Ukrainian Journal of Ecology

Ukrainian Journal of Ecology, 2018, 8(4), 314-319

ORIGINAL ARTICLE

Assessment of drought resistance indices in spring bread wheat under various environmental conditions

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Received: 18.10.2018. Accepted: 25.11.2018

Drought stress is the most important factor limiting wheat yield in the Altai Territory, Russia. Several selection criteria have been proposed to select genotypes based on their performance in stressful and non-stressful environments. We tested seventy-five genotypes of spring bread wheat in a randomized complete block design with three replications for three years (2010-2012). The trials were conducted in the Altai Research Institute of Agriculture, Russia. Six drought resistance indices, including Sensitivity drought index (*SDI*), Mean productivity (*MP*), Tolerance index (*Tol*), Stress susceptibility index (*SSI*), Geometric mean productivity (*GMP*) and Stress tolerance index (*STI*) were calculated for each genotype based on grain yields under non-stress and three stress conditions. Stress intensity indices (*SI*) in the first, second, and third environments were low (*SI* = 0.39), moderate (*SI* = 0.56), and high (*SI* = 0.80), respectively. We found that different indices give a similar characteristic of the most drought-resistant and drought-susceptible genotypes. *SSI* fully corresponds to the *SDI* value, and *STI* corresponds to the *GMP* value (r = 1.00). Tolerance is closely related to *SDI* (r = 0.83-0.86). *SDI* and *SSI* are offered as useful indices for wheat breeding where stress is severe, while *STI*, *MP* and *GM*P are suggested if stress is less severe. Genotypes with high yield potential can be identified under moderate drought, but not under severe drought stress.
Keywords: wheat; drought; resistance indices; grain yield

Drought is the most destructive abiotic stressor accompanying the entire history of agriculture. According to the time of onset and duration, drought may be short-term (at the beginning, middle or end of the growing season) and long-term (throughout the growing season), of varying degrees of intensity. This phenomenon is not just a shortage of water, but a complex combination of water deficiency, temperature stress, hot wind, soil salinity and other abiotic factors. Damage from it exceeds the damage from any other stressor. During 1967-1991, droughts affected 50 % of the 2.8 billion people who suffered from weather-related disasters (Kogan, 1997). Drought stress of varying degrees can be observed in almost all climatic zones (Passioura, 2007) and reduce wheat yields by up to 50 % (Reynolds et al., 2007) due to significant reductions in plant growth and shoot production (Ehdaie et al., 2008, 2012). In the Russian Federation, a particularly severe drought was in 2010 and 2012, which led in some regions to a complete or substantial loss of crop yields, including wheat. The peculiarity of the growing season in Siberia is the development of drought from the stage of germination through to flowering. The lack of moisture is often accompanied by high temperatures. Flowering and grain filling usually take place with a sufficient amount of precipitation.

An effective way to reduce damage from drought is to cultivate drought-resistant cultivars. But breeding for drought resistance is complicated by the lack of fast, reproducible screening techniques and the inability to routinely create defined and repeatable water stress conditions, when a large amount of genotypes can be efficiently evaluated (Ramirez & Kelly, 1998). Drought susceptibility of a genotype is often measured as a function of the reduction in yield under drought stress (Blum, 1988). In Russia, as a criterion for assessing drought tolerance of a cultivar, the value of the yield reduction in dry years to the yield of the cultivar in years with sufficient rainfall during the growing season is used (Litvinenko & Leshin, 1993). It coincides with the Sensitivity drought index (*SDI*) proposed by Farshadfar & Javadinia (2011a). The genotypes with low value of this index will be more desirable.

