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RESEARCH

Trait analysis, diversity, and genotype × environment interaction in some wheat landraces evaluated under drought and heat stress conditions

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Both drought and heat stress are responsible for decline in wheat (*Triticum aestivum* L.) production in many regions of the world. Intergovernmental Panel on Climate Change (IPCC) has predicted increase in these areas. Development of heat and drought tolerant genotypes is on priority. Landraces are unexploited genetic resources for various agronomic traits contributing tolerance to abiotic stress. Twenty-five wheat genotypes were evaluated in irrigated timely, rainfed timely and irrigated late sown conditions for 2 yr using 10 agronomic traits for their response to drought and heat stress and four stress indices (stress susceptibility index, stress tolerance index, mean productivity, and stress tolerance) were calculated. Variability averaged over traits was highest under rainfed conditions. Grain yield, plant height, and productive tillers were more sensitive and test grain weight as tolerant under drought. Under heat stress grain yield, grain weight, test grain weight and phenological traits were more sensitive. Productive tillers and grain number per spike were identified as important selection parameters for drought and grain weight (per spike and test grain weight) as for heat tolerance. Genotypes IC 321987, IC 322005, IC 138852, IC 138870 adapted to stressed environments or genotypes CPAN 4079 and NEPAL 38 stable over all environments can be used for introgression of the stress tolerance in elite cultivars.

Key words: Drought stress, genotype by environment interaction, heat stress, land races, wheat.

INTRODUCTION

Drought is the most common environmental stress affecting wheat (*Triticum aestivum* L.) cultivation in developing as well as developed countries. Water and heat are the two main causes of drought stress. In India, nearly 80% wheat is cultivated under irrigated conditions, 66% of it receives only partial (1-2) irrigations, and the remaining 20% is grown under rainfed environments. Wheat yields have been reported to reduce by 50-90% of their irrigated potential by drought in marginal rainfed environments (Reynolds et al., 2005; Ortiz et al., 2007). Heat stress on the other hand is affecting around 13.5 million ha grown under wheat in India (Joshi et al., 2007). Terminal heat stress is responsible for decline in wheat production in 36 million ha of the world (Hays et al., 2007). High temperatures during grain filling period adversely affect the plant growth, yield, and grain quality. Climate change is set to increase the frequency and severity of environmentally limited production as global warming will cause more frequent extreme temperature events. Due to global warming, by 2020 in south Asia, the Rabi (wheat) season will face an increase of 1.08 °C in minimum and 1.54 °C in maximum temperature.

Utilization of new diversity is essential to overcome narrow genetic base in wheat. Landraces, which have arisen through a combination of natural selection and the selection performed by farmers, have a broader genetic base and can, therefore, provide desirable characteristics (Dotlacil et al., 2010). Landraces are also believed to have more stable yield under stress conditions than the modern high-yielding wheat cultivars (Blum, 1996). Therefore, for future gains in yield potential under stress conditions, there is need to exploit the largely untapped sources of genetic diversity housed in collections of wheat landraces and wild relatives (Skovmand et al., 2001). This study was, therefore, undertaken to evaluate wheat landraces housed in germplasm bank of the Directorate of Wheat Research (DWR), Karnal, India, as genetic resources for various agronomic and developmental traits contributing tolerance to water and heat stress during grain filling.

MATERIALS AND METHODS

Field trials

Every year about 500 germplasm lines housed in germplasm bank of the DWR, Karnal, are characterized. Twenty-five of these genotypes having pale green foliage, medium to strong waxiness, and more than 40 g thousand grain weight (TGW) were selected for the present study. Field experiments were conducted during two successive crop seasons (2010-2011 and 2011-2012) at the farm

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of DWR, Karnal (29°43’ N, 76°48’ E; 245 m a.s.l.), India. Three experiments namely irrigated timely sown (irrigated timely, IT), rainfed timely sown (drought timely, DT) and irrigated late sown (heat stress late, HL) were laid out in lattice square (5 × 5) design in two replicates. Timely sown were planted during mid November while late sown were planted during mid December in both crop seasons. Plot size was kept at two rows of 2 m length with 23 cm spacing. Seed rate was 100 kg ha^{-1}. Standard agronomic practices were followed to raise the crop. In the timely sown trial, the first irrigation was applied 21 d after sowing, while the other three were applied after a gap of 25 d. In the late sown trial, the first irrigation was after 21 d but the other three were applied after a gap of 20 d . No irrigation was applied to rainfed trial. Weeds were mechanically controlled and, where necessary, plants were chemically protected against main pathogens (*Puccinia* spp.) by spraying tilt (propiconazole). Daily mean maximum and mean minimum temperatures were recorded for characterization of environments. Mean minimum and maximum temperatures before and after heading were calculated by taking into consideration the minimum number of days to heading and maximum number of days to maturity. Details of temperature regime during crop season (November-April) are given in Table 1.

