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Relationships and repeatability of drought tolerance indices in wheat-rye disomic addition lines

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Abstract

This study was conducted to (i) investigate the relationships and repeatability among several drought tolerance/resistance indices obtained from the grain yield data of a set of wheat-rye [Chinese spring-Imperial (CS-IMP)] disomic addition lines (DALs) grown under rainfed and irrigated conditions for three years; and (ii) locate the genes controlling drought tolerance/resistance in rye (*Secale cereale*). The results of combined analysis of variance showed that the environment, genotype and GE interaction effects were highly significant ($P < 0.01$). Differences in ranking of genotypes based on each index from year to year, exhibited that drought tolerance of genotypes are influenced by year effect. Principal component analysis (PCA) based on the Spearman's rank correlation matrix revealed that drought tolerance/resistance indices were significantly inter-correlated with each other indicating that several of the indices probably measure similar aspects of drought tolerance/resitance. The stress tolerance index (STI), geometric mean productivity (GMP), harmonic mean (HM) and mean productivity (MP) were consistently correlated with each other over the years, indicating that they can be used as alternative for each other to select drought tolerant genotypes with high yield performance in both stress and non-stress conditions. The stress susceptibility index (SSI), yield stability index (YSI), tolerance (TOL) and sensivity drought index (SDI) showed repeatable correlations over the years and can be used to screen the drought resistant and stable genotypes. According to multiple year data, most of the genes controlling drought tolerance in rye are located on chromosome 7R, 5R and 3R, while the genes controlling drought resistance are located on chromosomes 2R, 4R and 6R.

Keywords: wheat-rye disomic addition lines, drought tolerance indices, principal component analysis, repeatability.
Abbreviations: ANOVA- analysis of variance; ChS- Chinese spring; CS-IMP- Chinese spring-Imperial; CV- coefficient of variation; DALs- disomic addition lines; GE- genotype × environment; GMP- geometric mean productivity; HM- harmonic mean; MP- mean productivity; PCA- principal component analysis; RIM- rye Imperial; SDI- sensivity drought index; SI- stress intensity; SSI- stress susceptibility index; STI- stress tolerance index; TOL- tolerance index; YI- yield index; Yp- yield under non-stress; Ys- yield under stress; YSI- yield stability index; TSS- total sum of squares.

Introduction

Genetic materials such as alien additions are valuable genetic resources for both plant breeding and basic research (Szakács and Molnár-Láng, 2010). Alien chromosome addition lines have been developed for a variety of plant species and have been used for many purposes such as introducing valuable traits to the recipient species, mapping genes and markers on introgressed alien chromosomes, examining alien gene regulation, understanding meiotic pairing behavior and chromosome structure and isolating individual chromosomes and genes of interest (Islam and Shepherd, 1990; Ananiev et al. 1997; Bass et al., 2000; Muehlbauer et al., 2000; Jin et al., 2004). Bread wheat (*Triticum aestivum* L.) addition lines have been produced with numerous species related to wheat, including rye (*Secale cereale*). Among these, the 'Chinese Spring' (CS)/'Imperial' wheat-rye disomic addition series has been widely used all over the world to study the effect of individual rye chromosomes on quality parameters and resistance to biotic and abiotic stresses in the wheat genetic background, and to locate various genetic markers in rye, such as storage proteins, isozymes, and RFLP or RAPD loci (Gallego et al., 1998; Taylor et al., 1998; Jianzhong et al., 2001; Aniol, 2004; Szakács and Molnár-Láng, 2010). By growing the disomic addition lines (DALs) under stress and non-stress growing conditions it is possible to find genes useful for making wheat adaptable to unpredictable conditions. Drought stress is one of the most important threatening factors for the production of crop plants in the arid and semi-arid regions of the world. Understanding plant responses to drought is of great importance and also a fundamental part of making crops stress tolerant (Reddy et al., 2004; Zhao et al., 2008). The relative yield performance of genotypes in drought-stressed and favorable environments seems to be a common starting point in the identification of desirable genotypes for unpredictable rainfed conditions (Nouri et al., 2011). Some researchers believe in selection under favorable conditions (Betran et al., 2003), others in a target stress condition (Mohammadi et al., 2011b) while others yet have chosen a mid-point and believe in selection under both favorable and stress conditions (Byrne et al., 1995; Rajaram and van Ginkel, 2001; Sio-Se Mardeh et al., 2006; Najafian, 2009; Mohammadi et al., 2010; Nouri et al., 2011). Various researchers have used different methods to evaluate genetic differences in drought tolerance. Drought resistance is defined by Hall (1993) as the relative yield of a genotype compared to other genotypes subjected to the same drought stress. Drought susceptibility of a genotype is often measured as a function of the reduction in yield under drought stress (Blum, 1996) while the values are confounded with differential yield potential of genotypes (Ramirez and Kelly, 1998). The stress susceptibility index (SSI) suggested by Fischer and Maurer (1978) for measurement of yield stability that apprehended the changes in both potential and actual yields in variable environments. Mohammadi et al. (2011a) used SSI to evaluate drought tolerance in durum wheat genotypes and found year-to-year and location to location variation in SSI for genotypes and could rank their pattern. Guttieri et al. (2001) suggested that SSI more and less than 1 indicates above and below-average susceptibility to drought stress, respectively. The stress tolerance (TOL) defined by Rosielle and Hamblin (1981) as the differences in yield between the stress and irrigated environments and mean productivity (MP) as the average yield of genotypes under stress and non-stress conditions. The stress tolerance index (STI) was defined by Fernandez (1992), which can be used to identify genotypes that produce high yield under both stressed and non-stressed conditions. The geometric mean productivity (GMP) is often used by breeders interested in relative performance, since drought stress can vary in severity in field environments over years (Ramirez and Kelly, 1998). The optimal selection criterion should distinguish genotypes that express uniform superiority in both stressed and non-stressed environments from the genotypes that are favorable only in one environment. The yield index (YI; Gavuzzi et al., 1997) and yield stability index (YSI; suggested by Bouslama and Schapaugh (1984) are the other yield-based estimates which evaluate the stability of genotypes in the both stress and non-stress conditions. Therefore, this research was investigated to (i) study the relationships and repeatability among several drought tolerance/resistance indices obtained from the grain yield data of a set of wheat-rye [Chinese spring-Imperial (CS-IMP)] disomic addition lines (DALs) grown under rainfed and irrigated conditions for three years; and (ii) locate the genes controlling drought tolerance/resistance in rye.

