Introduction

Drought is one of the most severe abiotic factors limiting agricultural production in arid and semi-arid regions (Delmer 2005). Drought can be prolonged or seasonal, since rainfall in such areas is very seasonal, and periodic drought occurs regularly. About 230 million ha of farm land is used for wheat cultivation world-wide, and half of this area is regularly affected by drought (Trethowan et al. 2007). Xinjiang has a temperate continental climate, with low rainfall and low humidity, and is typical of an arid or semi-arid desert region. The data on wheat drought tolerance research in Xinjiang is valuable for wheat breeders, especially for those working in drought-prone regions of the world.

Drought-stress results in average wheat yield losses of 17%–70% (Nouriganbalani et al. 2009). Breeding crop

Phenotyping and evaluation of CIMMYT WPHYSGP nursery lines and local wheat varieties under two irrigation regimes

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Accurate evaluation of morphological and physiological traits is critical for selection of wheat (Triticum aestivum L.) cultivars exhibiting high yield, which is stable over different growing conditions. In order to use selection index based on high yield, high grain quality and drought tolerance in wheat, a set of 145 CIMMYT Wheat Physiological Germplasm Screening Nursery lines and seven local spring wheat varieties were phenotyped and evaluated for physiological and yield traits under two irrigation regimes during the 2011 and 2012 growing seasons in Xinjiang, China. The results showed that drought-stress significantly increased canopy temperature but reduced grain yield, grain weight per spike, normalized difference vegetation index at the flowering and grain filling stages, chlorophyll content at the grain filling stage, grain number per spike, thousand-grain weight, and plant height. Grain weight per spike, plant height and grain plumpness explained 61.8% of the total phenotypic variation in grain yield under no-stress conditions, where they were the three principal factors most closely related to grain yield. Under drought-stress conditions, canopy temperature at the grain filling stage, plant height and grain plumpness were the three principal factors affecting grain yield, and contributed 44.8% of the total phenotypic variation in grain yield. Finally, ten genotypes, including three local varieties, ‘Xinchun 11’, ‘Xinchun 23’ and ‘Xinchun 29’, with appropriate plant height and high and stable yield under both no-stress and drought-stress conditions over the two years of trials, were identified and can be recommended as core parents for spring wheat drought tolerance breeding in Xinjiang, China.

Key Words: wheat, phenotype, evaluation, drought-stress.
Materials and Methods

Wheat genotypes

A total of 152 wheat genotypes were used in the trials, including seven Xinjiang locally bred spring wheat varieties, well adapted to conditions in the north of Xinjiang, and 145 lines from the CIMMYT Wheat Physiological Germplasm Screening (WPHYSGP) nursery in Mexico, where screening had been carried out for improved drought response. Of the seven local varieties, Xinchun 6, Xinchun 11, Xinchun 17 and Xinchun 29 are leading varieties in different regions of Xinjiang, while ‘Xinchun 6’ is also the local check variety in regional trials in Xinjiang.
Experimental conditions

Trials were conducted in two growing seasons (2011 and 2012) at the Junhu wheat experimental station of Changji, Xinjiang Academy of Agricultural Sciences, China: 43°96N, 87°01E, altitude 717.2 m, gray desert soil, soil depth 70 cm, soil pH~7.8, and 200 mm average annual precipitation.

Sowing was done by hand in plots with four rows, 2 m length, and 0.2 m inter-row spacing and 624 seeds m⁻² sowing density. Seeds were planted on April 11, 2011 and March 31, 2012. Before planting, 15 g and 6.8 g of N and P, respectively, were applied per plot in the seedbed. At the seeding (two to three leaves) and jointing stages, 13.8 and 14.5 g N per plot, respectively, were applied. The herbicide 2-methyl-4-chlorophenoxy acetic acid was applied once at the rate of 0.15 g m⁻² during the jointing stage.

