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Sources of tolerance to terminal drought in the chickpea (*Cicer arietinum* L.) minicore germplasm

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ABSTRACT

Chickpea cropping system is largely rainfed and terminal drought is a major constraint to its productivity. Currently available drought tolerant chickpea genotypes are very few. Considering that a large number of traits are collectively needed to confer yield under drought, there is a need to identify more genotypes to introduce diversity in drought tolerance breeding programs. The minicore ($n = 211$) chickpea germplasm collection has been evaluated over three years for drought tolerance index (DTI), calculated as the standard residuals, through a regression approach considering drought yield as a function of days to flowering, yield potential and the residual or drought response, in the short season environment of South-India. The minicore collection accessions exhibited large range of variations for days to 50% flowering (26–78 d) and maturity (70–120 d), shoot biomass (1500–4940 kg ha^{-1}) and seed yield (210–2730 kg ha^{-1}) under drought. The heritability for the shoot biomass and seed yields under drought stress (shoot biomass 0.118–0.461; seed yield 0.511–0.795) were relatively higher than that under optimally irrigated environment (shoot biomass 0.232–0.447; seed yield 0.322–0.631). Both the seed yield under drought and DTI showed significant accession × year interaction. A categorization of the DTI using a cluster analysis has revealed five major groups with 5 accessions in highly tolerant group, 78 in tolerant, 74 in moderately tolerant, 39 in sensitive and 20 in highly sensitive groups. ICC 4958, a previously identified drought tolerant genotype, was among the moderately tolerant while Annigeri, a well-adapted cultivar, was in the tolerant group. Though the heritability of DTI was slightly lesser than that of the yield, the DTI represented terminal drought tolerance *per se*, and was independent of phenology and yield potential influences.

1. Introduction

Globally, chickpea is the third most important pulse crop with a production of 9.3 M t from an area of 11.7 M ha (FAO STAT, 2007). About 90% of this crop is grown rainfed under receding soil moisture conditions in the postrainy season after the main rainy season by resource-poor farmers (Kumar and Abbo, 2001) with intensities and distribution of crop season rainfall varying from almost nil (Johansen et al., 1994) to >400 mm (Berger et al., 2004). Terminal drought stress of varied intensities is, therefore, a primary constraint to chickpea productivity. In the current scenario of water limitation, there is little scope to increase the irrigated areas of this crop. Moreover, the slow and steady migration of this crop towards lower latitudes in India (Gowda et al., 2009) and rainfed low input environments such as Australia, Myanmar, Canada and south eastern Africa, the chances of exposure of the crop to higher drought intensities and warmer environments constantly increases. In recent years, early maturing varieties that escape terminal drought and heat stress were developed by the breeders and were adopted by farmers with considerable success (Kumar and Abbo, 2001). However, drought escape fixes a ceiling on the potential yield and cannot utilize the opportunities, as and when available, of extended growing periods (Blum, 1988; Ludlow and Muchow, 1990; Bolanos and Edmeades, 1996). Therefore for achieving high and stable yields under drought, it is necessary to develop drought tolerant/avoiding varieties, i.e. capable of using more water and better (Ludlow and Muchow, 1990; Johansen et al., 1997).

Drought tolerance is a generic term for a highly complex phenomenon of plant responses. In a practical sense, it is the relative ability of the crop to sustain adequate biomass production and maximize crop yield under increasing water deficit through out the growing season, rather than the physiological aptitude for plant survival under extreme drought shock (Serraj and Sinclair, 2002), which has a limited economic interest for the farmers. This has led to a focus on escape and avoidance strategies such as breeding early maturing varieties (Kumar and Abbo, 2001) and selecting for large root systems that can sustain better productivity under

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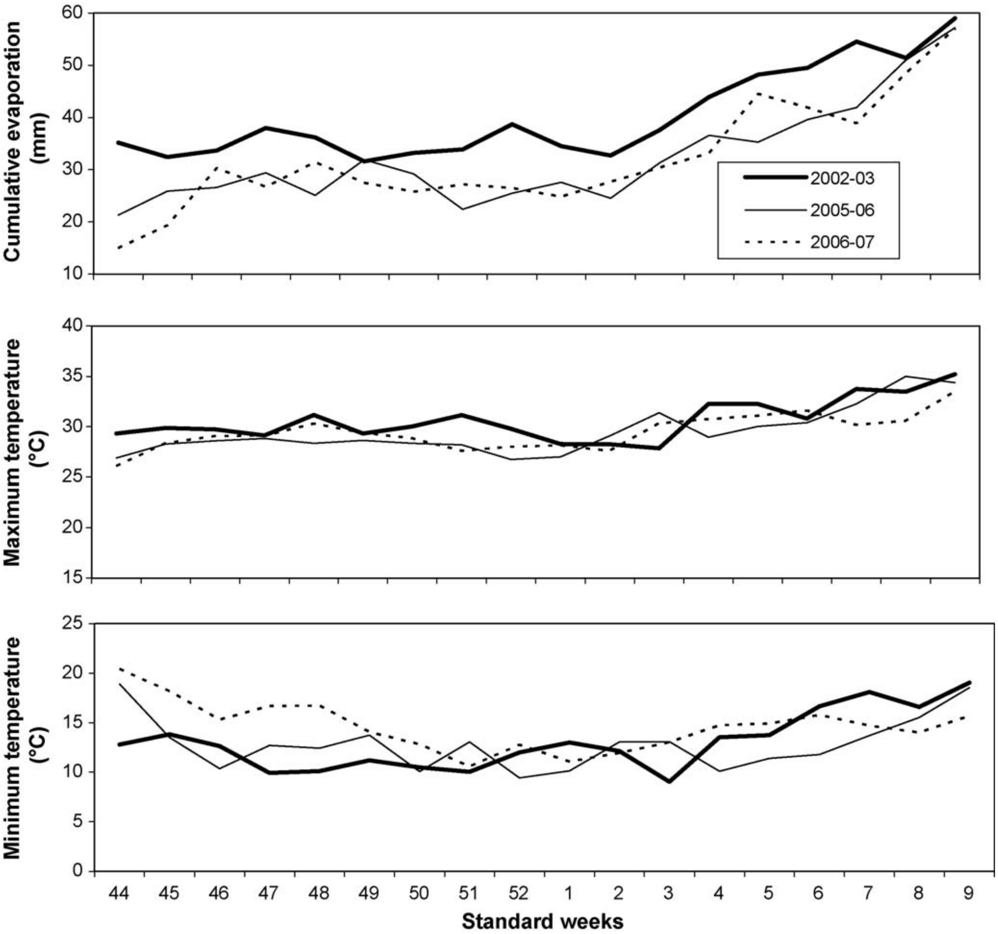