Results and discussion

Combined ANOVA and genotypic mean yields

The combined-ANOVA for grain yield data of disomic addition lines over six environments is given in Table 1. The main effects due to the environment (E), genotype (G), and GE interaction were found to be significant. The variance components for the E, G, and GE interaction giving an overall picture of the relative magnitudes of the genotype, environment and GE interaction variance terms. The E effect was the most important source of yield variation, accounted for 64.3% of total sum of squares (TSS) followed by GE interaction and genotype effects which accounted for 14.4 and 10.2% of TSS, respectively (Table 1). The effects due to year and location were also found to be significant (Table 1), indicating the ranks of genotypes are inflounced by both year and location effects. The mean yield of genotypes under stress condition varied from 19.2 gr corresponding to DAL R2 to 35.7 gr corresponding to donor parent (RIM), while mean yield of genotypes under non-stress condition ranged from 28.6 gr (correspond to R2) to 70.8 (correspond to R7). The results showed that none of the DALs were superior than the parents under stress condition, while under irrigated condition both parents were out-yielded by the DALs R7, R3 and R5. The mean yield of genotypes in the stress environments was 45% smaller than at the non-stress environments. In the other words, the stress intensity (SI; Fischer and Maurer, 1978) was equal to 0.45 indicating that the genotypes experienced a mild drought stress in the study. Genotypic yields under non-stress environment revealed greater variation than the stress environment (CV%= 26.0 *vs*. 19.8%). This variation can be explained, in part, by the fact that traits which are suitable for a given environment may be unsuitable in another environment (Van Ginkel et al., 1998; Mohammadi et al., 2010). Mean grain yield under stress condition was not significantly correlated (R^2= 0.237), with non-stress condition (Fig. 1) suggesting that a high yield under non-stress condition does not result in improved yield under stress condition. For instance, the DALs R7, R3 and R5 with the highest yield productions under non-stress condition were not also superior under stress condition. Thus, indirect selection for a drought-prone environment based on the results of non-stress condition will be moderately efficient. This is in agreement with those found in durum wheat (Mohammadi et al., 2010; Nouri et al., 2011) and bread wheat (Dadbakhsh et al., 2011) who found positive association, but non-significant, between genotypic yields under both stress and non-stress conditions. The drought resistance indices and the genotypic ranks based on the indices over three years are presented in Table 2. Differences in ranking genotypes were found from one drought resistance

Table 1. Combined analysis of variance for yield data of wheat-rye disomic addition lines tested across six environments.

Source	Df	MS	%TSS
Environment (E)	5	12881.6**	64.4
Year (Y)	2	15639.5**	31.3
Location (L)	1	21355.6**	21.4
Y x L	2	5886.8**	11.8
Rep/E	12	179.9	2.2
Genotype (G)	8	1272.1**	10.2
G × E	40	359.3**	14.4
G x Y	16	253.0	4.0
G x L	8	617.1	4.9
G x L x Y	16	336.7	5.4
Error	96	92.5	8.9
Total	161		

** Significant at 1% level of probability; %SST: Percentage relative to total sum of squares.

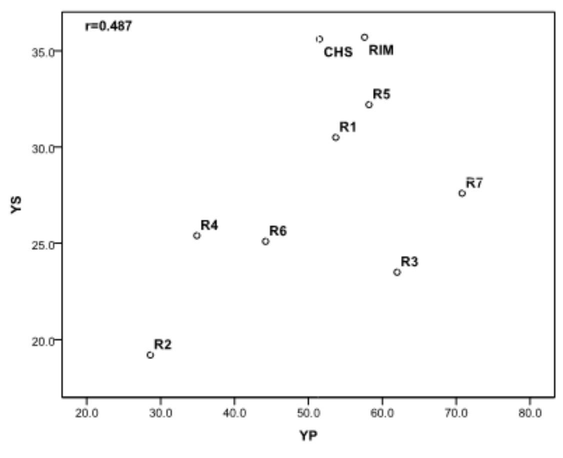

Fig 1. Relationships between genotypic mean yields under stress (Ys) and non-stress (Yp) conditions. Each points represent for mean yield of genotypes across six environments (combination of three years and two locations). R1-R7 are stand for disomic addition lines, CHS and RIM are stand for recipient and donor parents, respectively.