Data recording

Plants were scored for grain yield and its components and phenological traits viz; days to heading (DH), days to anthesis (DA), days to maturity (DM), grain filling duration (GFD), plant height (PHT), productive tillers (PTL), number of grains per spike (GN), grain weight per spike (GW), thousand grain weight (TGW), and grain yield (GY). Phenological traits were recorded at 50% of the stage. GN and GW were determined on five randomly selected spikes from each plot. GY was measured after harvesting plots at maturity. TGW was measured by taking random samples of 500 grains from plot yield and weighed.

Stress indices

To measure stress tolerance, four indices were calculated using the following relationships: i) Stress susceptibility index (SSI) = (1 - Ys/Yt)/(1 - Xs/Xt) (Fischer and Maurer, 1978); ii) Stress tolerance index (STI) = (Yt × Ys)/$(Xt)^2$ (Fernandez, 1992); iii) Mean productivity (MP) = (Yt + Ys)/2 (Rosielle and Hamblin, 1981); iv) Stress tolerance (TOL) = Yt - Ys (Rosielle and Hamblin, 1981), where Ys is the grain yield under stress (DT or HL), Yt is the grain yield under irrigation timely (IT), Xs and Xt are the mean yields of all genotypes under stress (drought and heat) and non-stress conditions, respectively.

Table 1. Mean maximum and minimum temperature and rainfall during crop seasons (November-April) of 2010-2011 and 2011-2012.

	November	December	January	February	March	April
Year 2010-2011						
Mean Max Temp	27.4	20.9	16.2	22.0	27.7	34.0
Mean Min Temp	12.3	6.6	5.6	9.1	13.1	17.0
Rainfall	0.0	28.0	2.2	37.2	10.9	25.0
Year 2011-2012						
Mean Max Temp	28.1	21.8	17.3	20.7	27.5	34.5
Mean Min Temp	12.8	6.9	6.2	6.9	11.5	17.8
Rainfall	0.0	0.0	9.4	1.8	0.4	24.3

Statistical analysis

Data were subjected to statistical analysis using SAS and CROPSTAT computer software. ANOVA was performed to determine the effect of genotype, environment, and genotype × environment interaction on the traits across environments (treatment-year combination). Summary statistic parameters were calculated to describe the variation of the traits. The biplots genotype-by-trait and genotype-by-stress indices were used for studying relationships amongst traits for each growing condition, as well as the relationship amongst the four stress indices.

RESULTS

The rainfed sowing was effective in providing drought treatment for each season, although yield reductions, in comparison with the irrigated treatment, varied considerably during two seasons; 18.2% and 42.1%, respectively. Similarly, late sowing was effective in providing heat treatment, yield reductions during 2 yr was 32.9% and 29.2%, respectively.

ANOVA and genotype × environment interaction

ANOVA across environments revealed that genotypic mean square were highly significant (P = 0.01) for all 10 traits studied (Table 2). The environment (sowing conditions and years) effects were also highly significant and appeared large for all traits except TGW under drought conditions. On an average, environment main effects (E) were the most important source of variation for all the traits. Genotypic main effect (G) averaged over all the traits contributed 46.9% (DT) and 29.6% (HL) variance, while genotype × environment interaction (GEI) accounted for 5.1% and 5.8% over 2 yr, respectively. The GEI was also highly significant for all traits except GW under heat stress (Table 2).

Diversity in grain yield and its components and phenological traits

Diversity in traits amongst genotypes studied under different environments is characterized in Table 3. In general, variability in different environments when averaged over traits was highest under rainfed conditions (mean coefficient of variation [CV] 14.5%) followed by irrigated timely sown (12.7%) and irrigated late sown (11.0%).

Diversity in terms of CV among landraces across environments ranged 2.2%-29.3%. Phenological traits and PHT were relatively less diverse with CV ranging 1.7%-10.7% while traits like PTL, GY, and GW recorded considerable diversity having CV 22.8%, 21.4%, and 19.5%,

Table 2. Mean sum of squares for genotypes, conditions, years, genotype × condition, year × genotype, year × conditions.

