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Screening of Chinese bread wheat genotypes under two water regimes by various drought tolerance indices

Tauqeer Ahmad Yasir[1], Xiaojie Chen[1], Long Tian[1], Anthony Gerard Condon[2] and Yin-Gang Hu[1,3,*]

[1]State Key Laboratory of Crop Stress Biology for Arid Areas and College of Agronomy, Northwest A&F University, Yangling, Shaanxi, 712100, China
[2]CSIRO Plant Industry, GPO Box 1600, Canberra, ACT 2601, Australia
[3]Institute of Water Saving Agriculture in Arid Regions of China, Yangling, Shaanxi, 712100, China

***Corresponding author: huyingang@nwsuaf.edu.cn**

Abstract

Forty-six Chinese bread wheat (*Triticum aestivum* L.) genotypes were evaluated for two growing seasons (2010-2012), under water-stressed and non-stressed environments, to classify them according to the target environment. The trial was conducted in a rainout shelter to avoid the effect of unpredictable rainfall. The results of combined analysis of variance for grain yield revealed that the effects of environment (E), genotype (G), year (Y) and their interactions were highly significant ($P< 0.01$). Based on the grain yield under water-stressed (Ys) and non-stressed (Yp) environments, several drought tolerance indices comprising of mean productivity (MP), geometric mean productivity (GMP), stress tolerance index (STI), stress stability index (SSI), tolerance index (TOL), yield index (YI) and yield stability index (YSI) were calculated for each genotype and compared. Grain yield under water-stressed (Ys) and non-stressed (Yp) environments were positively and significantly correlated with MP, GMP, and STI. Therefore, these indices were considered as a better predictor of Ys and Yp than TOL, SSI and YSI. Principal component analysis classified the genotypes into three groups. The first group contained genotypes with high drought susceptibility that are suitable for non-stressed environments only. The second group consisted of drought tolerant genotypes suitable for stressed environments. The third group included genotypes with low yields in both environments. Cluster analysis classified the genotypes into two groups, viz., drought tolerant with moderate to high yield stability and drought susceptible with high yield under stress-free conditions. MP, GMP and STI were found more effective in screening genotypes with different levels of drought tolerance. Therefore, these indices could be used successfully as selection criteria for the screening of genotypes for performance under various soil moisture levels.

Keywords: Chinese bread wheat; drought tolerance indices; principal component analysis; cluster analysis.
Abbreviations: Ys_grain yield under water-stressed environment, Yp_grain yield under non-stressed environment, SI_stress intensity, MP_mean productivity, GMP_geometric mean productivity, STI_stress tolerance index, SSI_stress susceptibility index, TOL_ tolerance index, YI_yield index, YSI_yield stability index, PCA_principal component analysis.

Introduction

Bread wheat (*Triticum aestivum* L.) is an important crop worldwide and is cultivated on about 217 million ha in a range of environments, with an annual production of about 651 million tons (FAO, 2012). Global wheat production must continue to increase 2% annually until 2020 to meet future requirements of an increasing population and prosperity growth (Abdel-Ghany et al., 2004). Approximately 32% of the wheat growing regions in developing countries face some sort of drought stress during the cropping season (Rajaram, 2001). The occurrence and severity of soil water deficit is generally greater for rainfed wheat crops. However, changing weather patterns and worldwide water deficiencies will probably result in irrigated wheat being cultivated with less applied water, increasing the likelihood of soil water deficits (Rebetzke et al., 2006). Insufficient water is the most critical threat to world food production (Farooq et al., 2009).

