the genotype VI 9004, while the FA2 factor provided for the lowest contribution to the genotypes VI 14668 and VI 9007 (Fig. 4d).

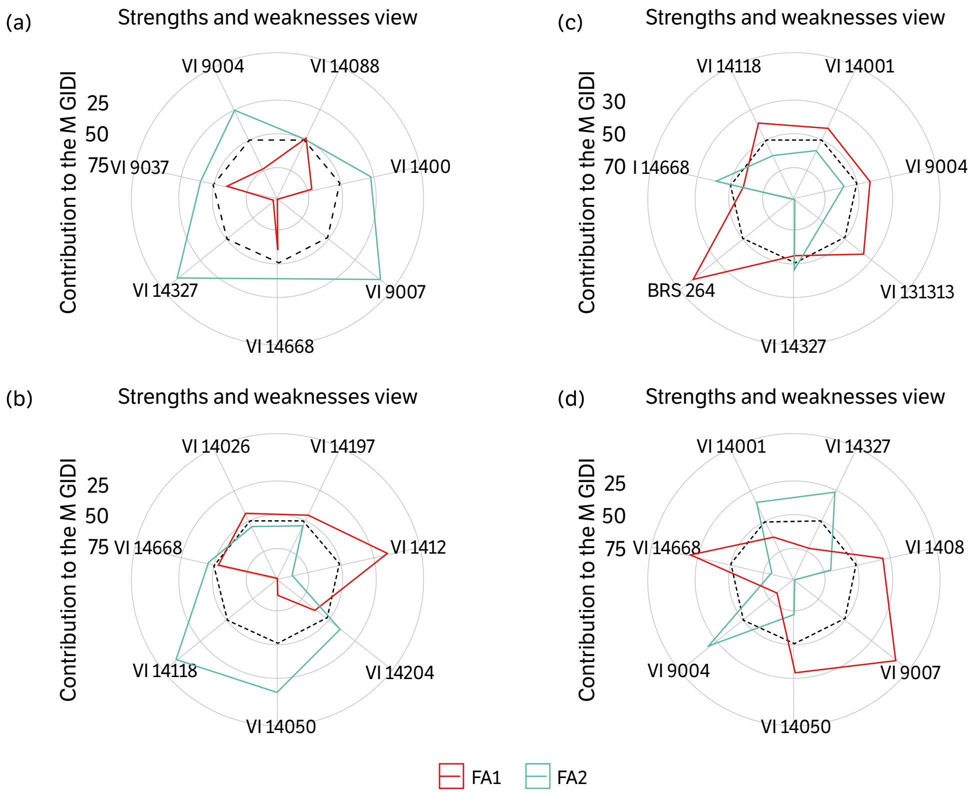


Figure 4. The strength and weakness view among selected genotypes considering four scenarios: (a) only agronomic traits in the stress experiment; (b) both agronomic traits and drought-tolerance indices in the stress experiment; (c) only agronomic traits in the nonstress experiment; (d) fourth both agronomic traits and drought-tolerance indices in the nonstress experiment. The dashed black line shows the theoretical value if all factors contributed equally.

DISCUSSION

The high significance of the genotype effect for the agronomic traits evaluated in the nonstress and stress experiments, as well as for the drought-tolerance indexes, indicates the existence of high genetic variability and the possibility of selection of superior and drought-resilient genotypes. The heritability estimates obtained indicate an important contribution of the genotypic variance to the total variation observed for the set of traits. Furthermore, the estimates obtained for selective accuracy express a high correlation between predicted and observed genetic values (Lima et al. 2022). The accuracy estimates obtained, in accordance with the residual variation coefficients, suggest high experimental quality and precision (Nardino et al. 2023), which gives security for carrying out selection decisions.

Once the existence of variability among the genotypes has been identified, strategies can be designed for the selection of genotypes with superior behavior. For this, it is important to know the correlation between the considered traits. The high correlations obtained between drought-tolerance indices and grain yield in both experiments indicate the existence of a high linear association between these traits, corroborating with the results found by Ayed et al. (2021). These results were expected since the indices were constructed based on phenotypic grain yield values observed in the nonstress and stress conditions. Thus, the inclusion of drought-tolerance indices with grain yield in selection indices could lead to high genetic gains in grain yield under drought-stress conditions. Mohammadi (2016) emphasized that the knowledge of the relationship between drought-tolerance indices and grain yield can be useful to improve the efficiency of breeding programs that aim to develop drought stress resilient genotypes.

The negative correlations found between days for heading and the drought-tolerance indices and grain yield suggest that early genotypes have greater capacity for drought-tolerance. Early maturity is an escape mechanism to drought, being one of the strategies employed by genotypes in conditions in which there is water limitation in critical periods of the development and ensures that genotypes complete their cycle quickly during the period of favorable conditions (Shavrukov et al. 2017).

Once relationship among traits was elucidated, strategies for the simultaneous selection of superior genotypes can be designed. The use of selection indices is an efficient strategy because it allows combining multiple pieces of information, so that it is possible to select based on a complex of variables that brings together several attributes of economic interest.

An optimal procedure for genotypic selection is through the MGIDI, given its ability to deal with multicollinearity and dismiss with the need to establish economic weights (Olivoto and Nardino 2020). The use of this index requires the application of a factor analysis, an effective method that fits the observed genotypes by unobserved latent factors, maximizing the common variance between correlated genotypes.