		Heat stress									
Source of variation	DF	PHT	PTL	DH	DA	DM	GFD	GN	GW	TGW	GY
Year	1	674.18**	18653.50**	51.00**	0.98	233.28**	204.02**	3218.18**	6.96**	118.67**	196595.00**
Genotype	24	510.74**	2459.16**	161.16**	126.81**	47.39**	32.18**	433.66**	0.83**	310.62**	39487.90**
Condition	1	2464.96**	29585.30**	4714.21**	5283.92**	10981.60**	1030.58**	189.11*	5.41**	1740.60**	1121470.00**
Replicate	1	4.38	0.45	7.61*	0.02	0.50	0.32	45.82	0.44	58.94	33389.30
Genotype × condition	24	56.80*	703.18	32.86**	19.05**	6.17**	17.04**	76.64	0.14	18.05	21505.90*
Year × genotype	24	158.84**	1762.46**	19.14**	16.75**	18.08**	22.65**	89.29*	0.184	34.14**	32594.3**
Year × condition	24	247.61**	6606.75**	1.45	24.5**	141.12**	283.22**	151.61	0.37	84.53*	51.55
Year × genotype × condition	49	98.47**	1231.39**	12.59**	11.88**	17.65**	22.04**	76.50*	0.17	38.64**	23507.30*
Residual	99	32.86	645.20	1.89	1.10	1.95	1.32	48.53	0.13	17.35	11397.70
Total (corrected)	199	124.84	1247.98	51.42	47.62	68.14	18.23	120.65	0.28	66.99	25319.30
		Drought stress									
Year	1	579.13**	4264.26**	4.21	6.13*	453.01**	564.48**	172.56	0.05	114.04**	584.89
Genotype	24	647.43**	2948.78**	341.40**	239.99**	76.61**	95.13**	410.26**	0.83**	326.63**	53691.00**
Condition	1	59.26	54.60	2.65	2.21	3.65	0.18	30.44	0.32	48.17*	115176.00**
Replicate	1	7626.13**	19159.00**	1676.20**	718.21**	1965.65**	307.52**	293.98*	0.30	12.76	1124420.00**
Genotype × condition	24	55.15*	911.38*	9.88**	4.82**	7.98	4.86	54.75	0.16	20.46*	22223.40*
Year × genotype	24	171.64**	737.15	48.30**	31.01**	32.13**	26.64*	66.14	0.301**	105.63**	21574.8**
Year × condition	24	1176.13**	100.11	39.61**	2.21	34.41	54.08*	978.86**	3.15**	129.72**	2283.43**
Year × genotype × condition	49	129.84**	773.13*	26.90**	16.38**	28.23**	23.79*	76.54*	0.27**	60.09**	22863.90**
Residual	99	30.34	519.55	2.47	1.38	15.75	15.04	49.95	0.12	11.37	9235.70
Total (corrected)	199	173.33	1032.37	58.68	37.89	37.16	29.78	100.27	0.24	62.73	25426.40

*, **Significant at P = 0.05 and P = 0.01, respectively.
DF: Degrees of freedom; PHT: plant height; PTL: productive tillers; DH: days to heading; DA: days to anthesis; DM: days to maturity; GFD: grain filling duration; GN: grain number per spike; GW: grain weight per spike; TGW: thousand grain weight; GY: grain yield.

Table 3. Mean, range, and coefficient of variation (CV%) of landraces under irrigated timely (IT), rainfed timely (DT), and irrigated late (HL) conditions.

	IT			DT			HL		
Variable	Mean	Range	CV%	Mean	Range	CV%	Mean	Range	CV%
PHT	107.1	91.7-124.2	7.9	94.7	79.8-114.1	10.7	100.1	87.5-116.5	8.3
PTL	91.1	64.0-152.5	25.2	71.5	41.6-125.1	29.3	115.4	86.1-147.5	14.1
DH	94.6	85.3-116.5	6.5	88.8	80.8-114.5	8.0	84.9	80.0-92.3	3.9
DA	100.9	93.8-121.3	5.1	97.1	91.0-120.5	6.0	90.6	85.8-99.0	3.4
DM	138.3	133.8-144.0	2.2	132.1	122.3-139.3	2.7	123.5	121.0-129.3	1.7
GFD	37.5	22.0-40.0	8.8	35.0	18.8-38.3	10.7	32.9	30.3-35.5	3.5
GN	46.2	32.7-57.7	17.3	43.7	29.6-55.8	16.6	44.2	30.6-54.2	18.1
GW	2.0	1.3-2.6	17.0	1.9	1.0-2.4	19.7	1.6	0.8-2.2	21.9
TGW	42.6	31.8-52.3	14.1	43.2	24.0-56.2	16.5	36.7	22.5-47.1	18.2
GY	484.5	184.4-710.0	22.8	334.5	114.5-521.3	24.6	334.9	223.0-431.3	16.8

PHT: Plant height; PTL: productive tillers; DH: days to heading; DA: days to anthesis; DM: days to maturity; GFD: grain filling duration; GN: grain number per spike; GW: grain weight per spike; TGW: thousand grain weight; GY: grain yield.

respectively. As expected, diverse environments particularly sowing conditions over years recorded considerably higher variability for PTL (CV 29.3%) and GY (CV 24.6%) under rainfed conditions followed by irrigated timely condition and in GW (CV 21.9%), TGW (CV 18.2%) and GN (CV 18.1%) under late sown conditions.