Table 2. Mean values and related ranks for tested genotypes based on grain yield under stress and non-stress conditions and drought tolerance/resistance indices over three years.

Code	YS	YP	STI	MP	GMP	TOL	SSI	YSI	YI	HM	SDI
R1	30.5	53.7	0.624	42.1	40.5	23.2	0.963	0.569	1.079	38.9	0.431
R2	19.2	28.6	0.209	23.9	23.4	9.4	0.736	0.670	0.678	23.0	0.330
R3	23.5	62.0	0.553	42.7	38.1	38.5	1.388	0.378	0.829	34.0	0.622
R4	25.4	34.9	0.337	30.2	29.8	9.4	0.604	0.730	0.899	29.4	0.270
R5	32.2	58.2	0.713	45.2	43.3	26.0	0.998	0.553	1.138	41.5	0.447
R6	25.1	44.2	0.422	34.6	33.3	19.1	0.963	0.569	0.887	32.0	0.431
R7	27.6	70.8	0.742	49.2	44.2	43.2	1.363	0.389	0.974	39.7	0.611
CHS	35.6	51.5	0.696	43.5	42.8	15.9	0.690	0.691	1.256	42.1	0.309
RIM	35.7	57.6	0.783	46.7	45.4	21.9	0.849	0.620	1.262	44.1	0.380
Rank											
R1	4	5	5	6	5	6	5	5	4	5	5
R2	9	9	9	9	9	2	3	3	9	9	3
R3	8	2	6	5	6	8	9	9	8	6	9
R4	6	8	8	8	8	1	1	1	6	8	1
R5	3	3	3	3	3	7	7	7	3	3	7
R6	7	7	7	7	7	4	6	6	7	7	6
R7	5	1	2	1	2	9	8	8	5	4	8
CHS	2	6	4	4	4	3	2	2	2	2	2
RIM	1	4	1	2	1	5	4	4	1	1	4

Ys: yield under stress; Yp: yield under non-stress; STI: stress tolerance index; YSI: yield stability index; YI: yield index; SDI: sensitivity drought index; HM: harmonic mean; TOL: tolerance index; SSI: susceptibility stress index; MP: mean productivity; GMP: geometric mean productivity.

index to another, indicating that the indices differ in discriminating drought tolerant genotypes. In the case of the indices STI and GMP, donor parent (RIM) followed by the DALs R7 and R5 were found to be drought tolerant genotypes, while the DALs R2, R4 and R6 with the lowest value of STI were found to be intolerant genotypes to drought stress. DALs R7 and R5 together with RIM displayed the highest values of mean productivity (MP) while, DALs R2, R4 and R6 revealed the lowest values of MP. DALs R4, R2 and recipient parent (ChS) with the least difference in both stress and non-stress conditions (with lowest TOL values) were found to be resistant genotypes. The indices SSI, YSI and SDI were similar in genotype rankings. According to these criteria R4, ChS and R2 were identified as resistant genotypes. YI parameter, proposed by Gavuzzi et al. (1997), ranks genotypes only on the basis of their yield under stress condition. According to YI, RIM, ChS and R5 were found to have high performance under stress condition (Table 2). The same result was obtained for HM index. Yields under irrigated condition had an increasing value about 45% than yields under stress conditions over three years. Since MP is the mean production under both stress and non-stress conditions, it will be correlated with yield under both stress and non-stress conditions (Table 3). For this reason, MP was able to differentiate genotypes belonging to group A from the others. As described by Hohls (2001) selection for MP should increase yield in both stress and non-stress conditions unless the correlation between yields in contrasting environments is highly negative. The genotypes with high yielding performance in both stress and non-stress conditions were found as genotypes with high values of MP. Mohammadi et al. (2010) used MP to identify high yielding genotypes in both stress and non-stress environments when the stress was mild. Nouri et al. (2011) used MP as a resistance criterion for wheat genotypes in moderate stress conditions. The MP was positively associated with STI, GMP and HM and negatively correlated with TOL. In general, similar ranks for the genotypes were observed by MP, GMP, STI and HM, which suggesting these indices are strongly correlated in ranking of genotypes (Table 2). In contrast, the TOL parameter was positively associated

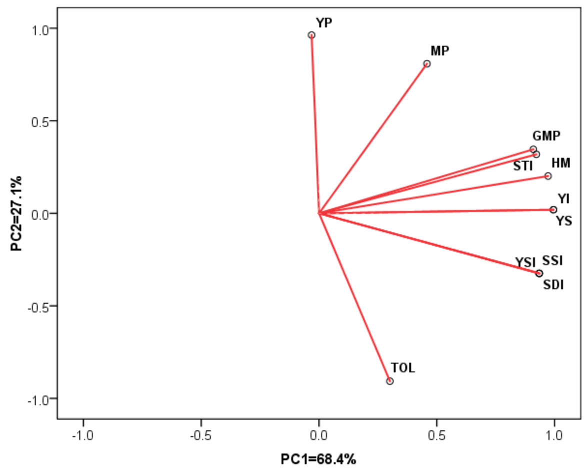

Fig 2. PCA biplot which shows relationships between the yields under stress and non-stress conditions and drought tolerance/resistance indices in the first year of conducting the experiment. Ys: yield under stress; Yp: yield under non-stress; STI: stress tolerance index; YSI: yield stability index; YI: yield index; SDI: sensitivity drought index; HM: harmonic mean; TOL: tolerance index; SSI: susceptibility stress index; MP: mean productivity; GMP: geometric mean productivity.