The productivity improvement of a crop in stress conditions requires genotypes with optimum stress tolerance and yield stability. Since drought tolerance is a quantitative trait characterized by low heritability and high interaction between genotype and environment, breeding for drought tolerance by empirical selection for yield is far from optimal (Fernandez, 1991; Farooq et al., 2009; Blum, 2011). Several management approaches have been proposed to deal with drought stress, but rapid and reproducible screening methods are rare (Ramirez-Vallejo and Kelly, 1998). Some researchers recommend selection under favorable environments, with a point of view that high yield potential is expected to sustain high yields under stress environments (Richards, 1996; Van-Ginkel et al., 1998; Betran et al., 2003). Other researchers advocate selection under stress conditions (Byrne et al., 1995; Gavuzzi et al., 1997). Many scientists have chosen a compromise solution and believe in selection under both stress and non-stress conditions (Fischer and Mourer, 1978; Clarke et al., 1992; Fernandez, 1992; Mitra, 2001; Mohammadi et al., 2010; Nouri et al., 2011). Selection for high yield in an optimum environment is effective because genetic variation is usually maximized and genotype-by-environment interactions are low (Richards, 1996). However, genotypes selected in optimum environments may not yield well in drought stress environments (Calhoun et al., 1994). On the other hand, selection under drought stress conditions is often complicated by low heritability of traits, non-uniform testing conditions and large genotype-by-environment interaction (Hamblin et al., 1980). Drought susceptibility of genotypes is usually estimated based on yield reduction under stress relative to yield under non-stress conditions (Fernandez, 1992; Blum, 2011). Fischer and Mourer (1978) proposed a stress susceptibility index (SSI) and showed that it is not independent of yield potential. Rosielle and Hamblin (1981) introduced a stress tolerance index (TOL) based on the differences in yields measured under non-stress (Yp) and stress (Ys) conditions. Genotypes with higher SSI and TOL values are considered less drought-tolerant. Rosielle and Hamblin (1981) defined mean productivity index (MP) as the average of Yp and Ys. But MP has an upward bias when there are larger differences between Yp and Ys. The geometric mean productivity (GMP), which is less sensitive to extreme values, is a better indicator than MP for separating superior genotypes in both stress and non-stress environments (Rosielle and Hamblin, 1981). Fernandez (1992) categorized genotypes into four groups based on their performance in stress and normal environments: genotypes that express uniform superiority in both stress and non-stress environments (Group A), genotypes that perform favorably only in non-stress environments (Group B), genotypes that yield relatively higher only in stress environments (Group C), and genotypes that perform poorly in both stress and non-stress environments (Group D). Fernandez defined a new stress tolerance index (STI), which can be used to identify genotypes which produce high yields under both stress and non-stress conditions. For selection based on a combination of indices, some researchers (Golabadi et al., 2006; Azizi Chakherchaman et al., 2009; Majidi et al., 2011) have used principal component analysis (PCA). PCA is one of the most successful techniques for reducing the multiple dimensions of the observed variables to a smaller intrinsic dimensionality of independent variables (Johnson and Wichern, 2007). These drought tolerance indices have been widely used in different regions for the evaluation of wheat genotypes (Mohammadi et al., 2010; Mohammadi et al., 2011; Khakwani et al., 2011; Anwar et al., 2011) but very limited work has been reported to date on Chinese bread wheat germplasm. To improve wheat yield and its stability in stress environments, there is a need to identify selection indices able to distinguish high yielding wheat cultivars in these conditions. Thus, the aim of this study was to evaluate the effectiveness of several drought resistance indices for screening and identification of drought tolerant Chinese wheat genotypes.

Results

ANOVA and ranking of genotypes

The results of the combined analysis of variance for grain yield under water-stressed and non-stressed environments over two consecutive growing seasons (2010-2012) are presented in Table 3. The effects due to the environment (E), year (Y), genotype (G), EY interaction, EG interaction and YG interaction were found to be significant ($P< 0.01$). The E effect was the most important source of yield variation, accounting for 49.38% of the total sums of squares (TSS) followed by YG interaction, genotype effect and EG interaction which accounted for 13.24%, 11.63% and 9.72% of TSS, respectively (Table 3). The two-year mean yield of genotypes under stress environment varied from 1.94 t ha^{-1} to 3.35 t ha^{-1}, while mean yield of genotypes under non-stressed environment varied from 3.15 t ha^{-1} to 7.03 t ha^{-1}. The genotypes G43, G30, G12, G46, G29, G37, G33, G5 and G41 had the best performance for grain yield in water-stressed conditions, while the genotypes G22, G34, G21, G32, G17, G44, G16, G18, G14 and G36 had the best performance under non-stressed conditions (Table 4). The genotypes also exhibited highly significant differences for all the drought tolerance indices (Table 3). The two-year mean values of screening methods for characterizing drought tolerance and adaptation of genotypes to different environments are presented in Table 4. According to SSI, the genotype G17, followed by G22, G21, G15 and G16 had the highest values, and were considered as genotypes with high drought susceptibility and poor yield stability in both limited and normal irrigated conditions. On the other hand, the genotype G37, followed by G9, G38, G2 and G46 had the lowest values and can be identified as having low drought susceptibility and high yield stability. The highest TOL value was calculated for G22, followed by G17, G21, G43 and G32, indicating that these genotypes had a greater GY reduction under restricted irrigated condition and higher drought sensitivity, whereas the lowest TOL value was found in G24, followed by G2, G44, G38 and G9, indicating these genotypes had a lower GY reduction in restricted irrigation condition. Based on ranking of MP, STI and GMP indices, genotypes G43, G30, G34, G33, G5 and G22 had the highest values, whereas the genotypes G19, G7, G24, G38 and G9 had the lowest values. Similar ranks of the genotypes for MP and GMP parameters as well as STI suggest that these three indices are comparable for selecting genotypes. The genotype G43, followed by G30, G12, G46 and G29 had the highest YI and the genotype G16, followed by G13, G14, G15 and G16 had the lowest YI value. The highest YSI was obtained by genotype G46, followed by G2, G38, G9 and G37, whereas the lowest YSI was obtained for genotype G16, followed by G15, G21, G22 and G17.

Interrelationships among drought tolerance indices

To determine the most desirable drought tolerance criteria, the genotypic correlation coefficients between Ys, Yp and other quantitative drought tolerance indices were calculated (Table 5). The yield under water-stressed (Ys) conditions was not significantly correlated with the yield (Yp) under non-stressed conditions and TOL. The Ys was significantly and positively correlated with MP, GMP, STI, YSI and YI, while significantly and negatively correlated with SSI. Similarly, Yp was significantly and positively correlated with TOL, MP, GMP, SSI and STI, but significantly and negatively correlated with YSI. Highly significant and positive correlations were observed among each pair of TOL, MP, GMP, SSI and STI ($P< 0.01$); in contrast, all these indices were correlated significantly and negatively with YSI. Positive and significant correlations of YI with MP, GMP, STI and YSI were also observed (Table 5).