In each of the two growing seasons, the experimental layout was randomized complete blocks design with three replicates under each of the irrigation regimes, namely no-stress (non-limited irrigation) and drought-stress (limited irrigation) conditions. Both of the no-stress and drought-stress treatments used drip irrigation which was independently controlled according to the irrigation regime, and the areas under the different irrigation regimes were separated by 4 m isolation zone. No-stress plots (T1) were watered seven times between April 28, 2011 and June 28, 2011, and eight times between April 18, 2012 and June 28, 2012, with irrigation intervals of 10 d. Drought-stress plots (T2) were irrigated twice in 2011 at the jointing and heading stages, respectively, and three times in 2012 at the jointing, heading and early grain filling stages. During the 2011 growing season, all plots of T1 and T2 received 105.3 mm rainfall, and plots T1 and T2 received an additional 420 mm and 120 mm irrigation water, respectively. During the 2012 growing season, all plots of T1 and T2 received 95 mm rainfall, and plots T1 and T2 received an additional 480 mm and 180 mm irrigation water, respectively.

Grain yield and DYI, WYI, and YH-WUEI

In both the 2011 and 2012 growing seasons, all the plants (except for those harvested earlier for individual agronomic traits) in the T1 and T2 plots were harvested by hand, threshed by machine, cleaned by hand, and the yield per plot weighed by hand. Weights were expressed at a moisture content of 13%. Performance of the genotypes in each year was evaluated by calculation of the yield statistic index (DYI), the water yield index (WYI) and the yield high water use efficiency index (YH-WUEI):

\[ \text{DYI} = \frac{Y_S}{\bar{Y}_S} \]
\[ \text{WYI} = \frac{Y_P}{\bar{Y}_P} \]
\[ \text{YH-WUEI} = \left[ \frac{(\text{DYI} + \text{WYI})}{2} \right] = \left[ \frac{(Y_S/\bar{Y}_S + Y_P/\bar{Y}_P)}{2} \right] \]

where \( Y_S \) and \( Y_P \) are the grain yields of each genotype under drought-stress (T2) and no-stress conditions (T1), respectively, and \( \bar{Y}_S \) and \( \bar{Y}_P \) are the mean grain yields of all the genotypes under drought-stress and no-stress conditions, respectively.

Agronomic traits

In both the 2011 and 2012 growing seasons, days to heading, plant height, grain plumpness, thousand-grain weight, spike number per plant, spikelet number per spike, spike length, grain number per spike, grain weight per spike, and grain weight per plant were determined. Days to heading was measured as the number of days from planting until 50% of the main culm spikes emerged from the boot in each plot. Plant height was measured as the distance from the ground to the top of spike (excluding the awns) at maturity. Physiological maturity was recorded when the green color was about to disappear from the upper portion of the main culm peduncle and there was complete loss of green color from the flag leaves. Days to physiological maturity was counted as the number of days from planting to physiological maturity. Grain plumpness was classified on a nine-class scale, from 1 (very shriveled) to 9 (well rounded). Ten whole-plant samples from each T1 and T2 plot were taken before harvesting and used for collecting spike number per plant, spikelet number per spike, spike length, grain number per spike, grain weight per spike, and grain weight per plant. Weights were expressed at a moisture content of 13%.

Physiological measurements

Previous studies had shown that reduction in canopy temperature at solar noon correlated better with yield than it did in the morning or late afternoon (Reynolds et al. 1994). CT was measured in both 2011 and 2012 at the mid-grain filling stage (18 d after flowering), using a hand-held infrared thermometer Optris LS LT (Optris Infrared Sensing, Portsmouth, NH, USA) between 13:00 and 15:00 h during the day, selecting days with clear skies and low wind, keeping the sun behind the operator and measuring the temperature of the canopy exposed to the sun (Reynolds et al. 1994).

Normalized difference vegetation index (NDVI) was determined with the Green Seeker 505 (NTech Industries Inc., Sunnyvale, CA, USA) on the central rows of all plots. In both the 2011 and 2012 growing seasons, NDVI was measured at the jointing stage, flowering stage and mid-grain filling stage. NDVI reflected the stay-green traits of plants. It mainly reflected the growth potential of plants during the vegetative growth period, and reflected the transformation ability of photosynthesis products of plants after flowering. Some studies have shown that stay-green traits have great potential in selecting for water-stress adaptation (Christopher et al. 2014, 2016).

The SPAD Minolta 502 Plus (Konica Minolta, Tokyo, Japan) was used to non-destructively determine chlorophyll content, measuring 10 main culm flag leaves from each replicate plot, and recording the mean data. In both the 2011 and 2012 growing seasons, SPAD was measured at the flowering stage and the mid-grain filling stage.