(P<0.01) with the SSI, SDI and YSI, showing that they are similar in identifying drought resistant genotypes.

Changes in ranking of genotypes in response to drought stress

Differences in ranking of genotypes based on grain yield and each drought resistance index were found from year to year, indicating that the drought tolerance of genotypes is influenced by the year effect (Mohammadi et al., 2011a; Mohammadi and Amri, 2011) (Tables 4, 5 and 6). Significant year effect was observed (Table 1) indicating the ranking of genotypes for each stress and non-stress conditions are

Table 3. Spearman's rank correlation coefficients between yields and drought tolerance/resistance indices over three years.

	YS	YP	STI	MP	GMP	TOL	SSI	YSI	YI	HM
YP	0.32									
STI	0.82**	0.75*								
MP	0.68*	0.85**	0.97**							
GMP	0.82**	0.75*	1.00**	0.97**						
TOL	-0.13	-0.95**	-0.62	-0.72*	-0.62					
SSI	0.18	-0.80**	-0.33	-0.47	-0.33	0.92**				
YSI	0.18	-0.80**	-0.33	-0.47	-0.33	0.92**	1.00**			
YI	1.00**	0.32	0.82**	0.68*	0.82**	-0.13	0.18	0.18		
HM	0.92**	0.58	0.93**	0.87**	0.93**	-0.42	-0.13	-0.13	0.92**	1.00**
SDI	0.18	-0.80**	-0.33	-0.47	-0.33	0.92**	1.00**	1.00**	0.18	-0.13

*, ** Significant at 5% and 1% level of probability, respectively. Ys: yield under stress; Yp: yield under non-stress; STI: stress tolerance index; YSI: yield stability index; YI: yield index; SDI: sensitivity drought index; HM: harmonic mean; TOL: tolerance index; SSI: susceptibility stress index; MP: mean productivity; GMP: geometric mean productivity.

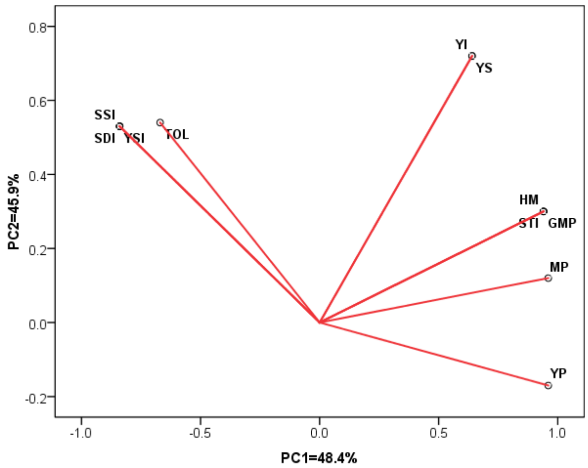

Fig 3. PCA biplot which shows relationships between the yields under stress and non-stress conditions and drought tolerance/resistance indices in second year of experiment. Ys: yield under stress; Yp: yield under non-stress; STI: stress tolerance index; YSI: yield stability index; YI: yield index; SDI: sensitivity drought index; HM: harmonic mean; TOL: tolerance index; SSI: susceptibility stress index; MP: mean productivity; GMP: geometric mean productivity.

significantly influenced by year. Under this situation, identify genotypes with consistent tolerance to drought from year to year would be useful. Under drought stress conditions, the yield in ChS, RIM and DAL R1 was the best in the first, second and third years, respectively. Under non-stress condition addition line R7 in the first and second years and RIM in the third year were the top yielding genotypes. The genotypes ChS, R5 and RIM with the highest STI were the most tolerant genotypes in first and second years; while the genotypes RIM, R7 and R3 were the best in third year, indicating that the tolerance of genotypes to stress is variable from year to year (Mohammadi et al., 2011a). For MP, the genotypes R7, R1 and ChS in the first year; R7, RIM and R3 in the second year and Rim, R7 and R3=R5 in the third year were the first three top yielding genotypes in both stress and non-stress conditions. According to GMP, ChS, R5 and RIM=R1 were the first three ranks genotypes in the first year, while in the second year the genotypes R7, Rim and R5; and in the third year the genotypes RIM, R7 and R3 were the first three top ranking genotypes. According to TOL index, the greater the TOL value, the larger the yield reduction under stress condition and the higher the drought sensitivity. In the first year, R2, ChS and R4; in the second year R2, R6 and RIM and in the third year R3, R6 and ChS had the least reduction in yield and can be characterized as resistant genotypes. According to SSI parameter, the resistant genotypes from year to year were not consistent. In other word, similar to other indices, the SSI gave different ranks to genotypes in different years. The genotypes with the least SSI value in the first year were RIM, ChS and R5; whereas those in the second year were R4, R2 and R6; and in the last year the genotypes R1, followed by recipient (ChS) and R3 had the highest resistance to drought stress. According to SSI parameter, the genotypes with SSI less than unit are drought resistant, since their yield reduction in drought condition is smaller than the mean yield reduction of all genotypes (Sio-Se Mardeh et al., 2006). This index (SSI) was used for identification of durum resistant genotypes under cold, moderate and warm conditions by Mohammadi et al. (2011a). In the case of YSI, ChS followed by RIM and R5 in the first year; R4, R2 and R6 in the second year; and R1 followed by ChS and R3 in the third year, were found to be high stable genotypes under different growing conditions (Tables 4, 5 and 6). Based on YI parameter, ChS, RIM and R5 in the first year; RIM, R7 and R5 in the second year; and R1, R3 and ChS in the third year, were appeared as the top genotypes under drought stress environments. The three first top genotypes based on the HM were ChS, RIM and R5 in the first year; R7, RIM and R5 in the second year; and RIM, R3 and R7 in the third year. The SDI gave dissimilar ranks to genotypes in different years. For instance, DALs R1, followed by, R7 and R2 in the first year; R4, followed by R2 and R6 in the second year; and R1 followed by ChS and R3 in the third year had the least sensitivity to drought stress. The genotypes with the highest HM value were: 2H followed by 3H and 6H in the first year; 7H followed by 2H and 4H in the next cropping season and 1H followed by 5H and 6H in last year. The results, however, suggest a remarkable