Principal component analysis

Principal component analysis was performed to assess the relationships between all attributes to identify superior genotypes for both water-stressed and non-stressed environments. The first and second components justified 65.3% and 34.2% of total variation, respectively, with different drought tolerance indices (Table 6) and accounted for 99.5% of total variation. When both components were considered simultaneously, three groups were identified (Fig. 1). The Yp, MP, GMP, STI, TOL and SSI indices clustered in group I, while Ys was associated with group II and YSI with group III. In group I, MP, GMP, STI, TOL and SSI were strongly correlated with yield under normal irrigation and have significantly negative correlations with YSI, indicating

Table 1. List of genotypes with their planting regions and origins used in this study.

No.	Genotype	Planting Region	Origin
G1	Luohan 6	Huang-huaiWWR	Henan
G2	Xinmai 19	Huang-huaiWWR	Henan
G3	Zhou 17	Huang-huaiWWR	Henan
G4	Zhou 19	Huang-huaiWWR	Henan
G5	Luohan 21	Huang-huaiWWR	Henan
G6	Shijiazhuang 8	Northern WWR	Hebei
G7	Yunhan 22-33	Northern WWR	Shanxi
G8	Hanyou 98	Huang-huaiWWR	Shandong
G9	Changwu 134	Northern WWR	Shaanxi
G10	Changwu 863	Northern WWR	Shaanxi
G11	Changwu 521-7	Northern WWR	Shaanxi
G12	Shaan 229	Huang-huaiWWR	Shaanxi
G13	Xiaoyan 6	Huang-huaiWWR	Shaanxi
G14	Shaanmai 168	Northern WWR	Shaanxi
G15	Pubing 201	Northern WWR	Shaanxi
G16	Shaan 512	Huang-huaiWWR	Shaanxi
G17	Xiaoyan 22-3	Huang-huaiWWR	Shaanxi
G18	Pubing 143	Northern WWR	Shaanxi
G19	Xinong 389	Huang-huaiWWR	Shaanxi
G20	Liken 2	Huang-huaiWWR	Shaanxi
G21	Lantian 10	Northern WWR	Shaanxi
G22	Xinong 811	Huang-huaiWWR	Shaanxi
G23	Qinnong 712	Northern WWR	Shaanxi
G24	Jiufeng 22	Northern WWR	Shaanxi
G25	Ligao 6	Huang-huaiWWR	Shaanxi
G26	Changwu 58-61	Northern WWR	Shaanxi
G27	Yuanfeng 175	Huang-huaiWWR	Shaanxi
G28	Yuanfeng 139	Huang-huaiWWR	Shaanxi
G29	Fengchan 3	Huang-huaiWWR	Shaanxi
G30	Xinong 889	Huang-huaiWWR	Shaanxi
G31	Xinong 979	Huang-huaiWWR	Shaanxi
G32	Xinong 928	Northern WWR	Shaanxi
G33	Shaan 7859	Huang-huaiWWR	Shaanxi
G34	Xifeng 20	Northern WWR	Gansu
G35	Zhonghan 110	Northern WWR	Beijing
G36	Jing 411	Northern WWR	Beijing
G37	Xiaoyan 81	Northern WWR	Beijing
G38	Youmai 2	Northern WWR	Shandong
G39	Jinmai 47	Northern WWR	Shanxi
G40	Jinan 18	Northern WWR	Shandong
G41	Jining 13	Northern WWR	Shandong
G42	Jining 18	Northern WWR	Shandong
G43	Jinmai 33	Northern WWR	Shanxi
G44	Jing 2001	Northwest WWR	Gansu
G45	Ningchun 45	Northwest SWR	Ningxia
G46	Mianyang 11	Southwestern WWR	Sichuan

WWR – Winter wheat region; SWR – Spring wheat region.

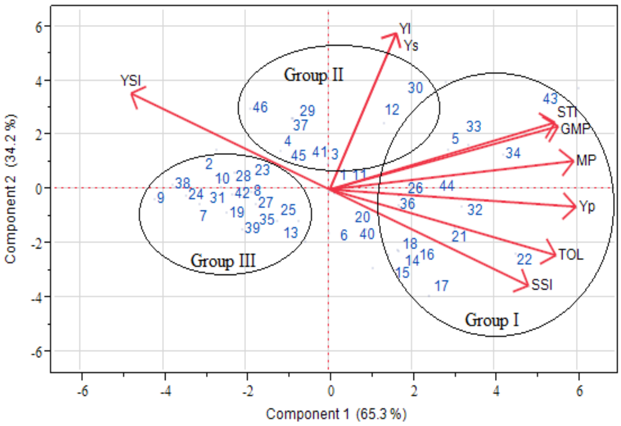

Fig 1. Biplot of principal component analysis of wheat genotypes and various drought tolerance indices. Group I – high yielding drought susceptible genotypes; Group II – high yielding drought tolerant genotypes; Group III – low yielding drought tolerant genotypes.

that these indices are able to select drought susceptible genotypes which only perform well under non-stressed conditions and have poor yield stability. The group I includes the genotypes G43, G34, G33, G5, G22, G32, G44, G21, G17, G15, G16, G14, G18, G26, G36, G20 and G40. In group II, Ys has a significantly positive correlation with YSI, MP, GMP and STI, and a significantly negative correlation with SSI, indicating that these indices are also able to select drought tolerant genotypes which performed well under water-stressed conditions and have low to moderate yield stability. Group II includes genotypes G30, G12, G29, G37, G46, G4, G45, G41 and G3. Group III consists of genotypes G2, G38, G9, G24, G10, G28, G31, G7, G23, G42, G19 and G8, which have good yield stability and moderate to high resistance to drought stress (Fig 1).