Statistical analysis

Restricted maximum likelihood (REML) variance components analysis was conducted on the data in 2011 and
were very similar under both irrigation regimes (Fig. 1B). NDVI continued to rise from the seedling stage onwards, reaching its peak at the flowering stage then decreasing at the grain filling stage (Fig. 1D). NDVI at the jointing stage under the no-stress and stress conditions were similar because drought-stress occurred mainly after the flowering stage. NDVI under drought-stress was lower than that under no-stress conditions at the flowering and grain filling stages. Chlorophyll content at the flowering stage was higher under drought-stress conditions, compared to the no-stress conditions, but decreased sharply at the grain filling stage under the stress conditions (Fig. 1C).

Evaluation of grain yield of test genotypes under two irrigation regimes

Under no-stress conditions, 22 genotypes showed at least 10% higher grain yield and water yield index (WYI) than the mean value of the 152 genotypes. These genotypes were 9645, ‘Xinchun 29’, 9611, 9650, 9637, 9653, 9657, ‘Xinchun 6’, 9692, 9638, 9655, 9606, ‘Xinchun 23’, 9639, 9744, 9608, 9727, 9630, 9649, ‘Xinchun 11’ and 9729. Among these genotypes, ‘Xinchun 29’, ‘Xinchun 6’, ‘Xinchun 23’ and ‘Xinchun 11’ were local varieties, while the others were CIMMYT lines (Table 3). Of the 22 genotypes, five genotypes (9645, ‘Xinchun 29’, 9611, 9650 and 9637) achieved 3% higher yield than the local check variety ‘Xinchun 6’. CIMMYT genotypes 9672, 9703, 9788, 9701, 9711, 9659, 9661, 9706, 9767, 9702, 9663, 9605, 9662, 9732, 9704, 9684, 9675, 9665, 9670, 9679, 9740 and 9664 showed 10% lower grain yield than the mean grain yield of the 152 genotypes and 21% lower grain yield than the check variety ‘Xinchun 6’, and also had lower water yield index values (WYI) (Table 3).

Under stress conditions, 26 genotypes achieved grain yields 10% higher than that of ‘Xinchun 6’ as well as high DYI. These genotypes were 9643, 9646, 9612, 9689, 9642, 9640, 9692, 9729, 9698, 9638 9645, 9606, 9650, 9720, 9627, 9699, 9735, 9611, 9730, 9637, ‘Xinchun 29’, 9644, 9725, 9655, ‘Xinchun 33’ and 9726. Of these superior genotypes, only ‘Xinchun 29’ and ‘Xinchun 33’ were local varieties, while the others were from CIMMYT. CIMMYT genotypes 9660, 9679, 9662, 9716, 9691, 9661, 9676, 9634, 9674, 9620, 9678, 9668, 9733, 9731, 9670, 9673, 9677, 9732, 9602, 9664, 9617, 9740, 9619, and 9705 had lower yields, with values 10% and 9.5% less than the mean grain yield of the 152 genotypes and the check variety, ‘Xinchun 6’, respectively.

Higher DYI, WYI and YH-WUEI values >1.05 were observed in 24 genotypes, consisting of twenty-one CIMMYTY nursery lines and three local varieties (Table 4). These genotypes showed high grain yield potential and good yield stability under both no-stress and drought-stress conditions. Acceptable plant height was considered to be between 70 and 90 cm, which was adapted to and acceptable for local irrigated wheat production. Ten genotypes, ‘Xinchun 29’, 9692, 9638, 9606, ‘Xinchun 23’, 9639, ‘Xinchun 11’,...
### Table 1. REML variance components analysis for two treatments in 2011 and 2012 growing seasons