In general, the genetic gains observed for the set of traits in all considered scenarios, although satisfactory, were of low magnitude. This may be explained due to the set of genotypes used in this study. Because the genotypes are high performing lines in advanced breeding stage, they already have a high frequency of favorable alleles accumulated. Thus, the genetic gains were expected to be low/moderate. Additionally, the genetic gains in the set of the traits varied regarding the scenarios considered, which may lead to differences in the performance of the genotypes in each situation.

The predicted gains from selection showed in the first and second scenario allowed for selecting superior genotypes and obtaining balanced genetic gains for the set of traits under drought-stress condition. Both selection strategies increased precocity and disease resistance with the selected genotypes. Although both strategies provided for positive gains for grain yield, the percentage gain for this trait when drought-tolerance indices were included outstood (second scenario). This result allows to infer that the use of drought-tolerance indices in selection strategies enables superior genetic gains in grain yield and is useful in the identification of genotypes resilient to drought stress, corroborating the results found by Mohammadi (2016).

In the third scenario, only two genotypes selected (VI 14118 and VI 14668) were also selected in the first or in the second scenario, in which drought-stress condition occurred. This reinforces the fact that differences regarding genotypes indicated for selection may occur according to the scenarios. It may be explained by the fact that genes express differentially in stress and nonstress conditions, making it necessary to evaluate and select drought-resilient genotypes in drought environments.

The selection strategies used in this work presented differences regarding the genotypes indicated for selection. The results indicate that the genotypes selected according to the second scenario have a high frequency of favorable alleles for drought-tolerance due to the superior genetic gain in grain yield. According to Ali et al. (2020), the main mechanism of drought-tolerance is due to the maintenance of turgor by osmotic adjustment, which increases cell elasticity and reduces cell size. Moreover, in periods of water shortage, genotypes use various physiological adjustments to cope with cell dehydration. Wheat genotypes able to assimilate and rapidly adjust the photosynthetic machinery are more likely to tolerate water stress or fluctuations in precipitation (Nardino et al. 2022).

A previous study indicated that the genotype VI 14001, first selected in the second scenario, presents high stability in stomatal conductance and inhibition of ferric reducing antioxidant power as physiological and biochemical responses to water stress (Nardino et al. 2022). In this same study, it was also demonstrated that the genotype VI 14668 (selected in the second scenario) presents higher stomatal conductance and increased proline content. Under stress conditions, the accumulation of osmoprotectants, such as proline, helps genotypes to perform basic metabolic functions, improving the maintenance of osmotic balance, the protection of cells and organelles against dehydration, the stabilization of membranes, and the detoxification of reactive oxygen species (Nadeem 2020).

The BRS 264 genotype, selected in the second scenario, presents high genetic potential regarding productive performance (Caierão et al. 2014), being widely recommended for cultivation in the Brazilian Cerrado region, the second largest biome in Brazil, with great potential for wheat production, however with limited water availability during wheat growing seasons (Pereira et al. 2019).

The lower contribution provided for the FA1 factor to BRS 264 genotype emphasizes the superiority of this genotype regarding yield potential and drought-tolerance. The contributions provided the factor FA2 for the genotypes VI 14668 and VI 14327 suggest that they have higher precocity and higher disease resistance under drought stress conditions.

The results of this study showed that the inclusion of drought-tolerance indices along with other agronomic traits in the MGIDI selection index provides balanced gains for the set of traits. Moreover, the inclusion of the indices provides higher gains in grain yield compared to non-inclusion, due to the high linear association between the indices and grain yield. It was shown that the genotypes selected in the second scenario present a high frequency of favorable alleles for grain yield, short cycle and resistance to diseases under drought-stress conditions. The selected genotypes should be included in the crossing blocks of breeding programs aiming the improvement of wheat for drought-tolerance.

CONCLUSION

Drought-tolerance indices are appropriate for characterizing the response of wheat genotypes to drought stress. The inclusion of drought-tolerance indices along with agronomic traits in multi-trait selection strategies provides superior gains in grain yield compared to not including the indices. The genotypes VI 14001, VI 9004, VI 131313, VI 14327, BRS 264, VI 14668, and VI 14118 should be used strategically in breeding programs due their superiority in drought-tolerance and other agronomic traits of interest in wheat breeding.

AUTHORS' CONTRIBUTION

Conceptualization: Machado e Silva, C., Mezzomo, H. C., Ribeiro, J. P. O., Freitas, D. S. and Nardino, M.; **Methodology:** Machado e Silva, C., Mezzomo, H. C., Freitas, D. S. and Nardino, M.; **Investigation:** Machado e Silva, C., Mezzomo, H. C., Ribeiro, J. P. O., Freitas, D. S. and Nardino, M.; **Writing – Original Draft:** Machado e Silva, C., Mezzomo, H. C., Nardino, M.; **Writing – Review and Editing:** Machado e Silva, C., Mezzomo, H. C., Ribeiro, J. P. O., Freitas, D. S. and Nardino, M.; **Funding Acquisition:** Nardino, M.; **Supervision:** Nardino, M.

DATA AVAILABILITY STATEMENT

The data that support this study were obtained from UFV Wheat Breeding Program by permission. Data will be shared upon reasonable request to the corresponding author with permission from UFV Wheat Breeding Program.

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