Table 4. Mean values and related ranks for tested genotypes based on grain yields under stress and non-stress conditions and drought tolerance/resistance indices in the first year of experiments at Kermanshah location.

Code	Ys	Yp	STI	MP	GMP	TOL	SSI	YSI	YI	HM	SDI
R1	38.6	87.4	0.543	63.0	58.1	48.9	0.962	0.441	1.168	53.5	0.559
R2	20.5	49.6	0.164	35.0	31.9	29.1	1.010	0.413	0.621	29.0	0.587
R3	20.5	89.6	0.296	55.1	42.9	69.1	1.328	0.229	0.621	33.4	0.771
R4	27.8	62.6	0.281	45.2	41.7	34.8	0.956	0.445	0.843	38.5	0.555
R5	41.2	84.5	0.561	62.8	59.0	43.3	0.882	0.488	1.248	55.4	0.512
R6	32.6	77.6	0.407	55.1	50.3	45.0	0.999	0.420	0.987	45.9	0.580
R7	24.3	101.9	0.399	63.1	49.8	77.6	1.310	0.239	0.737	39.3	0.761
CHS	48.1	77.8	0.603	62.9	61.2	29.7	0.656	0.619	1.458	59.4	0.381
RIM	43.2	78.2	0.544	60.7	58.1	35.0	0.770	0.552	1.309	55.6	0.448
Ranks											
R1	4	3	4	2	3.5	7	5	5	4	4	5
R2	8.5	9	9	9	9	1	7	7	8.5	9	7
R3	8.5	2	7	6.5	7	8	9	9	8.5	8	9
R4	6	8	8	8	8	3	4	4	6	7	4
R5	3	4	2	4	2	5	3	3	3	3	3
R6	5	7	5	6.5	5	6	6	6	5	5	6
R7	7	1	6	1	6	9	8	8	7	6	8
CHS	1	6	1	3	1	2	1	1	1	1	1
RIM	2	5	3	5	3.5	4	2	2	2	2	2

Ys: yield under stress; Yp: yield under non-stress; STI: stress tolerance index; YSI: yield stability index; YI: yield index; SDI: sensitivity drought index; HM: harmonic mean; TOL: tolerance index; SSI: susceptibility stress index; MP: mean productivity; GMP: geometric mean productivity

inconsistency in ranking of genotypes as tolerant/resistant based on each of the indices over years.

Relationships and repeatability of drought tolerance indices

Spearman's rank correlation coefficients between the drought tolerance/resistance indices and mean yields under stress and non-stress conditions for each set of yearly data are given in Table 7. The relationship between yields under both stress and non-stress conditions was found to be non-significant in all three years, indicating that the relationship between genotypic yields are not influenced by year effect although the year effect was significant (Table 1). Significant relationships ($P<0.01$) were observed between the Ys with the STI, GMP, MP and HM in two out of three years, indicating that selection genotypes for these indices will not always improve yield under stress condition. Significant positive correlations were also found between Yp with the indices STI, GMP, MP and HM in two out of three years, showing that they are ranking the genotypes in similar fashions. These results can be supported with other works (Farshadfar and Sutka, 2002; Mohammadi et al., 2010; Nouri et al., 2011). The four indices STI, GMP, MP, HM were significantly correlated with grain yield under both stress and non-stress conditions in two out of three years, indicating that these indices are able to discriminate group A genotypes (genotypes with high yield in both stress and non-stress conditions) in these years. Repeatable relationships were observed between STI, GMP, MP and HM over three year, suggesting that one of them can be used as alternative for others for evaluation of drought tolerant genotypes. The three indices YSI, SSI and SDI were cosistently associated ($P<0.01$) with each other over three years, indicating that they are identical in screening drought resistant genotypes. Significant relationship ($P<0.01$) between YSI and SSI has already been reported by Mohammadi et al. (2010) and Nouri et al. (2011). Repeatable correlations (P<0.01) over the years were also observed between yield under stress (Ys) and yield index (YI), indicating that one of them can be used to identify genotypes under stress condition. This is in agreement with the results reported by Nouri et al. (2011) in durum wheat.