| Trait                  | Source of variation | df | Wald statistic | F value  |
|------------------------|---------------------|----|----------------|----------|
| **GY, kg/ha**          | Genotype (G)        | 151| 1810142.85     | 2.0***   |
|                        | Irrigation treatment (I) | 1  | 3085829921.37  | 3431.8***|
|                        | Year (Y)            | 1  | 899176.21      | 1.0NS    |
|                        | G × I               | 151| 419969420.06   | 46.7***  |
|                        | G × Y               | 151| 1020276.18     | 1.1NS    |
|                        | I × Y               | 1  | 216462509.56   | 240.7*** |
|                        | G × I × Y           | 151| 894905.09      | 1.0NS    |
| **TGW, g**             | Genotype (G)        | 151| 101.10         | 10.4***  |
|                        | Irrigation treatment (I) | 1  | 15938.45       | 532.6*** |
|                        | Year (Y)            | 1  | 0.83           | 1.2NS    |
|                        | G × I               | 151| 48.25          | 79.3***  |
|                        | G × Y               | 151| 1.11           | 1.8***   |
|                        | I × Y               | 1  | 67.14          | 110.3*** |
|                        | G × I × Y           | 151| 0.69           | 0.8NS    |
| **Grain plumpness**    | Genotype (G)        | 151| 2.65           | 4.4***   |
|                        | Irrigation treatment (I) | 1  | 324.14         | 532.6*** |
|                        | Year (Y)            | 1  | 0.83           | 1.2NS    |
|                        | G × I               | 151| 48.25          | 79.3***  |
|                        | G × Y               | 151| 1.11           | 1.8***   |
|                        | I × Y               | 1  | 67.14          | 110.3*** |
|                        | G × I × Y           | 151| 0.69           | 0.8NS    |
| **CT mid-grain filling** | Genotype (G)        | 151| 60.88          | 21.0***  |
|                        | Irrigation treatment (I) | 1  | 2433.76        | 840.1*** |
|                        | Year (Y)            | 1  | 2.72           | 0.9NS    |
|                        | G × I               | 151| 85.75          | 29.6***  |
|                        | G × Y               | 151| 2.88           | 1.0NS    |
|                        | I × Y               | 1  | 2.13           | 0.7NS    |
|                        | G × I × Y           | 151| 2.11           | 0.7NS    |
| **NDVI jointing**      | Genotype (G)        | 151| 0.03           | 6.5***   |
|                        | Irrigation treatment (I) | 1  | 0.32           | 71.7***  |
|                        | Year (Y)            | 1  | 3.61           | 801.4*** |
|                        | G × I               | 151| 0.00           | 1.1NS    |
|                        | G × Y               | 151| 0.01           | 2.6***   |
|                        | I × Y               | 1  | 0.50           | 110.1*** |
|                        | G × I × Y           | 151| 0.00           | 0.8NS    |
| **NDVI flowering**     | Genotype (G)        | 151| 0.02           | 2.5***   |
|                        | Irrigation treatment (I) | 1  | 20.54          | 2548.9***|
|                        | Year (Y)            | 1  | 0.01           | 0.9NS    |
|                        | G × I               | 151| 8.86           | 1099.7***|
|                        | G × Y               | 151| 0.01           | 1.3*     |
|                        | I × Y               | 1  | 1.47           | 182.5*** |
|                        | G × I × Y           | 151| 0.01           | 0.9NS    |
| **NDVI mid-grain filling** | Genotype (G)        | 151| 0.02           | 2.0***   |
|                        | Irrigation treatment (I) | 1  | 28.12          | 3034.3***|
|                        | Year (Y)            | 1  | 0.01           | 0.9NS    |
|                        | G × I               | 151| 0.27           | 29.1***  |
|                        | G × Y               | 151| 0.01           | 1.4*     |
|                        | I × Y               | 1  | 0.54           | 58.4***  |
|                        | G × I × Y           | 151| 0.01           | 1.2NS    |
| **SPAD flowering**     | Genotype (G)        | 151| 37.79          | 3.8***   |
|                        | Irrigation treatment (I) | 1  | 593.15         | 59.9***  |
|                        | Year (Y)            | 1  | 444.73         | 44.9***  |
|                        | G × I               | 151| 8.60           | 0.9NS    |
|                        | G × Y               | 151| 10.61          | 1.1NS    |
|                        | I × Y               | 1  | 2.04           | 0.2NS    |
|                        | G × I × Y           | 151| 7.54           | 0.8NS    |
| **SPAD mid-grain filling** | Genotype (G)        | 151| 139.75         | 2.0***   |
|                        | Irrigation treatment (I) | 1  | 41963.19       | 596.2*** |
|                        | Year (Y)            | 1  | 53581.70       | 761.3*** |
|                        | G × I               | 151| 116.49         | 1.7***   |
|                        | G × Y               | 151| 128.74         | 1.8***   |
|                        | I × Y               | 1  | 47971.88       | 681.6*** |
|                        | G × I × Y           | 151| 106.55         | 1.5***   |
9729, 9746 and 9730 exhibited acceptable plant heights and had high and stable yield under both no-stress and stress conditions. Twenty-four CIMMYT genotypes were classified as exhibiting low water-use efficiency (DYI < 0.95, WYI < 0.95, YH-WUEI < 0.95) and they were 9675, 9663, 9659, 9711, 9713, 9672, 9665, 9660, 9679, 9662, 9716, 9661, 9674, 9620, 9678, 9670, 9673, 9677, 9732, 9664, 9617, 9677 and 9705. The other 106 genotypes were classified as exhibiting moderate water-use efficiency. Among them, CIMMYT genotypes 9630, 9741, 9671, 9625 and 9616 showed high grain yield under no-stress conditions (WYI > 1.05), but low grain yield under drought-stress conditions (DYI < 0.95), indicating that they were very sensitive to drought-stress. CIMMYT genotypes 9702 and 9669 showed high grain yield and drought yield index (DYI > 1.05) under drought-stress conditions. However, low grain yield and WYI (<0.95) were observed for these two genotypes under no-stress conditions.