Cluster analysis

Cluster analysis based on drought tolerance indices and grain yield under stressed and non-stressed conditions classified the genotypes into two groups with 27 and 19 genotypes (Fig. 2), respectively. The first group contained the genotypes with higher Ys and YSI values and is considered as a drought resistant group with moderate to high yield stability. The second group consisted of genotypes with higher Yp, MP, GMP, TOL and SSI values and is considered as a drought susceptible group with high yield performance under favorable environments.

Discussion

Favorable drought tolerance indices

Highly significant differences among genotypes for grain yield (Table 2) indicate the existence of genetic variation and the possibility of selection for suitable genotypes in both types of environment. The environment and year effects were also found to be significant (Table 4), demonstrating that the ranks of genotypes are influenced by both factors. The mean yield of 46 genotypes in the stressed environment was reduced by 53% compared to the non-stressed environment, indicating that the genotypes experienced a moderate drought stress. The yield under water-stressed conditions (Ys) had a very weak association with the yield under non-stressed conditions (Yp), indicating that high potential yield under optimal conditions does not necessarily result in improved yield in a drought-prone environment. For example, the genotypes G22, G34, G21 and G32 produced the highest yield under non-stressed conditions but failed to produce high yields in the stressed environment. Therefore, indirect selection for such conditions based on the results of optimum conditions will not be efficient. These results are supported by those of Gholipouri et al. (2009), Karimizadeh et al. (2011) and Anwar et al. (2011) who found a positive but non-significant association between yield in stress and non-stress environments. The results showed that the greater the TOL and SSI values, the higher the yield production under non-stressed conditions and conversely, there was a trend for smaller TOL and SSI values to be associated with larger yield production under stressed conditions (Table 4). These relationships are obvious in Table 5, in that Yp significantly and positively correlated with TOL and SSI, but Ys correlated negatively with SSI and TOL. These results suggest that selection based only on low values of TOL and SSI will result in reduced yield under non-stressed conditions. Similar results were reported by Clark et al. (1992), Sio-Se Mardeh et al. (2006), Talebi et al. (2009) and Karimizadeh et al. (2011).

Grain yields under moisture-stressed conditions (Ys) and non-stressed conditions (Yp) were significantly and positively correlated with MP, GMP and STI, which indicated that they were better predictors of Ys and Yp than TOL and SSI. The indices, MP, GMP and STI were able to identify high yielding wheat genotypes in both water-stressed and non-stressed conditions and these findings are consistent with the findings of Fernandez (1992), Mohammadi et al. (2003), Golabadi et al. (2006), Mohammadi et al. (2010) and Nouri et al. (2011). These three indices were correlated with yield under both water environments (Table 5). The YI and YSI were significantly and positively correlated with Ys (r = 1.0 and 0.315, respectively), and negatively correlated with TOL and SSI (Table 5), indicating that these two indices are useful to discriminate drought tolerant and yield stable genotypes. YSI was found to be a more useful index to discriminate drought tolerant from drought susceptible genotypes (Mohammadi et al., 2010) due to its negative correlation with TOL and SSI. Bansal and Sinha (1991) used SSI as stability parameter to identify drought-resistant genotypes of wheat. In this study, genotype G37, followed by G9, G38, G2 and G46 had the lowest SSI values and therefore, these genotypes have low drought susceptibility and high yield stability in both conditions, whereas the genotype G17, followed by G22, G21, G15 and G16 had the highest SSI value can be considered as genotypes with high drought susceptibility and poor yield stability in both restricted and normal irrigated conditions. Similar results were reported in durum wheat by Golabadi et al. (2006), Talebi et al. (2009) and Nouri et al. (2011).

Screening based on a combination of indices

Selection based on a combination of indices may provide a more suitable criterion for improving drought tolerance of wheat, and the study of correlation coefficients is useful in finding the degree of overall linear association between any two attributes (Golabadi et al., 2006; Talebi et al., 2009). In addition to correlation analysis, a biplot based on principal component analysis was constructed to identify superior genotypes for both water-stressed and non-stressed environments. Biplot analysis revealed that the first PCA explained 65.3% of the variation with Yp, TOL, MP, GMP, SSI and STI (Fig. 1). Thus, the first component can be named the yield potential and drought susceptible dimension. Considering the high and positive value of this PCA on the biplot, selected genotypes will be high yielding only in non-stressed environments and susceptible to drought under water-stressed conditions. The second PCA explained 34.2% of the total variability with Ys, YI, YSI, GMP and STI. Therefore, the second component can be considered the drought tolerance and yield stability dimension and it separated the drought tolerant genotypes from drought susceptible ones. Thus, genotypes that have high PC1 and low PC2 (G43, G34, G33, G5, G22, G32, G44, G21, G17, G15, G16, G14, G18, G26, G36, G20 and G40) are suitable only for non-stressed environments. Similarly, Nouri et al. (2011) used a biplot analysis to discriminate high yielding durum wheat genotypes, which were highly adapted to irrigated conditions. The genotypes G30, G12, G29, G37, G46, G4, G45, G41 and G3 with high PC2 and low PC1 were drought resistant and suitable for water-stressed environments. Likewise, Akcura and Ceri (2011) also screened out some oat genotypes for rainfed environments