Drought resistance in a broader agronomic sense is determined by the ability of a cultivar to produce the highest yield compared to other cultivars under drought conditions (Y_s – grain yield under drought condition). Estimation by absolute yield and comparison of yield in dry and wet years, taken separately, do not provide an exhaustive picture of the practical drought tolerance of the cultivar and should be carried out in parallel (Kumakov, 1985). Currently, researchers seek a comprehensive assessment of the drought tolerance of cultivars using drought tolerance indices (Golabadi et al., 2006; Farshadfar & Sutka, 2003). Many authors studied the relationships of these indices with grain yield under stress and non-stress conditions. Aliakbari et al. (2013) found that tolerance *Tol* and *MP* indices appeared to be the most appropriate ones for screening drought tolerant genotypes. Sio-Se Mardeh et al. (2006) used drought tolerant indices in wheat and stated that under moderate stress, *MP*, *GMP* and *STI* were more effective in identifying high-yielding cultivars under both drought-stressed and

irrigated conditions. Under severe stress, none of the indices used were able to identify a group of high-yielding cultivars. They concluded that the effectiveness of selection indices in differentiating resistant cultivars varies with the stress severity.
In the above and similar works, two backgrounds are used: irrigated and non-irrigated conditions. These experiments require the use of special techniques, are able to evaluate a small number of genotypes and do not fit well into the breeding process. In the works of Russian breeders to assess the adaptive properties of wheat, different years and agrotechnical options are used (sowing date, predecessor) (Ziborov, 2013). Given the distribution of precipitation in Siberia, which consists in a lack of moisture before flowering and excessive precipitation in the second half of the growing season, additional irrigation in the first half of the growing season will almost certainly cause lodging of all cultivars. In this regard, the arid conditions are modeled by growing wheat after the stubble predecessor. The aim of the study is to compare the selection criteria at different stress intensity to identify drought-tolerant wheat genotypes suitable for cultivation in arid zones of the Altai Territory, Russia.

Material and Methods

We studied 75 cultivars of spring bread wheat of various ecological and geographical origin and different ripening groups. The tests were carried out in the Altai Research Institute of Agriculture, The Altai Territory, Russia in 2010-2012. Cultivars were planted in a randomized complete block design with three replications. Sowing was carried out after fallow and cereal crop predecessor in the second decade of May. The size of the plot was 2 m^2 (7 rows, 2 m long and 15 cm between rows). Drought tolerance indices were calculated using the following relationships:

$$SDI = \frac{(Y_p - Y_s)}{Y_p}$$ (Farshadfar & Javadinia, 2011a) (1);

$$MP = \frac{Y_s + Y_p}{2}$$ (Rosielle & Hamblin, 1981) (2);

$$Tol = Y_p - Y_s$$ (Rosielle & Hamblin, 1981) (3);

$$SSI = \frac{1 - Y_s / Y_p}{1 - Y_{sm} / Y_{pm}}$$ (Fischer & Maurer, 1978) (4);

$$GMP = \sqrt{Y_s \times Y_p}$$ (Fernandez, 1992) (5);

$$STI = \frac{Y_s \times Y_p}{Y_{pm} \times Y_{pm}}$$ (Fernandez, 1992) (6),

where Y_p is grain yield of a cultivar under favorable conditions; Y_s is grain yield of a cultivar under drought conditions; Y_{sm} and Y_{pm} are the mean yields of all cultivars under stress and non-stress conditions, respectively, and $1 - \frac{Y_{sm}}{Y_{pm}}$ is the stress intensity index (*SI*) (Ramirez-Vallejo & Kelly, 1998).
Tests with different levels of stress included: fallow predecessor 2010 (Y_p) which is the favorable conditions, cereal crop predecessor 2011 (Y_{s1}) which is mild stress (*SI* = 0.39), fallow predecessor 2012 (Y_{s2}) which is moderate stress (*SI* = 0.56), and cereal crop predecessor 2012 (Y_{s3}) which is severe stress (*SI* = 0.80). Meteorological data of the test location in 2010-2012 are shown in Tables 1 and 2.

Table 1. Monthly precipitation during the growing season 2010-2012, mm

Year	May	June	July	August	The amount for the growing season
2010	18	45	120	13	195
2011	32	30	42	36	140
2012	24	10	97	44	175

Table 2. Average monthly air temperature during the growing season 2010-2012, °C

Year	May	June	July	August	The average for the growing season
2010	10,2	18,6	17,5	17,6	16,0
2011	12,2	20,2	18,1	16,4	16,7
2012	12,1	22,1	22,1	18,4	18,7

The reliability of the differences among the mean values of a pair of genotypes was tested using the Least Significant Differences ($LSD_{0,05}$). The results were statistically processed using the Microsoft Office Excel 2010 application software.