Fig. 1. Weather during the crop growing seasons (November to February) of 2002–03, 2005–06 and 2006–07.

opportune environments (Saxena et al., 1995; Singh et al., 1995; Kashiwagi et al., 2005). Drought tolerant genotypes, on the basis of yield under drought, have been identified in the past by screening accessions of chickpea germplasm that were known to come from drought-prone areas (Saxena, 1987, 2003; Saxena et al., 1993). However, the extent of genotypic variation for drought tolerance available in the germplasm bank is not clear. Yet, it is desirable to have greater genetic options and diversity for better breeding success. The establishment of the minicore collection (10% of the core collection and 1% of entire collection) of chickpea germplasm representing most of the genetic diversity available in the entire collection (Upadhyaya and Ortiz, 2001) offered an opportunity to tap new sources of terminal drought tolerance in a more systematic manner.

Chickpea yields are highly prone to large genotype by environment (G × E) interactions (Saxena, 1987; Krishnamurthy et al., 1999, 2004; Berger et al., 2004, 2006; Kashiwagi et al., 2008a). Several traits are expected to play a collective role in adaptation to terminal drought (Ludlow and Muchow, 1990; Saxena and Johansen, 1990; Johansen et al., 1997; Soltani et al., 2000) and these traits are less likely to be influenced by G × E. Under such circumstances, a better strategy of breeding for drought tolerance is to select for traits, which can be more readily related to crop performance under particular environment, rather than yield. To mention some of them are early growth vigor, harvest index, larger root system (as seen in ICC 4958), twin pods for rapid remobilization (JG 62), smaller pinnules (ICC 10448) or fewer pinnules (ICC 5680) for less transpirational demand (Saxena, 2003). However, prior to consideration for breeding, the magnitude of contribution of these traits in the target environments need to be ascertained and confirmed to be significant for prioritization. Such contributions were established to be major in terminal drought-prone chickpea (Kashiwagi et al., 2006) or for sorghum and maize (Sinclair and Muchow, 2001; Hammer et al., 2009) for traits like larger and deeper root system and for the rate of partitioning (Krishnamurthy et al., 1999), while for others, such estimations are still required. Therefore the key characteristics for selection still remain to be biomass and the yield.

Yield under drought can be explained by traits that are fully independent of the response of genotypes to the drought environment. As mentioned above, crop duration in chickpea plays a critical role and so, while selecting germplasm for "drought tolerance", it is important to properly separate attribute that are inherent to a given line (constitutive traits) from those that only reflect a genotype's response to stress (adaptive traits). Also crop duration is a major characteristic that contributes to G × E interactions in chickpea (Berger et al., 2004, 2006). In the past a drought tolerance index (DTI), based on the seed yield under drought after removal of the known contributory effects of drought escape (flowering time) and yield potential, has been successfully employed to assess the drought response in pearl millet and chickpea under terminal drought-prone conditions (Bidinger et al., 1987, Saxena, 1987, 2003), and has pointed to several processes explaining DTI differences under stress, i.e. seed setting and grain filling.

The objective of this study was to assess the extent of variation available in the chickpea minicore germplasm collection for drought tolerance, assessed with the DTI, and identify contrasting sources of tolerance to diversify the genetic base of breeding programs.

2. Materials and methods

2.1. Crop management

Field evaluation of the minicore collection of chickpea germplasm ($n = 211$) plus five more popular chickpea genotypes was conducted during the postrainy seasons of 2002–03, 2005–06 and 2006–07 on a Vertisol (fine montmorillonitic isohyperthermic typic pallustert) at ICRISAT, Patancheru (17° 30′ N; 78° 16′ E; altitude 549 m) in peninsular India. The soil depth of the fields used in the three seasons was ≥1.2 m and these soils retained about 230 mm of plant available water in the 120-cm (maximum rooting depth) soil profile. The fields used were solarized using polythene mulch during the preceding summer to sanitize the field, particularly to eradicate *Fusarium oxysporum* wilt causing fungi as chickpea was often grown in these fields. Following solarization, a cowpea cover crop was raised for about 55 days and turned over in the soil only during the rainy season in 2002 preceding the experimental chickpea crop. In the rest of the two seasons the field was kept fallow after the summer solarization. Glyphosate (Roundup®) herbicide was applied prior to land preparation only during 2005–06.

The fields were prepared into broad bed and furrows with 1.2 m wide beds flanked by 0.3 m furrows for all the experiments. Surface application and incorporation of 18 kg N ha^{-1} and 20 kg P ha^{-1} as di-ammonium phosphate was carried out in all the experiments. The plot size for the 2002–03 and the 2006–07 experiments were 4.5 m × 2 rows and the 2005–06 experiments was 4 m × 2 rows. The experiments were conducted with two irrigation levels as main plot treatments (1. Drought stressed: nonirrigated except for a post-sowing irrigation and 2. Irrigated: optimally irrigated depending on the need) in a 12 × 18 alpha design (216 accessions) with three replications. Seeds were treated with 0.5% Benlate® (E.I. DuPont India Ltd., Gurgaon, India) + Thiram® (Sudhama Chemicals Pvt. Ltd., Gujarat, India) mixture in all the three seasons. All the experiments were hand planted at the first opportunity after the cessation of the rains on 31 Oct 2002, 15 Nov 2005 and 2 Nov 2006 in rows 30-cm apart with 10 cm between plants at 3–5 cm depth with two seeds per hill which was later thinned to one. During all the seasons, the fields were inoculated with Rhizobium strain IC 59 using liquid inoculation method (Brockwell, 1982). A 50 mm irrigation through perforated pipes in 2002 and 2006 and a 20 mm in 2005 was applied the next day to ensure complete emergence. Successive irrigations, to the irrigated treatments were through furrow irrigation. Intensive protection against pod borer (*Helicoverpa armigera*) was provided and the plots were kept weed free by manual weeding.