Sensitivity of the traits to drought and heat stress

Accessions under DT and HL conditions had 29.1% and 26.4% lower GY, respectively as compared to that under IT environment (Table 4). Characters namely GY, PHT, and PTL were more sensitive under drought reducing to the extent of 11% to 29% than DH, DA, DM, GFD, and GN having around 5% reduction. The TGW was more drought-tolerant which showed marginal increase in performance rather than decrease, probably due to compensation effect resulting from reduced number of grains per spike. Reduced kernel number (sink size) under drought resulted in greater dry weight of remaining kernels at plant maturity.

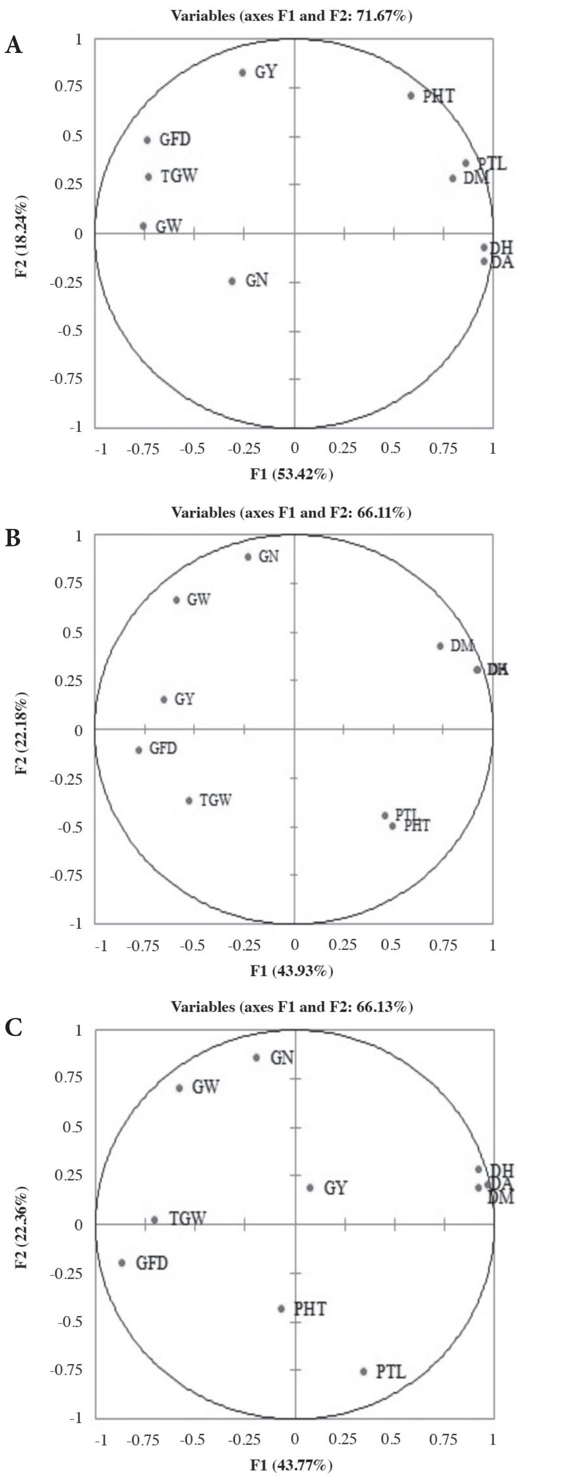
Table 4. Reduction (%) in various wheat traits under drought and heat stress conditions.

Trait	Drought stress	Heat stress
Plant height	11.6	6.5
Productive tillers	19.7	-31.1
Days to heading	6.2	10.1
Days to anthesis	3.8	10.1
Days to maturity	4.5	10.7
Grain filling duration	6.7	11.3
Number of grains per spike	4.4	3.3
Grain weight per spike	3.7	16.8
Thousand grain weight	-1.1	14.1
Grain yield	29.1	26.4

Similarly high sensitivity to heat stress was observed in traits like GY, GW, TGW, DH, DA, DM, and GFD as measured in terms of reduction in performance to the extent of 10% to 26%. GN and PHT reduced about 3%-6% thus exhibited low sensitivity. Conversely, PTL was the only trait which showed enhanced performance (up to 31%) instead of reduction under heat stress.