Table 2. Mean monthly temperature and relative humidity during the crop growing season 2010-2011 and 2011-2012.

Climatic parameters	Year	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun
Mean Temp (°C)	2010-11	13.2	7.32	2.44	-3.21	3.14	7.20	16.20	20.04	24.28
	2011-12	13.85	8.58	0.64	-1.70	1.20	7.30	16.30	20.10	25.10
Relative Humidity (%)	2010-11	88.13	74.53	57.36	61.23	67.07	56.74	60.23	72.77	69.90
	2011-12	86.48	86.47	72.23	73.10	60.46	65.77	56.73	70.35	55.73

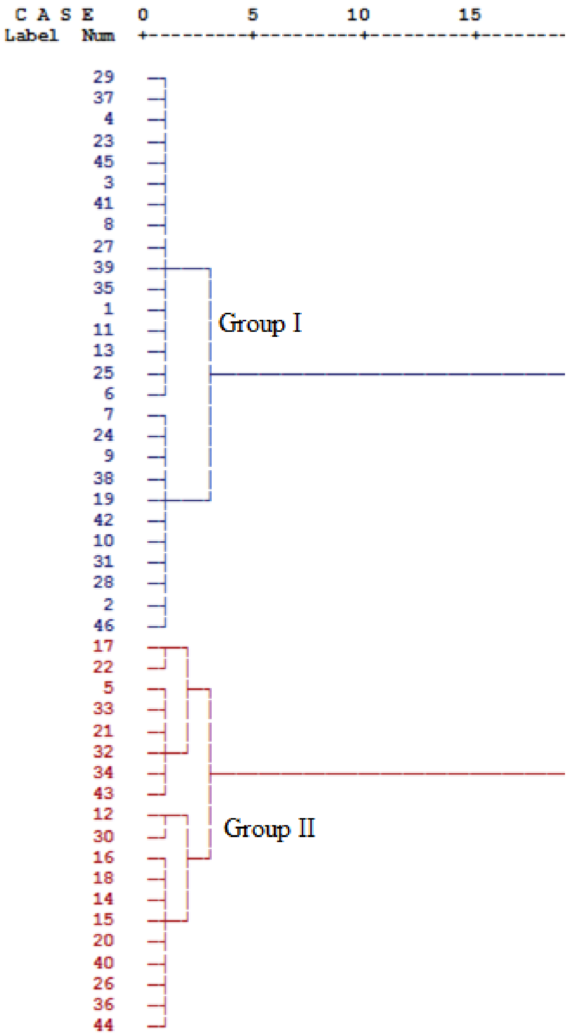

Fig 2. Dendrogram of wheat genotypes based on cluster analysis using various drought tolerance indices. Blue color – Group I including 27 genotypes (drought tolerant with moderate to high yield stability group) and, red color – Group II including 19 genotypes (drought susceptible with high yield under stress-free condition group).

based on a drought tolerant PC2 dimension. Also, using the YSI, the genotypes G2, G38, G9, G24, G10, G28, G31, G7, G23, G42, G19 with high PC2 were more yield stable genotypes, having less yield reduction under water-stressed and non-stressed conditions (Table 5). Thus, these genotypes are suitable to grow in high to moderate water-stressed environments. Cluster analysis classified the genotypes into two groups (Fig 2). The first group contained 27 genotypes with higher Ys and YSI values (Table 5) and these two indices have a highly significant correlation with each other. Therefore, genotypes of this group were considered to be drought resistant with moderate to high yield stability and suitable for high to moderate water stress conditions. The second group consisted of 19 genotypes with higher Yp, MP, GMP, TOL and SSI values (Table 5). Thus, these genotypes were considered to be drought susceptible and only suitable for irrigated conditions. The three indices MP, GMP and STI were able to identify genotypes producing high yield in water-stressed and non-stressed environments by their positive and significant correlations with Yp and Ys. Furthermore, TOL and SSI could not identify drought tolerant genotypes, while YSI was able to differentiate yield stable genotypes having less yield reduction under stressed environment. The potential yield greatly impacts yield under water stress (Blum, 1996; Pantuwan et al., 2002; Shirinzade et al., 2009), therefore, the effectiveness of selection indices depends on the stress severity. The significant reduction in yield under water-stressed environment suggested the genetic variability for drought tolerance in the genotypes. Yield performance under any given environment may not be useful as a sole selection criterion for increasing yield under drought stress conditions. The significant and positive correlations of MP, GMP and STI with Ys and Yp showed that these indices were more effective than the other indices in identifying high yielding cultivars under both stress and non-stressed conditions.