By regular observation, the date when 50% or more of the plants in a plot flowered was recorded as 50% flowering time of the plot and when 80% of the pods in a plot were dried was recorded as the time of maturity for each plot.

2.2. Soil moisture measurements

Neutron moisture meter access tubes were installed in 2 spots in 2002–03, 7 in 2005–06 and 8 in 2006–07 in each replication and treatment at random. Neutron moisture meter (Depth Moisture Gauge, Model 3332, Troxler Electronic Laboratories Inc., NC, USA) readings at soil depths of 15 cm increments up to a depth of 120 cm were made before and after each irrigation as well as matching it at about 10 d intervals or close by. The Troxler soil moisture observations were corrected using a calibration curve developed for each depth separately using the data collected gravimetrically across the season. Moisture content of the surface soil (0–15 cm) was measured only gravimetrically.

2.3. Final harvest

At physiological maturity, plant aerial parts were harvested from an area of 3.08 m^2 in 2002–03 and 2006–07 and 2.7 m^2 in 2005–06 in each plot, dried to constant weight in hot air dryers at 45 °C, and total shoot dry weights were recorded. Grain weights were recorded after threshing. Harvest index (%) was calculated as 100 × (seed yield/total shoot biomass at maturity).

2.4. Drought tolerance index (DTI) estimation

Differences in crop duration and yield potential (Saxena, 1987) are known to contribute to the seed yield under drought stress and the removal of these effects from seed yield under stress provides a reliable measure of stress tolerance *per se* (Vadez et al., 2007). This was in part explained by the fact that the testing environment at ICRISAT, Patancheru, India, is a short-duration environment for chickpea and does not favor long-duration genotypes because these genotypes have to fill their seeds under increasing temperatures and terminal drought (Saxena, 1987). Previous work has shown that the residual after the removal of effects of drought escape (early flowering) and yield potential (optimally irrigated yield) of a genotype gave a good indication of the true drought tolerance of this genotype (Bidinger et al., 1987; Saxena, 1987, 2003; Vadez et al., 2007). The residuals were calculated using the multiple regression approach of Bidinger et al. (1987). Briefly this approach considers grain yield under drought stress condition (Y_s) as a function of yield potential (Y_p), time to 50% flowering (F), and a drought tolerance index (DTI) such that the yield of a genotype can be expressed as follows:

$$Y_{si} = a + bY_p + cF_i + \mathrm{DTI}_i + E,$$

where E is random error with zero mean and variance σ. Standard residuals, that is the Drought Tolerance Index (DTI) were calculated as the difference between the actual and estimated yields under stress upon the standard error of the estimated yield (σ). For this multiple regression, 50% flowering (F_i) under stress for every individual plot and for the Yield potential (Y_p) arithmetic mean across the three replications were considered.

2.5. Statistical analysis

The replication-wise values of DTI were used for statistical analysis of each environment using ReML considering genotypes as random. Variance components due to genotypes ($\sigma^2{}_g$) and error ($\sigma^2{}_e$) and their standard errors were determined. Environment wise best linear unbiased predictors (BLUPs) for the mini core accessions and others were calculated. Heritability was estimated as $h^2 = \sigma^2{}_g/(\sigma^2{}_g + \sigma^2{}_e)$. The significance of genetic variability among accessions was assessed from the standard error of the estimate of genetic variance $\sigma^2{}_g$, assuming the ratio $\sigma^2{}_g/\mathrm{SE}\,(\sigma^2{}_g)$ to follow normal distribution asymptotically.

For the pooled analysis, homogeneity of variance was tested using Bartlett's test (Bartlett, 1937). Here, the year (environment) was treated as a fixed effect and the genotype (G) × environment (E) interaction as random. The variance due to (G) ($\sigma^2{}_{g)}$ and (G) × (E) interaction ($\sigma^2{}_{gE)}$ and their standard error were determined. The significance of the fixed effect of the year was assessed using the Wald statistic that asymptotically follows a χ^2 distribution.

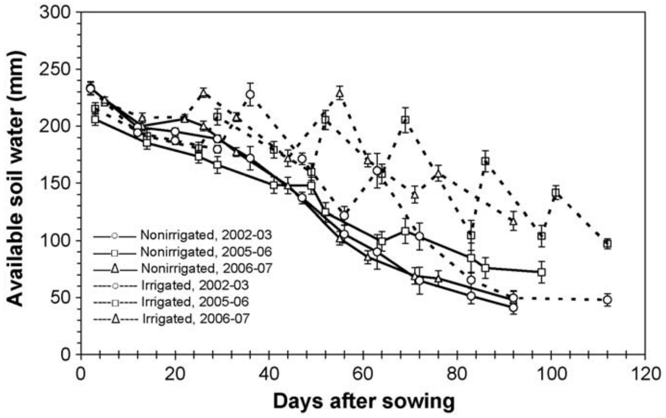

Fig. 2. Changes in available soil moisture up to a soil depth of 1.2 m across the crop growing seasons of 2002–03, 2005–06 and 2006–07. Vertical bears denote standard error of differences (±).

3. Results

3.1. Weather during crop growth season

The weather during the crop growing seasons varied largely in the time of cessation of rains and explained the differences in time of sowing. There were overcasts and rains during 2006 at the time of sowing totaling about 25-mm over 10 days. The preceding rainy season rains were 573, 1070 and 661-mm during 2002, 2005 and 2006, respectively, resulting in a fully saturated soil profile at sowing. However, the seasons were free from rains except for a 3-mm rain during third week of December 2005. The maximum temperatures during most of 2002 were relatively high reflecting in the evaporative demand in this season (Fig. 1). The temperatures in the weeks 6–9 (February) were relatively cooler during 2007.