**Relationships between grain yield and agronomic traits**

Significant negative correlations were obtained between grain yield and CT at the mid-grain filling stage, with coefficients of −0.440 and −0.494 (p < 0.001) for no-stress and drought-stress conditions, respectively (Table 5). At the mid-grain filling stage, CT also correlated significantly negatively with plant height, days to heading, spikelets per spike, spike length, grain number per spike and grain weight per spike under either irrigation regimes, and with thousand-grain weight but only under drought-stress conditions.

Grain yield was positively correlated with NDVI at the

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**Table 1. (continued)**

| Trait          | Source of variation | df  | Wald statistic | F value |
|----------------|---------------------|-----|----------------|---------|
| Spike length   | Genotype (G)        | 151 | 24.81          | 1.5***  |
|                | Irrigation treatment (I) | 1  | 52.10          | 3.3NS   |
|                | Year (Y)            | 1   | 1215.27        | 75.9*** |
|                | G × I               | 151 | 14.68          | 1.0NS   |
|                | G × Y               | 151 | 16.24          | 2.2NS   |
|                | I × Y               | 1   | 34.90          | 1.0NS   |
|                | G × I × Y           | 151 | 15.47          |         |
| SPS            | Genotype (G)        | 151 | 16.74          | 16.2*** |
|                | Irrigation treatment (I) | 1  | 1.3            | 1.1NS   |
|                | Year (Y)            | 1   | 7644.53        | 7386.7*** |
|                | G × I               | 151 | 0.86           | 0.8NS   |
|                | G × Y               | 151 | 2.40           | 2.3***  |
|                | I × Y               | 1   | 14.42          | 13.9*** |
|                | G × I × Y           | 151 | 0.77           | 0.7NS   |
| GNPS           | Genotype (G)        | 151 | 129.42         | 4.3***  |
|                | Irrigation treatment (I) | 1  | 17242.87       | 575.5*** |
|                | Year (Y)            | 1   | 35.47          | 1.2NS   |
|                | G × I               | 151 | 11016.32       | 367.7*** |
|                | G × Y               | 151 | 39.59          | 1.3*    |
|                | I × Y               | 1   | 4026.35        | 134.4*** |
|                | G × I × Y           | 151 | 26.80          | 0.9NS   |
| GWPS           | Genotype (G)        | 151 | 0.20           | 3.0***  |
|                | Irrigation treatment (I) | 1  | 107.78         | 1581.8*** |
|                | Year (Y)            | 1   | 0.10           | 1.1NS   |
|                | G × I               | 151 | 0.07           | 1.0NS   |
|                | G × Y               | 151 | 0.07           | 1.0NS   |
|                | I × Y               | 1   | 12.10          | 177.6*** |
|                | G × I × Y           | 151 | 0.06           | 0.9NS   |
| Days to heading| Genotype (G)        | 151 | 46.07          | 33.0*** |
|                | Irrigation treatment (I) | 1  | 1.35           | 1.0NS   |
|                | Year (Y)            | 1   | 5.02           | 3.6NS   |
|                | G × I               | 151 | 2.26           | 1.6***  |
|                | G × Y               | 151 | 5.27           | 3.8***  |
|                | I × Y               | 1   | 107.09         | 76.8*** |
|                | G × I × Y           | 151 | 1.57           | 1.1NS   |
| Plant height   | Genotype (G)        | 151 | 387.63         | 11.9*** |
|                | Irrigation treatment (I) | 1  | 80000.46       | 2457.1*** |
|                | Year (Y)            | 1   | 25697.52       | 789.3*** |
|                | G × I               | 151 | 77.61          | 2.4***  |
|                | G × Y               | 151 | 40.74          | 1.3*    |
|                | I × Y               | 1   | 18939.96       | 581.7*** |
|                | G × I × Y           | 151 | 37.04          | 1.1NS   |