Trait associations

To visualize similarities/dissimilarities of the interrelationships among yield and phenological traits in



DH: Days to heading; DA: days to anthesis; DM: days to maturity; PHT: plant height; PTL: productive tillers; GN: grain number per spike; GW: grain weight per spike; TGW: thousand grain weight; GY: grain yield; GFD: grain filling duration.

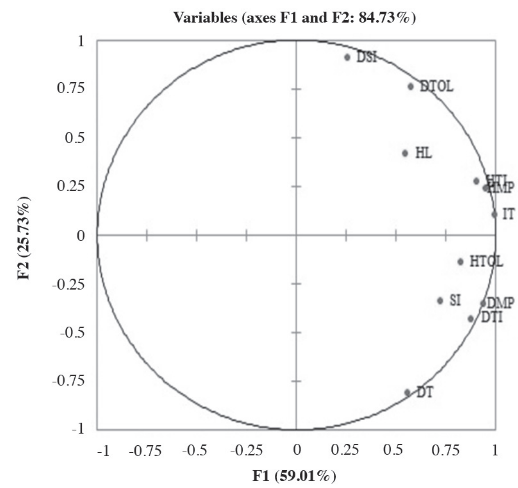
Figure 1. Genotype-by-trait biplot showing interrelationships among traits under different sowing conditions: (a) rainfed timely, (b) irrigated timely, (c) irrigated late.

each environment, genotype-by-trait biplots are presented in Figure 1. Biplots were based on the first two principal components derived from subjecting the standardized genotype-by-trait table. The biplot for each environment explained 66% to 72% of the total variation of a two way table. In general, a varied pattern of trait associations between the treatments was obtained (Figure 1a-c). The GY showed significant positive association ($P = 0.01$) with its component traits such as TGW, GW, and GFD under IT (indicated by acute angles between vectors for these traits), with GFD under DT while with none of these traits under HL environment. GW was significant positively associated with GN and negatively with PTL in all the environments, so was the trend for negative association of TGW with DH, DA, and DM (as indicated by the obtuse angles between their vectors). Interestingly, there were no significant correlations of GY with PHT, PTL, and DM in all environments, besides DH and DA also showed zero correlation in DT and none of the traits under HL environment.

Among phenological traits acute angles among vectors of DH, DA, and DM showed significant and positive association while obtuse angles between vectors of days to GFD with DH and DA exhibited significant and negative association in all environments. In general, no association was observed among phenological and agronomic as well as yield components such as PHT, PTL, GN, and GW under IT and HL conditions while positive with PHT and PTL, negative with TGW, GW and GFD, and no correlation with GY and GN under DT environment.

Stress indices

A genotype by stress indices biplot was used to compare



DSI: Drought susceptibility index; DTOL: drought tolerance level; DMP: drought mean productivity; DTI: drought tolerance index; HIS: heat susceptibility index; HTOL: heat tolerance level; HMP: heat mean productivity; HTI: heat tolerance index; HL: grain yield under heat stressed late sowing; IT: grain yield under irrigated timely sowing; DT: grain yield under rainfed timely sowing.

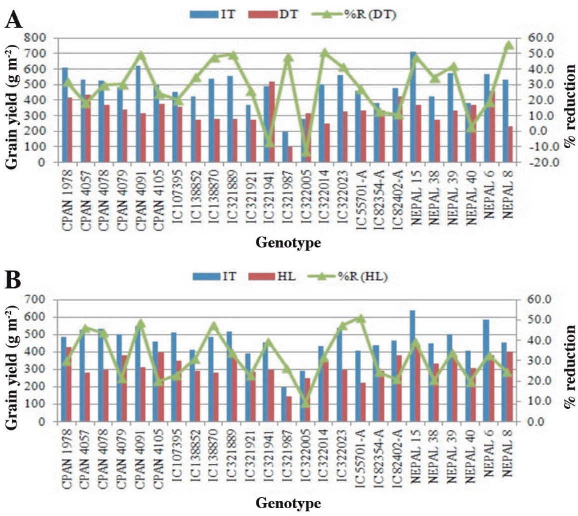
Figure 2. Genotype-by-stress indices biplot showing interrelationships.

the interrelationships among stress indices (Figure 2). There was a significant positive correlation among all indices under HL conditions as indicated by the small acute angle between their vectors. HMP and HTI had highest r = 0.99 while HSI and HTI the lowest r = 0.38. GY showed significantly positive correlation with HTI and HMP and no correlation with HSI and HTOL. Under DT sown conditions, there was a high significant positive correlation between DMP and DTI, as indicated by the small acute angle between their vectors. Similarly DSI had significant positive correlation with DTOL. DSI and DTOL showed near zero correlation with DMP and DTI, as indicated by their nearly perpendicular vectors. Grain yield had positive correlation with DTI, DMP, negative with DTOL and near zero with DSI.