3.2. Changes in soil moisture across growing season

The pattern and the rate of soil moisture depletion did not vary between the 2002–03 and 2006–07 seasons. In 2005–06 the stored soil moisture was marginally less in the first 40 days after sowing, the soil moisture use was slower and at maturity relatively more moisture was left unutilized by the crop (Fig. 2). Irrigations at the early stages of the season raised again the total available soil water to initial levels whereas as the season advanced did not charge the profile fully, although the water available was sufficient to fully support plant growth in the irrigated treatment.

3.3. Variation in phenology of the minicore germplasm accessions

The overall means for each irrigation treatment across years had shown that irrigation delayed the days to 50% flowering and the days to maturity (Table 1). The range of predicted means did not show this effect because some early duration accessions flowered early in the drought treatment and a few late duration accessions flowered later under drought stressed condition. The accessions ranged and varied widely for days to 50% flowering with a maximum difference of about 40 days and for days to maturity with a maximum difference of about 35 days. The heritability values were the highest for the days to 50% flowering and for days to maturity under drought stressed environment whereas it turned out to be less when irrigated (Table 1). Few minicore accessions (ICC 762, -1161, -2210, -3218, -6306, -8195 and ICC 13441) that flowered close to 70 DAS used more time than expected to reach maturity and were forced into maturity by the increasing temperature, yielding very few or no pods. The maturity dates for these entries were marked as the latest to avoid treating them as missing plots. A plot of either the days to 50% flowering (Fig. 3) or days to maturity (data not shown) against the seed yield under drought stress revealed a linear negative relationship (Fig. 3). Top yielding accessions in 2002–03 and 2005–06 had a flowering time between 45 and 50 DAS, whereas top yielders in 2006–07 had yet shorter flowering time, 40 DAS.

3.4. Influence of flowering time and yield potential on drought tolerance

The seed yield under drought stress was negatively associated to the time to flowering (r^2 = 2002–03 = 0.43, 2005–06 = 0.52 and 2006–07 = 0.41) (Fig. 3). Similarly, the seed yield under drought stress was positively associated to the irrigated seed yield and considered here as yield potential (r^2 = 2002–03 = 0.50, 2005–06 = 0.18 and 2006–07 = 0.51) (Fig. 3). Therefore, categorization of the accessions in terms of seed yield under drought stress for drought response would partly lead to a categorization for time to flowering and yield potential. Therefore drought tolerance indices were computed to characterize the drought tolerance *per se* in this study, i.e. the portion of the genetic variation for seed yield under terminal drought that was not accounted for differences in time to flowering and yield potential.

3.5. Variation in yield and yield components

Under irrigated conditions, both the shoot biomass and the seed yield produced at maturity were slightly higher during 2002–03 (Table 2). It is speculated that slightly cooler maximum temperatures and slightly warmer minimum temperatures in 2005–06 might have explained the lower values in thermal time accumulation that was 2067, 1897 and 2007 °C d in 2002–03, 2005–06 and 2006–07, respectively. However, cumulative solar radiation incidence was similar across the seasons (1546, 1585 and 1475 MJ m^{-2}). Under drought stress condition, both the shoot biomass and the seed yield produced at maturity was the highest during 2002–03. Drought stress reduced the seed yield by 26, 61 and 34% and the shoot biomass at maturity by 31, 63 and 43% during 2002–03, 2005–06 and 2006–07 seasons, respectively (Table 2).

There were highly significant variations for the shoot biomass as well as seed yield across the accessions and these variations were about two-fold for the shoot biomass at maturity and many-fold for seed yield among the accessions tested. Heritability indices for the seed yield under drought stressed environment was the highest followed by the optimally irrigated environment and the shoot biomass under both environments (Table 2). The variation among accessions for DTI was also large and highly significant. The heritability index was fairly high for this trait for the years 2002–03 and 2006–07, although lower than the heritability for yield. It was low in 2005–06. The variance component for the seed yield of accessions under drought stress across years had shown the existence of a large and significant accession effect (105,766 ± 11,728) compared to a relatively small but significant year × accessions interaction (31,248 ± 3638). In spite of this interaction the yield of accessions across years were closely associated. The yields of accessions in 2002–03 accounted for 55% of the variation in 2005–06, 2005–06 accounted for 55% of 2006–07 and 2002–03 accounted for 64% of 2006–07 variation. Similarly the variance of the DTI of accessions across years (0.2021 ± 0.0309) was large whereas the year × accessions interaction (0.1261 ± 0.0235) was significant but relatively small.

Table 1
Trial means, range of best linear unbiased predicted means of RILs (BLUPs) and analysis of variance of the 211 accessions of minicore chickpea germplasm with five other popular varieties for days to 50% flowering and days to maturity in the field experiments during 2002–03, 2005–06 and 2006–07 postrainy seasons.

Season/environment	Trial mean	Range of predicted means	S.Ed	σ^2_g (SE)	Heritability (h^2)
Days to 50% flowering					
2002–03					
Drought stressed	50.1	25.5–74.1	3.2	86.4 (8.5)	0.942
Optimally irrigated	53.1	26.9–71.7	3.0	48.7 (4.9)	0.906
2005–06					
Drought stressed	53.3	31.5–78.8	2.3	65.4 (6.5)	0.907
Optimally irrigated	55.6	31.5–71.8	1.9	45.0 (4.5)	0.884
2006–07					
Drought stressed	49.5	31.5–71.8	1.95	74.5 (7.4)	0.928
Optimally irrigated	51.0	32.3–69.7	1.96	57.4 (5.4)	0.907
Days to maturity					
2002–03					
Drought stressed	98.9	82.9–119.2	3.8	69.5 (7.0)	0.898
Optimally irrigated	102.1	85.5–113.7	3.1	14.5 (1.7)	0.661
2005–06					
Drought stressed	92.5	77.4–115.9	2.5	48.9 (4.9)	0.877
Optimally irrigated	108.1	69.8–113.8	1.9	11.2 (1.3)	0.633
2006–07					
Drought stressed	92.5	69.8–113.8	2.3	57.9 (5.9)	0.880
Optimally irrigated	104.1	98.2–115.1	2.0	13.2 (1.5)	0.667