Materials and methods

Plant material

Forty-six Chinese bread wheat (*Triticum aestivum* L.) genotypes, widely used in wheat production in irrigated and rainfed areas of China and as parents in Chinese wheat breeding programs, were used in this study (Table 1). These genotypes included 20 varieties from Huanghui winter wheat region, 23 from Northern winter wheat region, 2 varieties from Northwest spring wheat region and 1 from Southwest winter wheat region.

Experimental arrangement

In order to eliminate the effect of rainfall and impose a drought stress, the trial was carried out under controlled irrigation in a rainout shelter at the Institute of Water-Saving Agriculture in Arid Regions of China, Northwest A&F University, Yangling (34° 17.7´ N, 108° 4.05´ E), Shaanxi, China, during two cropping season (2010-2011 and 2011-12). Some climatic parameters during the growing seasons are given in Table 2. The soil was Loutu (Chinese soil Taxonomy) with pH 7.8 and organic matter less than 1%. The genotypes were evaluated in a randomized complete block design with two replications in two separate experiments under stressed and non-stressed environments. The water-stressed experiment received a total of 1200 m^3/ha water (about 120 mm) divided into applications at the onset of winter dormancy (400 m^3/ha), ‘greening up’ stage in early spring (400 m^3/ha), and booting stage (400 m^3/ha), while the non-stressed experiment received a total of 2000 m^3/ha water (about 200 mm), applied at the onset of winter dormancy (400 m^3/ha), ‘greening up’ stage (400 m^3/ha), booting stage (400 m^3/ha) and grain filling stage (800 m^3/ha). In the two

Table 3. Combined analysis of variance for grain yield of 46-bread wheat genotypes under water-stressed and non-stressed environments.

SOV	DF	MS	%TSS
Replication (R)	1	0.006	
Environment (E)	1	467.40**	49.38
Year (Y)	1	39.7**	4.10
Genotype (G)	45	2.45**	11.63
E × Y	1	23.79**	2.51
E × G	45	2.04**	9.72
Y × G	45	2.79**	13.24
Error	228	0.39	
Total	367		

** Significant at 1% level of probability, MS – Mean square, %TSS – Percentage relative to total sum of squares.

Table 4. The mean of two years of grain yield of 46-bread wheat genotypes under water-stressed and non-stressed environments and their corresponding drought tolerance indices.