Mean grain yield and stress tolerant genotypes

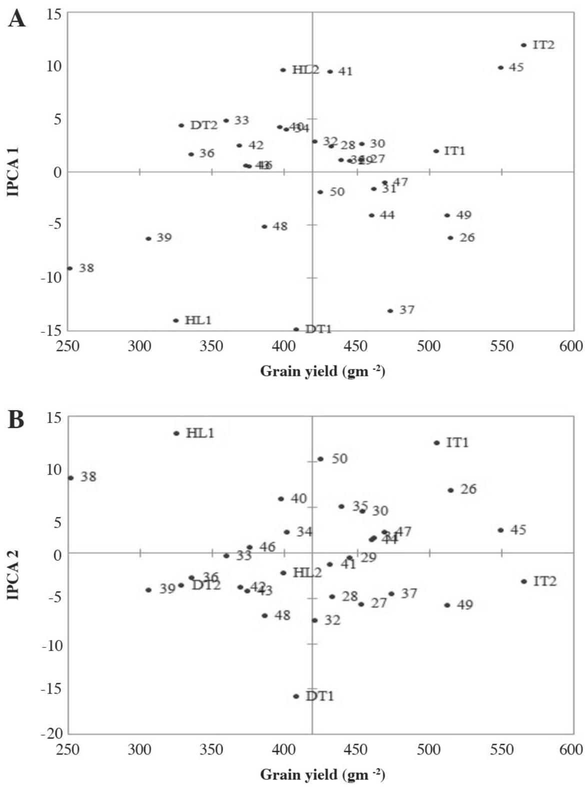
The genotypic mean grain yield (g m^{-2}) under all three environments was recorded over 2 yr trials. The average over environments and years and reduction in percent under DT and HL over IT environment is presented in Figures 3a and 3b. It varied from 251 to 548 g m^{-2} under normal and stress conditions over years and environments. Genotype NEPAL 15 recorded highest grain yield (548 g) over all environments followed by CPAN1978 (513 g) and NEPAL 6 (511 g). Reduction in grain yield under stress as an indicator of tolerance revealed that genotypes IC 322005, IC 321941, and NEPAL 40 had minimum reduction of -13%, -7%, and 3% under DT conditions and genotypes IC 322005, NEPAL 40, and CPAN 4105 had 9%, 20%, and 20%, respectively under HL conditions. These genotypes were considered as drought and heat tolerant, respectively compared to others where reduction was to the extent of 56% in NEPAL 8 and 51% in IC322014 under DT conditions and 51% in IC55701A, 49% in CPAN4091, 48% in IC138870, and 47% in IC322023 under HL conditions. Of these, IC321941 gave maximum yield under DT conditions and CPAN4105 gave high grain yield than the population mean under all environments.

The first two IPCA (interaction principal component axes) 1 and 2 explained 69.84% of the total interaction variance. Biplot graphical analysis for IPCA 1 against the environment means (Figure 4a) revealed that CPAN 4057, CPAN 4078, CPAN 4079, CPAN 4091, IC 321889, IC 322023, and NEPAL 15 are adapted to IT environments. IC 321987, IC 322005, and NEPAL 40 are adapted to DT environment. IC 138852, IC 138870, IC 321921, IC 322014, and IC 55701-A had positive interaction with HL environments. Genotypes CPAN 4079, IC 82354-A, and NEPAL 38 had IPCA score near zero and hence, can be considered as stable. The biplot graphical analysis for IPCA 2 (Figure 4b) showed that CPAN 1978, CPAN 4057, CPAN 4078, CPAN 4091, CPAN 4105, IC 321889, IC 321941, IC 322023, IC82402-A, NEPAL 15, NEPAL



HL: grain yield under heat stressed late sowing; IT: grain yield under irrigated timely sowing; DT: grain yield under rainfed timely sowing; %R(DT): grain yield reduction under rainfed conditions; %R(HL): grain yield reduction under heat stress conditions.

Figure 3. Grain yield of landraces and reduction under (a) drought stress and (b) heat stress.



26 CPAN 1978	33 IC 138852	40 IC 322014	47 NEPAL 39
27 CPAN 4057	34 IC 138870	41 IC 322023	48 NEPAL 40
28 CPAN 4078	35 IC 321889	42 IC 55701-A	49 NEPAL 6
29 CPAN 4079	36 IC 321921	43 IC 82354-A	50 NEPAL 8
30 CPAN 4091	37 IC 321941	44 IC 82402-A	
31 CPAN 4105	38 IC 321987	45 NEPAL 15	
32 IC 107395	39 IC 322005	46 NEPAL 38	

Figure 4. AMMI biplot graph for grain yield and (a) IPCA 1 and (b) IPCA 2. Genotypes plotted as numerical numbers.