3.6. *Drought response categorization*

As there was a significant interaction between accessions and years, the DTI of the accessions were grouped into representative groups using the BLUPs for the seed yield by a hierarchical cluster analysis (using Ward's incremental sum of squares method) and this analysis yielded five groups at 75% similarity level. Based on the extent of cluster group means of DTI these can be identified as: (1) highly tolerant (with DTI means 0.92, 0.43 and 1.08 during 2002–02, 2005–06 and 2006–07, respectively), (2) tolerant (0.39, 0.08 and 0.29), (3) moderately tolerant (−0.33, 0.04 and 0.04), (4) sensitive (0.19, −0.20 and −0.36) and (5) highly sensitive (−0.93, −0.21 and −0.85). The highly tolerant group comprised of five accessions, while the highly sensitive group comprised of 20 accessions out of the 216 used for clustering (Table 3). The tolerant group comprised of 78 accessions (Table 4). The moderately tolerant and the sensitive groups comprised 74 and 39 entries, respectively (Table 5). Annigeri, a familiar well adapted and well-known genotype, with DTIs 0.79, 0.14 and −0.32 and seed yields 2734, 1010 and 1702 kg ha^{-1} represented the tolerant group with DTI means 0.39, 0.08 and 0.29 and seed yields 1885, 773 and 1380 kg ha^{-1} (Table 4) while ICC 4958, a well characterized germplasm acces-

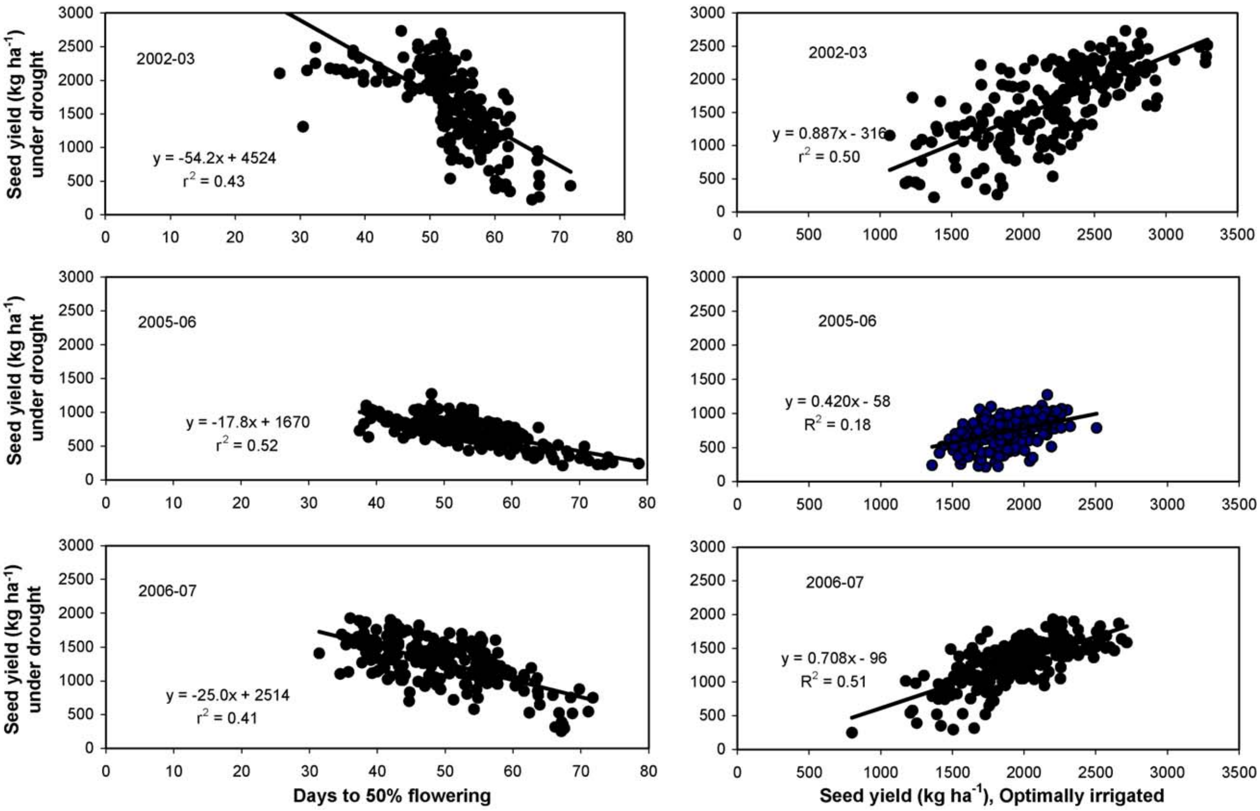

Fig. 3. Relationship between days to 50% flowering and the seed yield under drought stress (all the three seasons in column 1) and between the seed yield under optimal irrigation (yield potential) and the seed yield under drought stress (all the three seasons in column 2).

Table 2

Trial means, range of best linear unbiased predicted means of accessions (BLUPs) and analysis of variance of the 211 accessions of minicore chickpea germplasm with five other popular varieties for shoot biomass at maturity, seed yield and drought tolerance index in the field experiments during 2002–03, 2005–06 and 2006–07 postrainy seasons.

Season/environment	Trial mean	Range of predicted means	S.Ed	Heritability σ^2_g (SE)	(h^2)
Shoot biomass (kg ha^{-1})					
2002–03					
Drought stressed	3815	2797–4937	501.6	200,064 (31,556)	0.371
Optimally irrigated	5512	3606–7278	802.9	456,456 (85,234)	0.295
2005–06					
Drought stressed	1824	1499–2101	200.1	25,366 (9605)	0.118
Optimally irrigated	4925	3995–6055	507.0	245,094 (53,007)	0.232
2006–07					
Drought stressed	2940	2030–3670	278.3	132,170 (18,378)	0.461
Optimally irrigated	5182	3992–6823	442.4	325,490 (45,837)	0.447
Seed yield (kg ha^{-1})					
2002–03					
Drought stressed	1643	220–2734	378.7	348,975 (36,769)	0.795
Optimally irrigated	2210	1069–3292	489.4	264,233 (33,462)	0.548
2005–06					
Drought stressed	724	213–1272	182.1	51,147 (6615)	0.511
Optimally irrigated	1860	1359–2506	233.1	65,792 (11,259)	0.322
2006–07					
Drought stressed	1274	250–1928	170.1	124,583 (13,622)	0.734
Optimally irrigated	1936	800–2716	208.5	133,589 (15,488)	0.631
Drought tolerance index (DTI)					
2002–03	0.00	−1.86–1.32	0.702	0.4440 (0.0628)	0.444
2005–06	0.00	−0.52–0.64	0.422	0.1262 (0.0346)	0.173
2006–07	0.00	−1.47–1.26	0.512	0.4329 (0.0612)	0.434