Results and Discussion

Grain yield varied widely between environments and genotypes. The highest average yields (202-402 g m^{-2}) were obtained in the Y_p. They were lower in the Y_{s1} and Y_{s2} (138-236 g m^{-2} and 73-198 g m^{-2}, respectively) and the lowest (31-90 g m^{-2}) in the Y_{s3}. The average yields for all cultivars in the environments were 295 g m^{-2} (Y_p), 181 g m^{-2} (Y_{s1}), 130 g m^{-2} (Y_{s2}), 60 g m^{-2} (Y_{s3}).

The yield and drought tolerance indices of some genotypes are presented in Table 3. The indices evaluate different aspects of drought tolerance of cultivars, therefore full compliance between them, with rare exception, is not observed. Astana is characterized by the lowest yield in all environments, but according to *SSI*, *Tol* and *SDI*, this sample should be recognized as drought-resistant. Saratovskaya 72 is characterized by similar values of drought tolerance indices, but, unlike Astana, this genotype has a rather high yield in arid conditions.

Table 3. Yield (g m^{-2}) and tolerance indices of 10 contrast wheat cultivars (averaged over 2010-2012 years)

Genotype	Y_p	Y_{s1}	Y_{s2}	Y_{s3}	*SSI*	*STI*	*Tol*	*MP*	*GMP*	*SDI*	Y_s*
Lutescens 697	360	230	182	88	0,92	0.69	193	263	241	0.54	167
Svetlanka	309	231	164	82	0.80	0.56	149	234	217	0.48	159
Lutescens 36/c	318	190	161	90	0.94	0.54	171	232	214	0.54	147
Saratovskaya 72	229	182	162	81	0.62	0.37	87	185	178	0.38	142
Lutescens 43/c	267	171	155	87	0.84	0.42	129	202	190	0.48	137
Lutescens 622	373	187	124	81	1.16	0.56	242	252	218	0.65	131
Lutescens 259	382	218	110	51	1.16	0.55	255	254	211	0.67	126
Astana	218	173	112	55	0.78	0.28	105	166	154	0.48	114
Tulajkovskaya ostistaya	347	156	73	48	1.31	0.37	255	220	174	0.73	92
Altajskaya 325	320	163	87	41	1.22	0.36	223	208	170	0.70	97
$LSD_{0,05}$	**54**	**37**	**30**	**28**	**0.25**	**0.15**	**31**	**15**	**27**	**0.10**	**31**

Note: * – $Y_s = (Y_{s1} + Y_{s2} + Y_{s3})/3$

In general, various indices give a similar characteristic to the three most drought-tolerant and drought-susceptible genotypes. In environments where the frequency of favorable years is high and droughts are not of an extreme nature, assessments related to the determination of average values of yield and the degree of its decline come to the fore. In environments where the frequency of drought occurrence is high enough, grain yield under drought condition is crucial, and all indicators based on the assessment of potential yield reduction should be used with caution, as the cultivar can have a low yield in favorable conditions, which will overstate *SSI* and *SDI*. Two cultivars with either high or low yield in both stress and non-stress environments may produce equal *SSI*. For this reason, selection based on this index, confuses the breeders (Mollasadeghi et al., 2001). In this case, there can be 4 variants of the reactions of cultivars in accordance with Fernandez (1992). These are high yields in all environments (Lutescens 697), significant grain productivity in favorable conditions and low grain productivity during drought (Lutescens 259, Lutescens 622, Tulaikovskaya ostistaya, Altajskaya 325), high Y_s combined with a small Y_p (Lutescens 43/c, Saratovskaya 72) and low yield in all environments (Astana).

To examine the relationship between drought tolerance indices, a correlation analysis was conducted in three environments with increasing drought stress (Tables 4, 5 and 6).