*Significant at the 0.05 probability level, ** Significant at the 0.01 probability level, *** Significant at the 0.001 probability level, NS, non-significant at the 0.05 probability level.
Phenotyping and evaluation of wheat under two irrigation regimes

Under no-stress conditions, the correlation between NDVI and grain yield at the flowering stage was more significant than that at the jointing and mid-grain filling stages. At the jointing stage, NDVI was significantly correlated with plant height, days to heading, thousand-grain weight, spike length, spikelet number per spike, grain number per spike and grain jointing (correlation coefficients of 0.551 \( p < 0.001 \)), flowering (\( r = 0.543; \ p < 0.001 \)) and mid-grain filling stages (\( r = 0.249; \ p < 0.001 \)) in each of the two irrigation regimes. The correlation coefficients were more significant at the jointing and flowering stages than at the mid-grain filling stage under no-stress conditions. However, under drought-stress conditions, the correlation between NDVI and grain yield at the flowering stage was more significant than that at the jointing and mid-grain filling stages. At the jointing stage, NDVI was significantly correlated with plant height, days to heading, thousand-grain weight, spike length, spikelet number per spike, grain number per spike and grain jointing.

Table 2. Characteristics of a set of CIMMYT WPHYSGP nursery and local varieties in two regimes in 2011 and 2012 growing season at Changji, Xinjiang

| Trait                     | No stress condition | Stress condition |
|---------------------------|---------------------|------------------|
|                           | Av                  | Min              | Max              | Av                  | Min              | Max              |
| GY, kg/ha                 | 6440.8              | 3870.0           | 7995.0           | 3360.6              | 2066.0           | 4492.0           |
| TGW, g                    | 35.6                | 27.0             | 48.0             | 28.3                | 21.0             | 37.7             |
| Grain plumpness           | 4.4                 | 2.5              | 6.2              | 3.4                 | 1.8              | 5.0              |
| CT mid-grain filling, °C  | 22.2                | 21.3             | 23.4             | 24.9                | 23.0             | 27.2             |
| NDVI jointing             | 0.5153              | 0.3726           | 0.6439           | 0.4806              | 0.3259           | 0.6327           |
| NDVI flowering            | 0.8027              | 0.6433           | 0.9064           | 0.5565              | 0.3668           | 0.7068           |
| NDVI mid-grain filling    | 0.6619              | 0.5515           | 0.7808           | 0.3625              | 0.2646           | 0.4948           |
| SPAD flowering            | 52.5                | 44.7             | 61.3             | 54.0                | 49.0             | 61.8             |
| SPAD mid-grain filling    | 52.3                | 45.0             | 60.6             | 40.3                | 25.0             | 63.0             |
| Spike length, cm          | 7.8                 | 4.8              | 9.8              | 7.7                 | 5.1              | 9.8              |
| Spikelet per spike        | 14.4                | 9.4              | 17.6             | 14.1                | 10.3             | 17.4             |
| Grains per spike          | 33.9                | 15.4             | 48.3             | 26.5                | 16.1             | 37.2             |
| Grain weight per spike    | 1.2                 | 0.5              | 1.7              | 0.6                 | 0.3              | 1.1              |
| Days to heading           | 47.5                | 41.8             | 52.7             | 47.4                | 42.3             | 52.2             |
| Plant height, cm          | 80.7                | 57.0             | 101.3            | 65.0                | 45.5             | 82.0             |