sion, considered drought tolerant and known for superior rooting characteristics, with DTIs −0.62, −0.02 and −0.27 and seed yields 2487, 1040 and 1771 kg ha^{-1} fell into the moderately tolerant group with DTI means −0.33, 0.04 and 0.04 and seed yields 1498, 743 and 1246 kg ha^{-1}

Most of the entries classified as highly tolerant entries were relatively late in flowering and maturity compared to Annigeri and these were all small-seeded desi types (data not shown). Accession ICC 867 flowered (4–8 d) and matured (3–4 d) later. The rest of the four were 10–20 d late in flowering and 7–17 d late in maturity. The tolerant group of accessions had 15 kabuli and 63 desi types (data not shown).

4. Discussion

This work has established the existence of a large variation for drought response in the minicore collection of chickpea, with germplasm accessions performing better than currently used

Table 3

Drought tolerance indices, shoot and seed yield at maturity of the highly drought tolerant and highly drought sensitive cluster group members of chickpea mini core chickpea germplasm. DTI, shoot and seed in the column heads below denotes drought tolerance index, shoot biomass kg ha^{-1} (with the usual pinnule loss) and seed yield kg ha^{-1}, respectively and the numbers denote the year of experimentation.

S. No	Accession	DTI-03	Shoot-03	Seed-03	DTI-06	Shoot-06	Seed-06	DTI-07	Shoot-07	Seed-07
Highly drought tolerant										
1	ICC 867	0.71	4275	2472	0.28	1879	924	1.26	3256	1620
2	ICC 1923	0.52	4349	1541	0.57	1959	1059	1.10	3372	1775
3	ICC 9586	0.90	4139	1900	0.31	1876	784	1.18	3256	1328
4	ICC 12947	1.36	4271	2368	0.50	1961	998	0.61	2840	1363
5	ICC 14778	1.11	4463	2570	0.47	1930	1035	1.24	3146	1636
	Mean	0.92	4299	2170	0.43	1921	960	1.08	3111	1544
Highly drought sensitive										
1	ICC 1052	−0.70	3688	1196	−0.09	1794	642	−0.76	2595	910
2	ICC 2242	−1.10	3377	261	−0.25	1851	226	−1.38	2810	376
3	ICC 2720	−0.86	3848	797	−0.35	1800	213	−1.44	2713	417
4	ICC 2990	−0.62	3668	945	−0.25	1726	431	−0.78	2714	913
5	ICC 3776	−1.35	2797	813	−0.03	1835	719	−0.63	2831	1027
6	ICC 4814	−0.79	3708	943	−0.18	1855	726	−0.64	2487	831
7	ICC 6263	−1.24	3043	1151	−0.04	1957	866	−0.95	2954	1175
8	ICC 6306	−0.41	3484	220	−0.10	1746	229	−1.02	3365	409
9	ICC 7184	−0.87	3365	827	−0.48	1726	457	−1.48	2579	762
10	ICC 7819	−0.42	3333	668	−0.02	1749	458	−1.06	3173	1046
11	ICC 8058	−1.18	3391	973	−0.31	1726	600	−0.82	2855	1057
12	ICC 11764	−0.90	3828	1013	−0.26	1831	429	−0.34	3105	968
13	ICC 11879	−0.93	3404	986	−0.12	1858	702	−0.68	3126	1138
14	ICC 12537	−0.58	3730	1873	−0.23	1709	683	−0.85	2296	1230
15	ICC 12928	−0.82	3781	1140	−0.40	1833	512	−0.68	2774	1130
16	ICC 13124	−1.25	3742	2252	−0.14	1860	1035	−0.55	3106	1753
17	ICC 13441	−0.78	3324	344	−0.02	1866	424	−1.15	2738	598
18	ICC 14669	−0.89	3364	1981	−0.31	1753	788	−0.54	2977	1709
19	ICC 16374	−1.66	3746	1306	−0.42	1787	632	−0.59	2891	1131
20	ICCV 2	−1.26	3700	2102	−0.23	1746	729	−0.60	2486	1403
	Mean	−0.93	3531	1090	−0.21	1800	575	−0.85	2829	999

Table 4
Drought tolerance indices, shoot and seed yield at maturity of the drought tolerant cluster group members of chickpea mini core chickpea germplasm. DTI, shoot and seed in the column heads below denotes drought tolerance index, shoot biomass kg ha^{-1} (with the usual pinnule loss), seed yield kg ha^{-1}, respectively and the numbers denote the year of experimentation.