NO	Ys	Yp	SSI	MP	TOL	STI	GMP	YI	YSI
G1	2.53(19)	4.72(22)	0.99(22)	3.63(24)	2.19(22)	0.52(23)	3.46(23)	1.00(19)	0.54(25)
G2	2.68(15)	3.66(42)	0.57(45)	3.17(37)	0.98(43)	0.43(35)	3.13(35)	1.06(15)	0.73(2)
G3	2.71(12)	4.66(23)	0.89(25)	3.68(20)	1.95(25)	0.55(15)	3.55(15)	1.07(12)	0.58(22)
G4	2.75(11)	4.21(31)	0.74(34)	3.48(28)	1.46(33)	0.50(26)	3.40(26)	1.09(11)	0.65(13)
G5	2.89(8)	5.85(8)	1.08(19)	4.37(6)	2.96(14)	0.74(5)	4.11(5)	1.14(8)	0.49(28)
G6	2.28(38)	4.80(20)	1.12(15)	3.54(26)	2.52(18)	0.48(30)	3.31(30)	0.90(38)	0.47(32)
G7	2.32(34)	3.52(43)	0.73(36)	2.92(43)	1.20(41)	0.36(43)	2.86(43)	0.92(34)	0.66(11)
G8	2.46(24)	3.98(34)	0.81(31)	3.22(34)	1.52(31)	0.43(33)	3.13(33)	0.97(24)	0.62(16)
G9	2.29(37)	3.15(46)	0.58(43)	2.72(46)	0.86(46)	0.31(46)	2.68(46)	0.90(37)	0.73(4)
G10	2.50(23)	3.71(41)	0.70(39)	3.10(39)	1.21(40)	0.40(38)	3.04(38)	0.99(23)	0.67(8)
G11	2.53(21)	4.78(21)	1.00(21)	3.65(21)	2.25(21)	0.53(20)	3.48(20)	1.00(21)	0.53(26)
G12	3.02(3)	5.13(18)	0.88(26)	4.08(10)	2.11(24)	0.68(8)	3.94(8)	1.19(3)	0.59(21)
G13	2.20(43)	4.56(24)	1.10(17)	3.38(32)	2.36(19)	0.44(32)	3.17(32)	0.87(43)	0.48(30)
G14	2.18(44)	5.51(13)	1.29(6)	3.84(16)	3.33(9)	0.52(22)	3.46(22)	0.86(44)	0.40(41)
G15	2.08(45)	5.36(16)	1.30(4)	3.72(19)	3.28(10)	0.49(28)	3.34(28)	0.82(45)	0.39(43)
G16	2.21(42)	5.61(11)	1.29(5)	3.91(14)	3.41(7)	0.54(17)	3.52(27)	0.87(42)	0.39(42)
G17	1.94(46)	6.14(6)	1.46(1)	4.04(11)	4.20(2)	0.52(24)	3.45(24)	0.77(46)	0.32(46)
G18	2.21(41)	5.59(12)	1.29(7)	3.90(15)	3.38(8)	0.54(18)	3.52(18)	0.87(41)	0.40(40)
G19	2.30(36)	3.77(39)	0.83(30)	3.03(42)	1.46(32)	0.38(42)	2.95(42)	0.91(36)	0.61(17)
G20	2.39(29)	5.10(19)	1.13(13)	3.74(18)	2.71(17)	0.53(19)	3.49(19)	0.94(29)	0.47(34)
G21	2.39(30)	6.18(4)	1.31(3)	4.28(8)	3.79(3)	0.64(10)	3.84(10)	0.94(30)	0.39(44)
G22	2.25(39)	7.03(1)	1.45(2)	4.64(3)	4.79(1)	0.69(6)	3.97(6)	0.89(39)	0.32(45)
G23	2.69(13)	4.09(32)	0.73(35)	3.39(31)	1.40(34)	0.48(29)	3.31(29)	1.06(13)	0.66(12)
G24	2.36(31)	3.41(44)	0.66(40)	2.88(44)	1.06(42)	0.35(44)	2.83(44)	0.93(31)	0.69(7)
G25	2.32(33)	4.46(26)	1.02(20)	3.39(30)	2.14(23)	0.45(31)	3.22(31)	0.92(33)	0.52(27)
G26	2.56(17)	5.46(15)	1.13(14)	4.01(12)	2.89(15)	0.61(11)	3.74(11)	1.01(17)	0.47(33)
G27	2.39(28)	4.03(33)	0.86(28)	3.21(35)	1.64(29)	0.42(37)	3.10(37)	0.94(28)	0.59(19)
G28	2.56(18)	3.82(37)	0.70(38)	3.19(36)	1.26(38)	0.43(36)	3.13(36)	1.01(18)	0.67(9)
G29	2.97(5)	4.29(27)	0.66(41)	3.63(23)	1.32(36)	0.56(13)	3.57(13)	1.17(5)	0.69(6)
G30	3.33(2)	5.64(10)	0.87(27)	4.49(5)	2.32(20)	0.82(2)	4.33(2)	1.32(2)	0.59(20)
G31	2.45(25)	3.71(40)	0.72(37)	3.08(40)	1.26(39)	0.40(40)	3.02(40)	0.97(25)	0.66(10)
G32	2.53(20)	6.18(5)	1.26(8)	4.35(7)	3.64(5)	0.68(7)	3.96(7)	1.00(20)	0.41(39)
G33	2.93(7)	6.05(7)	1.10(18)	4.49(4)	3.11(11)	0.77(4)	4.21(4)	1.16(7)	0.48(29)
G34	2.88(9)	6.46(3)	1.18(9)	4.67(2)	3.58(6)	0.81(3)	4.32(3)	1.14(9)	0.45(38)
G35	2.30(35)	4.25(30)	0.97(23)	3.28(33)	1.94(26)	0.43(34)	3.13(34)	0.91(35)	0.54(24)
G36	2.50(22)	5.48(14)	1.16(11)	3.99(13)	2.97(13)	0.60(12)	3.70(12)	0.99(22)	0.46(36)
G37	2.97(6)	4.28(29)	0.65(42)	3.62(25)	1.31(37)	0.55(14)	3.56(14)	1.17(6)	0.69(5)
G38	2.40(27)	3.30(45)	0.58(44)	2.85(45)	0.90(45)	0.35(45)	2.82(45)	0.95(27)	0.73(3)
G39	2.21(40)	3.92(36)	0.92(24)	3.07(41)	1.70(28)	0.38(41)	2.95(41)	0.88(40)	0.57(23)
G40	2.32(32)	5.19(17)	1.17(10)	3.75(17)	2.86(16)	0.53(21)	3.47(21)	0.92(32)	0.45(37)
G41	2.76(10)	4.52(25)	0.83(29)	3.64(22)	1.76(27)	0.54(16)	3.53(16)	1.09(10)	0.61(18)
G42	2.42(26)	3.81(38)	0.78(33)	3.12(38)	1.39(35)	0.40(39)	3.04(39)	0.96(26)	0.64(14)
G43	3.35(1)	7.03(2)	1.11(16)	5.19(1)	3.67(4)	1.03(1)	4.85(1)	1.33(1)	0.48(31)
G44	2.61(16)	5.69(9)	1.15(12)	4.15(9)	3.08(12)	0.65(9)	3.85(9)	1.03(16)	0.46(35)
G45	2.68(14)	4.29(28)	0.80(32)	3.48(27)	1.61(30)	0.50(27)	3.39(45)	1.06(14)	0.62(15)
G46	2.98(4)	3.93(35)	0.52(46)	3.45(29)	0.95(44)	0.51(25)	3.42(25)	1.18(4)	0.76(1)

The numbers in the parentheses are the ranks of the genotype for each index.