39, NEPAL 6, and NEPAL 8 had positive interaction with IT environments, IC 138870, IC 321921, IC 321987, IC 322005, IC 322014, IC 55701-A, IC82354-A, and NEPAL 40 had positive interaction with stressed environments. CPAN 4079, IC 138852, and NEPAL 38 had IPCA score near zero and hence, can be considered as stable.

Classification of environments

The AMMI (additive main effects and multiplicative interaction) IPCA 1 and IPCA 2 separated three environments. The DT environment had lower minimum (11.7 °C) and maximum (25.6 °C) temperatures during grain growth period and was deprived of irrigation whereas HL environment had high minimum (14.5 °C) and maximum (30.8 °C) temperatures. The IT environment having minimum and maximum temperature of 11.5 and 27.3 °C, respectively, gave higher grain yield while both the stressed environments recorded lower yield. The AMMI IPCA 1 and 2 divided these environments into two distinct groups: Group I comprised IT and Group II represented stress conditions of DT and HL.

DISCUSSION

The abiotic stresses particularly drought and heat reduce grain yield and contribute significantly to the low productivity of wheat (Reynolds et al., 2005; Hays et al., 2007; Ortiz et al., 2007). In present investigation there was 18.2% and 42.1% reduction in GY under DT conditions and 32.9% and 29.2% under HL conditions in two crop seasons. The drought environment in second year suffered more reduction in grain yield due to less rainfall during grain growth as well as pre-heading period. In fact, the rainfall occurred at crop maturity, hence remain unutilized for healthy grain development enhancing grain yield. The reduction in grain yield was attributed to reduced kernel growth which was dependent upon two phenomena, i.e. degree of water stress and stress development rate (Kobata et al., 1992). The HL environments suffered almost equivalent grain yield reduction in two different years probably due to more or less identical mean temperatures during critical period of grain development at pre-heading and grain growth stages. During these stages the mean maximum temperature was recorded between 30 and 35 °C except in 2nd year when it exceeded 35 °C after 30 d of heading (Figures 5a and 5b). Different phenological stages differed in their sensitivity to drought and high temperature heat stress and were dependent upon plant species and genotypes (Howarth, 2005).

Genetic diversity for heat and drought tolerance in wheat is well established (Sareen et al., 2012). The patterns of stress may vary widely in environments constituting different wheat growing regions indicating genotype by environment interaction. There were significant differences among accessions and conditions (normal and stress) for grain yield showing that genotypes

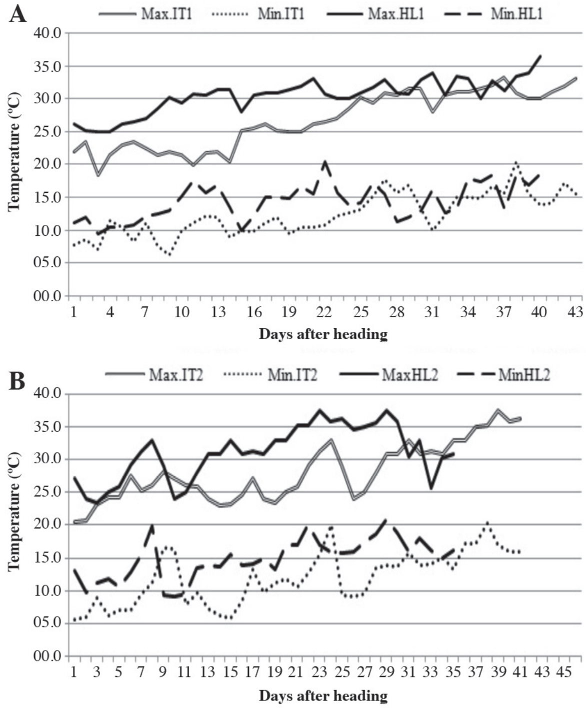


Figure 5. Post heading mean maximum and minimum temperature in irrigated timely (IT) and irrigated late (HL) trials during (a) 2010-2011 and (b) 2011-2012.

differed in their response to high temperature heat stress and drought. Genotype × condition interaction was also highly significant indicating that genotypes responded differently to normal and stress conditions. However, the variability was greater under rainfed drought conditions as compared to irrigated conditions. A study of variation in wheat yield in 57 countries over a 30-yr period showed that rainfall and its distribution were one of the factors contributing to this diversity (Singh and Byerlee, 1990). The CV of grain yield in countries where half of the land under wheat cultivation was on dryland farming doubled compared to countries where wheat was cultivated in mostly irrigated conditions (Trethowan and Pfeiffer, 1999). Diversity for phenological traits and PHT was relatively less compared to PTL, GY, and GW which could be due to diverse environments (sowing conditions) exerting greater influence on these traits.