S. No.	Accession	DTI-03	Shoot-03	Seed-03	DTI-06	Shoot-06	Seed-06	DTI-07	Shoot-07	Seed-07
Tolerant										
1	ICC 283	0.46	3844	2042	0.00	1801	812	0.71	3433	1878
2	ICC 456	0.78	3950	2215	0.15	1820	871	0.46	3103	1461
3	ICC 637	0.02	4358	2518	0.29	1920	758	0.64	2871	1122
4	ICC 708	1.24	3949	2163	0.06	1745	673	0.81	3212	1536
5	ICC 762	0.53	3806	807	0.07	1693	258	0.18	3007	722
6	ICC 1098	0.50	4240	2347	0.26	1768	842	−0.28	2858	1473
7	ICC 1164	0.26	3918	1928	0.14	1709	647	0.82	3088	1544
8	ICC 1180	0.52	4332	1796	0.18	1892	718	0.27	3454	1211
9	ICC 1230	0.30	3924	2219	0.15	1848	1049	0.19	3299	1780
10	ICC 1397	0.45	4181	1950	0.04	1825	774	1.13	3393	1577
11	ICC 1398	0.41	4088	2445	−0.03	1772	871	0.08	2831	1573
12	ICC 1422	−0.07	4013	2332	−0.01	1800	803	0.68	3163	1852
13	ICC 1882	0.11	4048	2305	−0.18	1726	762	0.24	2730	1478
14	ICC 1915	0.21	3685	429	0.01	1891	318	−0.68	3163	529
15	ICC 2065	0.34	3975	1530	0.02	1822	595	0.30	2834	1123
16	ICC 2580	0.24	4136	2278	0.10	1963	1021	−0.08	3006	1604
17	ICC 2969	1.02	3756	2218	0.11	1828	871	−0.20	2880	1492
18	ICC 3230	0.34	3733	1208	0.11	1782	517	0.06	2245	730
19	ICC 3325	1.20	4317	2497	0.19	1819	894	0.68	3147	1701
20	ICC 3421	0.28	3762	1361	0.02	1849	710	−0.62	2977	972
21	ICC 3946	−0.09	4102	1502	0.07	1778	633	0.74	3118	1190
22	ICC 4567	0.50	3860	1954	0.07	1803	715	−0.18	2987	1448
23	ICC 4593	0.92	4264	2109	0.04	1800	758	0.93	3222	1534
24	ICC 4639	0.58	3308	1453	−0.01	1763	570	0.28	2737	1146
25	ICC 4841	0.36	3660	1920	−0.01	1814	821	−0.86	2060	579
26	ICC 5434	0.26	3896	1708	0.22	1832	661	1.06	2655	1350
27	ICC 5613	0.67	4208	2318	0.46	2101	1272	−0.02	2749	1325
28	ICC 5639	0.51	3528	1900	0.06	1766	781	−0.55	2662	1142
29	ICC 5845	1.08	3971	1519	0.11	1702	496	−0.86	2299	716
30	ICC 5878	0.28	3661	2071	−0.17	1753	758	0.34	2440	1210
31	ICC 6537	0.35	3735	1900	0.23	1893	864	0.35	2796	1216
32	ICC 6571	0.20	4010	1982	0.16	1937	837	0.97	3162	1493
33	ICC 6579	1.04	3795	1918	0.05	1815	835	−0.15	2804	1304
34	ICC 6802	−0.08	3409	1133	−0.06	1796	686	0.49	2851	1265
35	ICC 6816	0.26	3449	2036	0.25	1864	998	−0.59	2749	1523
36	ICC 6874	0.09	3611	1833	0.07	1801	827	0.57	2780	1372
37	ICC 7441	1.03	4040	2287	−0.05	1696	712	0.77	3417	1804
38	ICC 8151	0.10	4216	1600	0.02	1980	820	0.43	3735	1389
39	ICC 8318	−0.03	3834	2176	0.23	1975	1100	0.79	3289	1861
40	ICC 8950	0.61	4028	2277	0.27	1859	957	0.07	2988	1627
41	ICC 9002	1.10	4063	2267	−0.01	1817	834	0.12	2756	1370
42	ICC 9643	0.24	3535	1334	0.21	1821	691	0.62	2571	983
43	ICC 9848	0.50	4001	1668	−0.01	1828	744	0.01	3055	1267
44	ICC 9862	0.48	3887	1719	−0.11	1763	657	0.25	2997	1298
45	ICC 10341	0.46	3964	1451	0.00	1792	584	−0.16	2816	1062
46	ICC 10945	−0.08	3792	2016	−0.03	1815	869	0.19	3025	1590
47	ICC 11121	0.10	3482	1683	0.05	1737	743	0.48	2918	1412
48	ICC 11198	0.69	3629	1704	0.24	1778	778	−0.10	2771	1283
49	ICC 11378	0.05	3806	1662	0.02	1799	650	0.80	3269	1614
50	ICC 11627	−0.04	3951	1504	0.26	1830	775	0.77	2893	1373
51	ICC 11944	0.79	4145	2241	0.07	1804	772	0.83	3491	1688
52	ICC 12037	0.03	3650	1366	−0.03	1765	682	0.25	2580	1027
53	ICC 12155	0.18	3987	2218	0.20	1909	1026	0.63	3169	1804
54	ICC 12307	0.17	3893	2109	−0.02	1793	845	0.65	3195	1707
55	ICC 12328	0.00	4218	1392	−0.17	1891	498	0.18	3351	1154
56	ICC 12824	0.15	4044	2225	0.07	1816	855	−0.59	2906	1548
57	ICC 13283	0.58	3673	1291	−0.11	1848	508	0.56	3367	1302
58	ICC 13461	−0.14	3680	1015	0.16	1863	686	0.54	2829	872
59	ICC 13523	−0.05	3662	1359	0.00	1841	701	0.22	2855	1209
60	ICC 13816	0.24	3884	1176	0.01	1855	589	−0.50	3191	1224
61	ICC 13892	0.06	3913	2125	−0.01	1735	779	−0.68	2946	1576
62	ICC 14051	−0.02	3957	2188	0.03	1822	920	0.63	3250	1747
63	ICC 14077	0.64	4011	2193	0.00	1779	835	−0.23	2551	1257
64	ICC 14402	0.38	4475	2538	−0.16	1926	893	0.23	3663	1927
65	ICC 14799	1.00	4744	2698	0.15	1905	953	0.73	3301	1613
66	ICC 15264	0.03	4667	1880	0.03	1973	923	0.82	3427	1513
67	ICC 15333	−0.22	4185	1496	0.14	1983	866	0.70	3642	1394
68	ICC 15435	0.17	4664	2006	−0.12	1911	775	1.06	3657	1565
69	ICC 15510	1.05	4580	2097	0.27	1904	841	0.59	3380	1564
70	ICC 15697	0.16	4202	1986	0.32	1980	990	0.65	3219	1377
71	ICC 15802	1.04	4937	2375	0.04	1867	739	0.73	3398	1419
72	ICC 15868	0.59	4111	2288	0.21	1831	896	−0.60	2836	1469
73	ICC 16207	0.04	3870	1761	0.15	1854	683	0.86	3462	1580