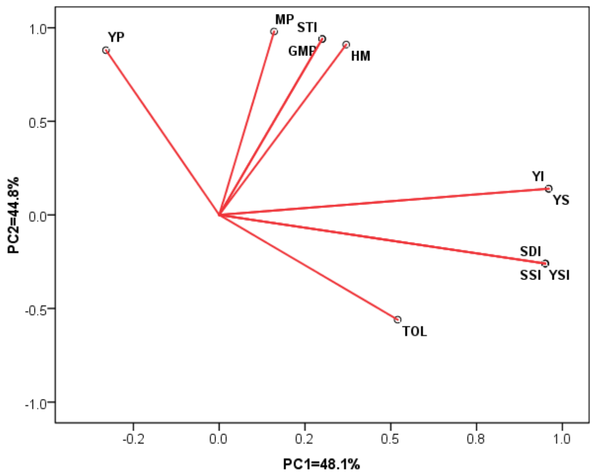

Fig 4. PCA biplot which shows relationships between the yields under stress and non-stress conditions and drought tolerance/resistance indices in the third year of experiment.
Ys: yield under stress; Yp: yield under non-stress; STI: stress tolerance index; YSI: yield stability index; YI: yield index; SDI: sensitivity drought index; HM: harmonic mean; TOL: tolerance index; SSI: susceptibility stress index; MP: mean productivity; GMP: geometric mean productivity.

Biplot analysis of relationships among drought resistance indices

Each of the studied drought tolerance/resistance indices produced a genotype order. To better understanding the relationships among screening methods and to separate drought resistant/tolerant/susceptible genotypes from each other, a principal component analysis (PCA) based on the rank correlation matrix was performed for each of the yearly data. Accordingly, selection based on a combination of indices may provide useful criteria for improving drought resistance of genetic materials. The first two PCAs accounted for 92.9 – 95.5% of total variation based on yearly data. In the first year, the first two PCAs accounted for 95.5% of total variation (Fig. 2). According to Fig. 2, a close correlation

Table 5. Mean values and related ranks for tested genotypes based on grain yields under stress and non-stress conditions and drought tolerance/resistance indices in the second year of experiments in Qazvin location.

Code	Ys	Yp	STI	MP	GMP	TOL	SSI	YSI	YI	HM	SDI
R1	28.2	56.7	0.624	42.4	40.0	28.5	1.402	0.497	0.869	37.6	0.503
R2	26.0	17.6	0.178	21.8	21.4	-8.4	-1.338	1.480	0.802	21.0	-0.480
R3	26.1	73.9	0.753	50.0	43.9	47.8	1.803	0.353	0.805	38.6	0.647
R4	33.4	11.1	0.144	22.2	19.2	-22.3	-5.615	3.016	1.030	16.6	-2.016
R5	36.6	62.8	0.899	49.7	48.0	26.2	1.160	0.583	1.131	46.3	0.417
R6	26.3	34.9	0.359	30.6	30.3	8.6	0.689	0.753	0.811	30.0	0.247
R7	39.7	81.0	1.257	60.4	56.7	41.3	1.419	0.491	1.226	53.3	0.509
CHS	34.9	56.7	0.773	45.8	44.5	21.8	1.071	0.616	1.077	43.2	0.384
RIM	40.6	60.7	0.963	50.7	49.7	20.1	0.923	0.669	1.253	48.7	0.331
Rank											
R1	6	5.5	6	6	6	7	7	7	6	6	7
R2	9	8	8	9	8	1	2	2	9	8	2
R3	8	2	5	3	5	9	9	9	8	5	9
R4	5	9	9	8	9	5	1	1	5	9	1
R5	3	3	3	4	3	6	6	6	3	3	6
R6	7	7	7	7	7	2	3	3	7	7	3
R7	2	1	1	1	1	8	8	8	2	1	8
CHS	4	5.5	4	5	4	4	5	5	4	4	5
RIM	1	4	2	2	2	3	4	4	1	2	4

Ys: yield under stress; Yp: yield under non-stress; STI: stress tolerance index; YSI: yield stability index; YI: yield index; SDI: sensitivity drought index; HM: harmonic mean; TOL: tolerance index; SSI: susceptibility stress index; MP: mean productivity; GMP: geometric mean productivity.

Table 6. Mean values and related ranks for tested genotypes based on grain yields under stress and non-stress conditions and drought tolerance/resistance indices in the third year of experiments in Qazvin location.

Code	Ys	Yp	STI	MP	GMP	TOL	SSI	YSI	YI	HM	SDI
R1	24.9	17.0	0.707	20.92	20.5	-7.9	-2.329	1.466	1.275	20.2	-0.466
R2	11.1	18.7	0.347	14.89	14.4	7.7	2.046	0.591	0.567	13.9	0.409
R3	23.8	22.5	0.896	23.12	23.1	-1.3	-0.296	1.059	1.220	23.1	-0.059
R4	15.1	30.9	0.783	23.02	21.6	15.8	2.557	0.489	0.775	20.3	0.511
R5	18.8	27.4	0.863	23.10	22.7	8.7	1.578	0.684	0.963	22.3	0.316
R6	16.5	20.0	0.551	18.21	18.1	3.5	0.878	0.824	0.844	18.0	0.176
R7	18.6	29.5	0.922	24.07	23.5	10.9	1.841	0.632	0.956	22.8	0.368
CHS	23.7	19.9	0.790	21.79	21.7	-3.7	-0.933	1.187	1.213	21.6	-0.187
RIM	23.3	33.9	1.326	28.62	28.1	10.6	1.562	0.688	1.196	27.6	0.312
Rank											
R1	1	9	7	7	7	5	1	1	1	7	1
R2	9	8	9	9	9	4	8	8	9	9	8
R3	2	5	3	3.5	3	1	3	3	2	2	3
R4	8	2	6	5	6	9	9	9	8	6	9
R5	5	4	4	3.5	4	6	6	6	5	4	6
R6	7	6	8	8	8	2	4	4	7	8	4
R7	6	3	2	2	2	8	7	7	6	3	7
CHS	3	7	5	6	5	3	2	2	3	5	2
RIM	4	1	1	1	1	7	5	5	4	1	5