Table 4. Simple correlation coefficients of stress indices with grain yield of 75 wheat cultivars at Y_p and Y_{s1}

	Y_p	*SSI*	*STI*	*Tol*	*MP*	*GMP*	*SDI*	Y_s
Y_p	1,00							
SSI	0,76	1,00						
STI	0,90	0,42	1,00					
Tol	0,91	0,95	0,64	1,00				
MP	0,95	0,55	0,99	0,75	1,00			
GMP	0,91	0,44	1,00	0,65	0,99	1,00		
SDI	0,76	1,00	0,42	0,95	0,55	0,44	1,00	
Y_s	0,45	-0,21	0,79	0,04	0,70	0,79	-0,21	1,00

Note: The critical value of the correlation coefficient is 0.22 (p = 0.05)

Identifying the relationship between Y_s and Y_p is important for the possibility of indirect selection of drought-resistant and productive genotypes in different conditions. Some studies have reported the absence of a positive correlation or a non-significant correlation between Y_s and Y_p (Sio-Se Mardeh et al., 2006; Zebarjadi et al., 2012; Yasir et al., 2013). Other studies have found a positive correlation between Y_s and Y_p (Farshadfar et al., 2012; Abdolshahi et al, 2013). This indicates that indirect selection for drought stress condition based on the result of normal condition would be efficient. In other hand, the high positive relationship between Y_s and Y_p indicates that the genotype × environment interaction in such an experiment is small, and in fact it is possible to avoid the irrigation option to assess drought tolerance.

According to our research, the correlation between yield in a favorable and arid environment was medium (r = 0.38–0.45) under mild and moderate stress. Under severe stress, correlation between Y_s and Y_p was non-significant.

Table 5. Simple correlation coefficients of stress indices with grain yield of 75 wheat cultivars at Y_p and Y_{s2}

	Y_p	*SSI*	*STI*	*Tol*	*MP*	*GMP*	*SDI*	Y_s
Y_p	1,00							
SSI	0,47	1,00						
STI	0,77	-0,16	1,00					
Tol	0,85	0,86	0,33	1,00				
MP	0,93	0,11	0,95	0,59	1,00			
GMP	0,78	-0,16	1,00	0,34	0,96	1,00		
SDI	0,47	1,00	-0,16	0,86	0,11	-0,16	1,00	
Y_s	0,38	-0,62	0,87	-0,16	0,70	0,87	-0,62	1,00

Abdolshahi et al. (2013) pointed out that the application of all drought-tolerant/susceptible indices simultaneously is a good approach for screening drought-tolerant genotypes. However, the results of our study suggest that *SSI* coincides with *SDI*, and *STI* coincides with *GMP*. Fernandez (1992) stated that *STI* is estimated based on *GMP* and thus the rank correlation between *STI* and *GMP* is equal to 1. *Tol* is closely associated with *SSI*, therefore it is also associated with *SDI* (r = 0.83–0.95) in three levels of stress. *GMP* and *MP*, and therefore *STI*, give a close assessment of the cultivars in mild and moderate drought. Therefore, the simultaneous calculation of these indices can be avoided so as not to clutter the study. Similar results were reported by Dadbakhsh et al. (2011) and Sareen et al. (2014).

Table 6. Simple correlations coefficients of stress indices with grain yield of 75 wheat cultivars at Y_p and Y_{s3}

	Y_p	*SSI*	*STI*	*Tol*	*MP*	*GMP*	*SDI*	Y_s
Y_p	1,00							
SSI	0,65	1,00						
STI	0,44	-0,35	1,00					
Tol	0,96	0,83	0,19	1,00				
MP	0,96	0,40	0,68	0,84	1,00			
GMP	0,45	-0,36	1,00	0,19	0,69	1,00		
SDI	0,65	1,00	-0,35	0,83	0,40	-0,36	1,00	
Y_s	-0,15	-0,83	0,81	-0,41	0,14	0,81	-0,83	1,00