Table 4 (*Continued*)

S. No.	Accession	DTI-03	Shoot-03	Seed-03	DTI-06	Shoot-06	Seed-06	DTI-07	Shoot-07	Seed-07
74	ICC 16261	0.44	4369	1718	0.13	1858	678	0.62	3407	1320
75	ICC 16269	−0.07	3727	1552	0.14	1805	688	0.64	3060	1399
76	ICC 16487	0.24	4080	1453	−0.09	1783	466	0.42	3039	1178
77	ICC 16524	0.76	4412	2323	0.37	1936	975	−0.02	3221	1430
78	Annigeri	0.79	4264	2734	0.01	1865	1009	−0.32	2875	1702
	Mean	0.39	3985	1883	0.08	1835	772	0.28	3027	1374

Table 5

Mean drought tolerance indices, shoot and seed yield at maturity of the moderately tolerant and the drought sensitive cluster groups of the chickpea mini core chickpea germplasm. DTI, shoot and seed in the column heads below denotes drought tolerance index, shoot biomass kg ha^{-1} (with the usual pinnule loss), seed yield kg ha^{-1}, respectively and the numbers denote the year of experimentation.

Number of accessions	Mean TI-03	Mean shoot-03	Mean seed-03	Mean DTI-06	Mean shoot-06	Mean seed-06	Mean DTI-07	Mean shoot-07	Mean seed-07
Moderately drought tolerant									
74	−0.33	3695	1498	−0.04	1849	743	−0.04	2951	1246
Drought sensitive									
39	0.19	3790	1562	−0.20	1758	634	−0.36	2767	1224

sources of tolerance such as ICC 4958, JG 62, ICC 10448 (Gaur et al., 2008; Saxena, 2003) in the desi types and FLIP 89-57C in Kabulis (Singh et al., 1996). There were 0, 15 and 16 accessions with greater absolute drought yields than that of Annigeri, considered the best-adapted genotype for the region, and 6, 7 and 9 accessions with greater yield than that of ICC 4958, the well-known drought tolerant germplasm accession with a large root system (Saxena et al., 1993), in years 2002–03, 2005–06 and 2006–07, respectively. Although early duration genotypes are considered to be the best adapted to peninsular India (Saxena, 1987; Gaur et al., 2008; Kumar and Abbo, 2001), such as Annigeri, these results showed that slightly later flowering genotypes reached higher yield under stress. Indeed, most short-duration ones are not capable of using extended growing opportunities when available (Johansen et al., 1997; Bolanos and Edmeades, 1996).

Also these sources are expected to have much wider adaptability as these were selected not simply on the basis of seed yield but by drought tolerance index that is to a large extent free from the effect of yield potential and flowering time. These genotypes represent an ideal material for further characterization of underlying mechanisms of tolerance involved. In an earlier study meant to verify and confirm the underlying mechanism of DTI, wherein 16 selected contrasting accessions from the very minicore collection had been included, mid afternoon canopy temperature at mid-reproductive stage (70 DAS) under drought stress using an infra red camera (FLEXCAM, Infrared Solutions, USA) had been measured. The canopy of most tolerant accessions, two such accessions confirmed to be highly tolerant in this study (ICC 867 and ICC 14778 in Table 3), had been found to maintain the coolest temperatures (Kashiwagi et al., 2008b). This study also confirmed that a greater canopy portions of the three highly sensitive accessions (ICC 3776, ICC 8058 and ICC 7184 in Table 3) maintained warmer temperatures, and we interpret this as resulting from differences in water extraction.

Water regimes have served different purposes in this study. Drought stressed treatment has served as the terminal drought environment for selection of phenology, yield and its components while the optimally irrigated regimes served to measure yield potential for use as a component in computing drought tolerance index. Surprisingly relatively large and consistent heritability indices, for all the characteristics that were studied, have been obtained under the drought stressed environment compared to the optimally irrigated environment. This was in contradiction to the experience with most of the drought resistance traits in peanut (Songsri et al., 2008) or many a characteristics including the phenology-based anthesis-silking interval in the low-land maize (Bolanos and Edmeades, 1996) where with increasing drought stress level the genetic variances have been shown to decrease while the error variances have increased leading to a decrease in broad sense heritabilities. The uniformity and consistency of the pattern of soil moisture receding in Vertisols, with a very little rainfall during the chickpea growing postrainy season and a stress level that were not overwhelmingly severe, remains as the key to this contradiction (Johansen et al., 1994). In fact, the heritability for yield under terminal drought and for the DTI was considerably lower in 2005–06, a year when the severity of the stress was higher that in other years. The heritability indices were not only high for the phenological traits but also for the seed yield in this environment indicating the possibilities of a direct selection for yield in chickpea. Considering that these heritability indices [calculated thus using the variances ($\sigma^2{}_g + \sigma^2{}_e$) of ReML analysis] are relatively closer to the narrow sense heritability indices than the broad sense ones, these values are considerably high permitting a direct drought yield based selection for drought tolerance. The heritability of DTI was relatively low as was shown in peanut compared to that of the absolute pod yield or plant biomass (Songsri et al., 2008). This is well expected as it is a ratio and depends upon the error variances of many characters such as yield under drought, yield under optimally irrigated condition as well as the days to 50% flowering. However, higher confidence level can be placed on this heritability index as this is likely to be reproducible across environments.

5. Conclusions

A large range of variation was available among the minicore germplasm accessions for their response to terminal drought. There are better sources of tolerance than either Annigeri or ICC 4958 that can be used for a better diversified drought tolerance breeding program. However, their seed size and agronomic acceptability may need further improvement. The heritability of yield under drought stress was good or even better than under optimally irrigated condition indicating that the direct selections for yield under receding soil moisture conditions of Vertisol is possible. Though the heritability of drought tolerance index was slightly lesser than that of the yield, the DTI represented a selection index devoid of the yield potential and phenology effects and this index potentially offers a selection criterion for adaptation to water limitation valid across wider agro-ecological zones.

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