Differential sensitivity of yield components such as PTL, GN, and GW and non-sensitivity of TGW to drought stress were indicative of their varied response. Accordingly PTL and GN could be considered as important selection parameters for drought. Shpiler and Blum (1991) also proposed the grain number per spike as an important selection criterion for drought tolerance. The productive tillers and grain number are reduced under water stress due to competition for photosynthesis assimilates during the stem elongation (Garcia del Moral et al., 1991). Reduced kernel numbers under drought resulted in higher dry weight during grain filling due to their receptiveness to available photosynthates and this could be the cause for test grain weight non-sensitivity and drought tolerance.

Similarly differential response of GY traits such as GW and TGW and non-differential of PTL and GN to heat stress could identify traits for its selection criterion. Since PTL and GN are determined during pre-heading phase, these were not affected under terminal heat stress conditions. Highly sensitive GW and TGW thus could be considered as important selection parameters for heat tolerance. Tyagi et al. (2003) reported grain weight per spike as a measure of heat tolerance. High temperature reduces grain weight (Wardlaw et al., 1980), due to reduction in both the duration and rate of grain filling and high respiration rate (Tashiro and Wardlaw, 1990). However, yield reduction is primarily due to reduction in grain weight (Guttieri et al., 2001). These workers also reported reduction in yield due to grain number per spike.

Significant positive association of GY with its components such as TGW and GW under IT suggested that yield could be enhanced by increasing GW for which GFD is an important factor. Richards (1996) also confirmed that wheat grain yield may be increased by increasing the kernel weight. Under drought conditions, GY showed significant positive association with GFD only. Contrary, Guendouz et al. (2012) reported a significant and positive correlation of grain yield with number of grains under both stressed and non stressed conditions and with test kernel weight in stressed condition. On the other hand, no association of GY with these traits under heat stress revealed inconsistent pattern, hence no single trait could be reckoned across environments. Similar is the case of GY with other traits namely PHT, PTL, and DM in all environments. In case of phenological traits 'r' values and acute angles among vectors of DH, DA, and DM showed significant and positive association while obtuse angles between vectors of days to GFD with DH and DA exhibited significant and negative association in all environments. In general, phenological traits did not exhibit association among agronomic as well as yield components such as PHT, PTL, GN, and GW under DT and HL conditions while PHT and PTL had positive, TGW, GW, and GFD negative and GY and GN showed no correlation under DT environment.

Drought and heat tolerance is usually quantified by grain yield under stress conditions. Genotypic differences in yield and its components among genotypes grown under stress conditions, could lead to identify the most tolerant and most sensitive ones (Menshawy et al., 2006). On the other hand, selection for yield under stress conditions is complicated by low heritability and large genotype-environment interactions (Golabadi et al., 2005). The most widely used criteria for selecting high yield performance are mean yield, mean productivity and relative yield performance in stressed and favorable environments (Rashid et al., 2003). Of the stress indices used, MP and STI were closely related similarly, SSI and TOL having $r > 0.9$ under both stress conditions. Selection for TOL will result in reduced yield in non-stressed conditions whereas SSI can be a useful indicator for wheat breeding under stress conditions (Sio-Se Mardeh et al., 2006). Genotypes with high mean productivity, coupled with low SSI should be used for improving drought tolerance (Dodig et al., 2008). Fischer and Maurer (1978) and Langer et al. (1979) used SSI to characterize the yield stability between two environments. Simultaneous selection for yield and stability of performance is an important consideration in breeding programs (Kang, 2002). Genotypes IC 321987, IC 322005, and NEPAL 40 are adapted to DT environment. IC 138852, IC 138870, IC 321921, IC 322014, and IC 55701-A had positive interaction with HL environments. Genotypes CPAN 4079 and NEPAL 38 had IPCA scores near zero and were considered as stable over all environments. These genotypes can be used in breeding program to introgress the stress tolerance in elite cultivars.

CONCLUSIONS

Productive tillers and grain number per spike can be used as important selection parameters for drought and grain weight (per spike and test grain weight) for heat tolerance. Genotypes IC 321987, IC 322005, and NEPAL 40 were adapted to DT environment. IC 138852, IC 138870, IC 321921, IC 322014, and IC 55701-A had positive interaction with HL environments. Genotypes CPAN 4079 and NEPAL 38 had IPCA scores near zero and were considered as stable over all environments.

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