To be of practical value, any drought index must show consistent results over different environments (Mohammadi, 2016). Fernandez (1992) believes that the optimal selection criterion should separate high-yielding genotypes from all other cultivars in arid and favorable conditions. He concluded that *MP*, *SSI* and *Tol* were not able to identify such genotypes, and *STI* was more suitable. Geravandia et al. (2011) came to a similar conclusion. Saba et al. (2001) found that narrow-sense heritability estimates were very low for *SSI* and *Tol*, but moderate for *GMP*, *MP* and *STI*. Thus, selection based on the latter indices could be more promising than on *SSI* and *Tol*. *STI* is a suitable yield-based drought resistance index that can be employed in plant breeding programs because of its high narrow-sense heritability and the inherent ability of selecting high-yielding genotypes in either stressed or non-stressed conditions (Farshadfar et al., 2011b). Abdoli & Saeidi (2012) and Mohammadi et al. (2011) concluded that *STI*, *GMP* and *MP* indices were appropriate indicators for identification of cultivars with high grain yield in both water deficiency and control treatments.

Significant relationships were observed between Y_s and *STI*, *GMP*, *MP* in all three years, indicating that the selection of genotypes for these indices will improve the yield under stress (Farshadfar et al., 2012). At the same time, Zebarjadi et al. (2012) reported that the correlation of *MP* with Y_s was not significant. We note that *MP* is not able to identify resistant genotypes only under severe stress, where Y_s and Y_p do not correlate with each other.

Correlation analysis showed that *STI* was positively correlated with grain yield under both conditions in all three years. Although with severe drought, the correlation between *STI* and Y_p decreases to a medium level (r = 0.44). Therefore, in such conditions, the *STI* is no longer a suitable index. *SSI* is more suitable. This result has been confirmed by other studies (Bayoumi et al., 2008; Akçura et al., 2011), but SSI should be used along with yield data under stress (Najaphy et al., 2011). No significant correlation was found between *SSI* and yield under mild stress conditions showing that *SSI* will not discriminate drought sensitive cultivars under such conditions. Ehdaie et al. (1996) also indicated that *SSI* is not able to identify potentially productive genotypes.

Yasir et al. (2013) noted that the genotypes with high values of *Tol* and *SSI* were able to produce high yield only in the non-stressed environment. *Tol* assesses the absolute difference in yield of a cultivar under favorable and arid conditions. This difference can be regarded as a decrease in yield under drought and as an increase in yield under favorable conditions in relation to the environment with a moisture deficit. Correlation analysis showed that *Tol* was closely related to Y_p, therefore, potentially productive cultivars significantly reduced grain productivity under drought. Farshadfar et al. (2014) found that no significant correlation was observed between Y_s and *Tol*. In our study, Y_s is weakly associated with *Tol* under moderate drought (Tables 4 and 5), which indicates the possibility selecting potentially productive cultivars under such conditions. A significant negative correlation coefficient between Y_s and *Tol* (Table 6) indicates that a high yield of a cultivar under severe drought conditions is associated with a low yield potential. Blum (1996) came to a similar conclusion.

Under severe drought conditions, *GMP* is more closely associated with Y_s compared to *MP*. The identification of drought-tolerant and potentially highly productive genotypes significantly depends on the conditions in which they are assessed.

Under the most severe drought, such criteria are *SSI* and *SDI* (Table 6), while under droughts of lower intensity they are *STI*, *MP* and *GMP* (Tables 4 and 5). In the transition from low-productive to high-productive environments, the correlation coefficient between *GMP* and *SDI* changes its sign to the opposite one, and the correlation between *SDI* and Y_S changes from a significant negative to an insignificant. Thus, the breeders should choose the indices on the basis of stress severity in the target environment (Akçura et al., 2011).

Conclusions

SSI fully corresponds to the value of *SDI*, and *STI* is fully consistent with the value of *GMP*. Therefore these indicators should not be used together to characterize genotypes. Under the most severe drought, the criteria for identifying drought-tolerant and simultaneously high yielding genotypes are *SSI* and *SDI*. Under drought of lower intensity, they are *STI*, *MP* and *GMP*. Genotypes with a high yield potential can be identified under moderate drought conditions, but cannot be identified under severe stress.

Conflict of interest

The authors declare that they have no conflict of interests.

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Citation:
Lepekhov, S.B., Khlebova, L.P. (2018). Assessment of drought resistance indices in spring bread wheat under various environmental conditions. *Ukrainian Journal of Ecology, 8*(4), 314-319.