Ys – grain yield (t ha^{-1}) under stressed environment, Yp – Grain yield (t ha^{-1}) under non-stressed environment, SI – stress intensity, MP – mean productivity, GMP – geometric mean productivity, STI – stress tolerance index, SSI – stress susceptibility index, TOL – tolerance index, YSI – yield stability index, YI – yield index.

Table 5. The correlation coefficient between Ys and Yp with various drought tolerance indices in two growing seasons.

	Ys	Yp	TOL	MP	GMP	SSI	STI	YSI
Yp	0.162							
TOL	-0.148	0.952**						
MP	0.431**	0.960**	0.829**					
GMP	0.622**	0.871**	0.680**	0.973**				
SSI	-0.351*	0.851**	0.962**	0.679**	0.508**			
STI	0.638**	0.857**	0.661**	0.964**	0.996**	0.481**		
YSI	0.351*	-0.851**	-0.962**	-0.679**	-0.508**	-1.000**	-0.481**	
YI	1.000**	0.162	-0.148	0.431**	0.622**	-0.351*	0.638**	0.351*

*and ** Significant at the 5% and 1% levels of probability, respectively.

Ys – grain yield under stressed environment, Yp – Grain yield under non-stressed environment, SI – stress intensity, MP – mean productivity, GMP – geometric mean productivity, STI – stress tolerance index, SSI – stress susceptibility index, TOL – tolerance index, YSI – yield stability index, YI – yield index.

Table 6. Principal component analysis for Ys, Yp and drought tolerance indices of 46-bread wheat genotypes in two years.

Traits	Component 1	Component 2
YS	0.111	0.548
YP	0.409	-0.060
TOL	0.376	-0.231
MP	0.406	0.099
GMP	0.379	0.222
SSI	0.330	-0.337
STI	0.374	0.235
YSI	-0.330	0.337
YI	0.110	0.548
Eigenvalue	5.879	3.080
Percent of variation	65.318	34.233
Cumulative percentage	65.318	99.541

Ys – grain yield under stressed environment, Yp – Grain yield under non-stressed environment, SI – stress intensity, MP – mean productivity, GMP – geometric mean productivity, STI – stress tolerance index, SSI – stress susceptibility index, TOL – tolerance index, YSI – yield stability index, YI – yield index.

successive cropping seasons the sowing dates were October 24, 2010 and October 20, 2011, respectively for the two experiments. For each genotype, two 100 cm rows were sown 25 cm apart at 6.7 cm seed spacing. The field management followed local agricultural practices. At maturity (Feekes stage 11.4), ten plants from each plot were harvested for the determination of grain yield, and then grain yield values were converted into t ha^{-1}

Estimation of drought tolerance indices

Drought tolerance indices for each genotype were calculated using the following formulas:

Yield stability index = $YSI = \frac{Ys}{Yp}$ (Bouslama and Schapaugh, 1984)

Yield index = $YI = \frac{Ys}{\bar{Y}s}$ (Gavuzzi et al., 1997)

Stress tolerance index = $STI = \frac{Yp \times Ys}{\bar{Y}p^2}$ (Fernandez, 1992)

Geometric mean productivity = $GMP = \sqrt{(Yp \times Ys)}$ (Fernandez, 1992)

Stress susceptibility index = $SSI = (1 - \frac{Ys}{Yp}) / SI; SI = 1 - \frac{\bar{Y}s}{\bar{Y}p}$ (Fischer and Maurer, 1978)

Mean productivity = $MP = \frac{Yp + Ys}{2}$ (Rosielle and Hamblin, 1981)

Tolerance index = $TOL = Yp - Ys$ (Rosielle and Hamblin, 1981).

where Ys is the grain yield of each genotype under water-stressed condition, Yp is the grain yield of each genotype under non-stressed condition, $\bar{Y}s$ and $\bar{Y}p$ are the mean yields of all genotypes under water-stressed and non-stressed conditions, respectively.

Statistical analysis

Analysis of variance, mean comparison and correlations between indices and grain yield were performed by SAS version 8.01 (SAS institute, 2001, Cary, NC, USA). A biplot derived from principal component analysis (PCA) based on the two-way data of selection criteria (drought tolerance indices) and genotypes was conducted using JMP 10 software (SAS institute, 2001, Cary, NC, USA). This was done to interpret relationships among selection criteria, to compare genotypes on the basis of drought tolerance indices and to identify genotypes or groups of genotypes with a certain level of drought tolerance. The cluster analysis based on squared Euclidean distance was also performed to classify genotypes by using SPSS 16.0 (SPSS Inc., 2007, Chicago, IL, USA).

Conclusion

It is concluded from positive and significant correlations of Ys and Yp with MP, GMP and STI that these indices were the best predictors of yield under water-stressed and non-stressed environments. YSI was also found to be a useful index to discriminate tolerant genotypes which were stable in different conditions and produced high grain yield under high to moderate water-stressed environments. The genotypes with high values of TOL and SSI were able to produce high yield only in the non-stressed environment. Drought stress significantly reduced the yield of some genotypes while some were tolerant to drought, indicating genetic variability for drought tolerance among the genotypes. Therefore, breeders can select suitable genotypes under water-stressed conditions and compare their performance under non-stressed conditions using MP, GMP and STI indices as a means to combine information on performance under both sets of conditions.

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