Ys: yield under stress; Yp: yield under non-stress; STI: stress tolerance index; YSI: yield stability index; YI: yield index; SDI: sensitivity drought index; HM: harmonic mean; TOL: tolerance index; SSI: susceptibility stress index; MP: mean productivity; GMP: geometric mean productivity.

was found between SSI, SDI and YSI, indicating that they are the same in ranking of genotypes. The angle between these three indices with TOL index was well below 90 degrees (acute angle) showing that they rank the genotypes in a similar fashion. A close angle was also observed between Ys and YI displaying that these indices are identical in genotype rankings. No relationship was found between the Ys and Yp as indcated by the right angle between their vectors. Positive correlations were also found between STI, GMP and HM. These three indices were also correlated with yield under stress as well as with the resistance indices (SDI, SSI and YSI). A PCA biplot based on rank correlation matrix of data in the second year was performed and accounted for 94.3% of total variation (Fig. 3). According to Fig. 3, strong positive correlations were found between the SSI, SDI, TOL and YSI, exhibiting that they are closely associated in ranking of the genotypes. This group of indices were negatively associated with yield under non-stress (Yp) condition and the indices STI, GMP, MP and HM. No relation was found between yield under stress and non-stress condition, as indicated by the right angle between their vectors. Fig. 4 shows the the biplot analysis based on the matrix data in the third year which accounted for 92.9% of total variation. According to Fig. 4, close correlations were found between SSI, YSI and SDI. The rank correlation between these indices was 1 (Table 6). This basically means that these three indices can be used interchangeably. These indices were strongly correlated with TOL as indicated by the acute angles between their vectors. As observed in two previous years (Figs. 2 and 3), a close correlation was found between Ys and YI revealing that these indices are identical in ranking of genotypes, as indicated by the zero angle between their vectors. Positive correlations were also found between STI, GMP, HM and MP. Negative correlation was

Table 7. Spearman's rank correlation coefficients between yields under stress and non-stress and drought tolerance/resistance indices based on each yearly data

	Ys	Yp	STI	MP	GMP	TOL	SSI	YSI	YI	HM
First year										
Yp	-0.03									
STI	0.92**	0.27								
MP	0.46	0.74*	0.64							
GMP	0.91**	0.28	1.00**	0.66						
TOL	0.26	-0.87**	0.00	-0.54	-0.03					
SSI	0.92**	-0.32	0.73*	0.18	0.71*	0.57				
YSI	0.92**	-0.32	0.73*	0.18	0.71*	0.57	1.00**			
YI	1.00**	-0.03	0.92**	0.46	0.91**	0.26	0.92**	0.92**		
HM	0.98**	0.15	0.97**	0.59	0.95**	0.10	0.83**	0.83**	0.98**	
SDI	0.92**	-0.32	0.73*	0.18	0.71*	0.57	1.00**	1.00**	0.92**	0.83**
Second year										
Yp	0.45									
STI	0.77*	0.87**								
MP	0.68*	0.93**	0.93**							
GMP	0.77*	0.87**	1.00**	0.93						
TOL	-0.17	-0.69*	-0.38	-0.58	-0.38					
SSI	-0.15	-0.89**	-0.63	-0.73*	-0.63	0.83**				
YSI	-0.15	-0.89**	-0.63	-0.73*	-0.63	0.83**	1.00**			
YI	1.00**	0.45	0.77*	0.68	0.77*	-0.17	-0.15	-0.15		
HM	0.77*	0.87**	1.00**	0.93	1.00**	-0.38	-0.63	-0.63	0.77*	
SDI	-0.15	-0.89**	-0.63	-0.73*	-0.63	0.83**	1.00**	1.00**	-0.15	-0.63
Third year										
Yp	-0.22									
STI	0.40	0.72*								
MP	0.29	0.81**	0.98**							
GMP	0.40	0.72*	1.00**	0.98**						
TOL	0.32	-0.62	-0.32	-0.46	-0.32					
SSI	0.87**	-0.52	0.03	-0.11	0.03	0.62				
YSI	0.87**	-0.52	0.03	-0.11	0.03	0.62	1.00**			
YI	1.00**	-0.22	0.40	0.29	0.40	0.32	0.87**	0.87**		
HM	0.47	0.68*	0.98**	0.95**	0.98**	-0.20	0.10	0.10	0.47	
SDI	0.87**	-0.52	0.03	-0.11	0.03	0.62	1.00**	1.00**	0.87**	0.10

*, ** Significant at 5% and 1% level of probability, respectively. Ys: yield under stress; Yp: yield under non-stress; STI: stress tolerance index; YSI: yield stability index; YI: yield index; SDI: sensitivity drought index; HM: harmonic mean; TOL: tolerance index; SSI: susceptibility stress index; MP: mean productivity; GMP: geometric mean productivity

observed between yields in the stress and non-stress conditions as indicated by the obtuse angle between their vectors. Comparison of relationships between the indices resulted from three years shows some repeatable correlations among indices (Figs. 2, 3 and 4). Repeatable correlations were found between SSI, YSI, TOL and SDI over three years. These indices were also negatively correlated with STI, GMP, HM and MP over three years, showing that these two groups of indices ranking the genotypes in opposite direction. The relationships between indices can be supported by the correlation coefficient analysis (Table 7). However, exact match is not to be expected, because the biplot describes the interrelationships among all traits on the basis of overall pattern of the data, whereas correlation coefficients only describe the relationship between two attributes (Yan and Rajcan, 2002).

Conclusion

In conclusion, **t**he findings from this study showed that the relationships between yield under both stress and non-stress conditions are influenced by year effect. Differences in ranking of genotypes based on each index from year to year, indicating that the drought tolerance of genotypes are also influenced by year effect. Highly significant correlations were found between several of the stability measures indicating that several of the indices measure similar aspects of drought tolerance/resistance. The "drought resistance" should be based on yield stability under water deficits. Thus the genotypes with low fluctuations under different stress environments can be considered as "drought resistant" genotypes. In our case the SSI, TOL and SDI can be used to screen "drought resistant" genotypes as they are strongly associated with YSI (yield stability index). In contrast, "drought tolerance" should not be based on yield stability but it refers to genotypes with acceptable yield performance under stress and high yield performance under non-stress environments. Thus, the STI, GMP, MP and HM can be considered as tools for screening "drought tolerant" genotypes as they are not associated with the YSI. According to multiple year data, most of the genes controlling drought tolerance in rye are located on chromosomes 7R, 5R and 3R, while the genes controlling drought resistance are located on the chromosomes 2R, 4R and 6R.

Materials and methods

Plant genetic materials

A set of wheat-rye disomic addition lines (CS-IMP disomic addition lines, i.e., R1 to R7) and their wheat (*Triticum arestivum* cv. Chinese Spring (2n=21W=42)) and rye (*secale cereale* cv. Imperial (2n=7R=14)) parents were used as experimental materials. The disomic addition line has a pair of homologous chromosomes of Imperial rye added to the genetic background of Chinese Spring wheat. The materials were evaluated under rainfed and irrigated conditions (two irrigation times during flowering to maturity) for three years at Kermanshah and Qazvin provinces, Iran. The experimental design was a completely randomized block design with three replications at each environment. The plots consisted of 2m and at 15×25 cm inter-plant and inter-row distances, respectively. Each plot consisted of 100 seeds (each row 50 seeds). At the time of harvesting 5 single plants were selected randomly and grain yield was measured.

Statistical analysis

The grain yield data were recorded for each genotype at each environment and were subjected to calculate the drought selection criteria. The drought tolerance/resistance indices were calculated using the following formulas:

(1) Stress susceptibility index; $SSI = \frac{1-Ys/Yp}{1-\overline{Ys}/\overline{Yp}}$

(Fischer and Maurer, 1987)

where Ys and Yp are the mean yield of genotypes under stress and non-stress conditions, respectively. $\overline{Ys}$ and $\overline{Yp}$ are the mean yield of all genotypes under stress and non-stress conditions, respectively.

$1-\overline{Ys}/\overline{Yp}$ is the stress intensity. The genotypes with SSI < 1 are more resistant to drought stress conditions.

(2) Stress tolerance index; $STI = \frac{(Ys)(Yp)}{(\overline{Yp})^2}$ (Fernandez, 1992); the genotypes with high STI values will be tolerant to drought stress.

(3) Tolerance; $TOL = Yp - Ys$ (Rosielle and Hamblin, 1981); the genotypes with low values of this index are more stable in two different conditions.

(4) Mean productivity; $MP = \frac{Ys + Yp}{2}$ (Rosielle and Hamblin, 1981); the genotypes with high value of this index will be more desirable.

(5) Geometric mean productivity; $GMP = \sqrt{(Ys)(Yp)}$ (Fernandez, 1992); the genotypes with high GMP value will be more desirable.

(6) Harmonic mean; $HM = \frac{2(Ys)(Yp)}{(Ys + Yp)}$; the genotypes with high value of this index will be more desirable.

(7) Yield stability index; $YSI = \frac{Ys}{Yp}$ (Bouslama and Schapaugh, 1984); the genotypes with high YSI values can be regarded as stable genotypes under stress and non-stress conditions.

(8) Yield index; $YI = \frac{Ys}{\overline{Ys}}$ (Gavuzzi et al., 1997); the genotypes with high value of this index will be suitable for drought stress condition.

(9) Sensitivity drought index; $SDI = \frac{Yp - Ys}{Yp}$ (Farshadfar and Javadinia, 2011); the genotypes with low value of this index will be more desirable.

After analysis of grain yield, ranks were assigned to genotypes for each drought resistance index. A genotype with the highest value for each of the criteria Ys, Yp, STI, GMP, MP, HM, YSI and YI received a rank of 1, while for genotypes with the lowest value for each of the indices SSI, SDI and TOL received a rank of 1 was. Spearman's rank correlation coefficients were calculated on the ranks to measure the relationship between the indices for each cropping season. A biplot analysis based on rank matrix data for each of the three years was also used to study the repeatability of relationships between the screening methods within and over the years.

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