Fig. 1. (A) The mean ± SD grain yield of 152 spring wheat genotypes under two irrigation regimes, T1 (no drought stress) and T2 (drought stress conditions) in 2011 and 2012. (B) The mean ± SD grain weight per spike, grain plumpness, grains per spike, TKW, plant height, spike length, spikelet per spike, days to heading, of 152 spring wheat genotypes under two irrigation regimes, T1 (no drought stress) and T2 (drought stress conditions) in 2011 and 2012. (C) The mean ± SD CT at grain filling stage, SPAD at flowering stage, SPAD at grain filling stage of 152 spring wheat genotypes under two irrigation regimes, T1 (no drought stress) and T2 (drought stress conditions) in 2011 and 2012. (D) The mean ± SD grain NDVI of 152 spring wheat genotypes under two irrigation regimes, T1 (no drought stress) and T2 (drought stress conditions) in 2011 and 2012. The different letters showed significant at the 0.05 probability level according to the ANOVA.
weight per spike under either irrigation regimes, and with grain plumpness under only drought-stress conditions. At the flowering stage, NDVI was significantly correlated with plant height, days to heading, spike length, spikelet number per spike and grain weight per spike under either irrigation regimes, and with thousand-grain weight and grain plumpness under drought-stress conditions. At the mid-grain filling stage, NDVI was significantly correlated with thousand-grain weight, grain plumpness, grain weight per spike and days to heading under drought-stress conditions. However, at the mid-grain filling stage, NDVI was correlated with days to heading only under no-stress conditions.

At the mid-grain filling stage, chlorophyll content (SPAD) was positively correlated with grain yield under drought-stress conditions. However, no correlation was observed between SPAD and grain yield at the flowering stage under drought-stress nor at the flowering or mid-grain filling stages under no-stress conditions. At the mid-grain

| Genotype Original GY in T1, kg/ha | Genotype Original GY in T1, kg/ha | Genotype Original GY in T1, kg/ha | Genotype Original GY in T1, kg/ha | Genotype Original GY in T1, kg/ha | Genotype Original GY in T1, kg/ha | Genotype Original GY in T1, kg/ha | Genotype Original GY in T1, kg/ha | Genotype Original GY in T1, kg/ha | Genotype Original GY in T1, kg/ha | Genotype Original GY in T1, kg/ha | Genotype Original GY in T1, kg/ha | Genotype Original GY in T1, kg/ha |
|---------------------------------|---------------------------------|---------------------------------|---------------------------------|---------------------------------|---------------------------------|---------------------------------|---------------------------------|---------------------------------|---------------------------------|---------------------------------|---------------------------------|---------------------------------|
| 9645 CIMMYT 7995 (1) 3811 (11) 9696 CIMMYT 6707 (51) 3077 (116) 9699 CIMMYT 6234 (99) 3841 (16) | Xinchun29 Local 7635 (2) 3793 (21) 9629 CIMMYT 6703 (52) 3386 (71) 9615 CIMMYT 6218 (100) 3297 (86) | Xinchun29 Local 7635 (2) 3793 (21) 9629 CIMMYT 6703 (52) 3386 (71) 9615 CIMMYT 6218 (100) 3297 (86) | Xinchun29 Local 7635 (2) 3793 (21) 9629 CIMMYT 6703 (52) 3386 (71) 9615 CIMMYT 6218 (100) 3297 (86) | Xinchun29 Local 7635 (2) 3793 (21) 9629 CIMMYT 6703 (52) 3386 (71) 9615 CIMMYT 6218 (100) 3297 (86) | Xinchun29 Local 7635 (2) 3793 (21) 9629 CIMMYT 6703 (52) 3386 (71) 9615 CIMMYT 6218 (100) 3297 (86) | Xinchun29 Local 7635 (2) 3793 (21) 9629 CIMMYT 6703 (52) 3386 (71) 9615 CIMMYT 6218 (100) 3297 (86) | Xinchun29 Local 7635 (2) 3793 (21) 9629 CIMMYT 6703 (52) 3386 (71) 9615 CIMMYT 6218 (100) 3297 (86) | Xinchun29 Local 7635 (2) 3793 (21) 9629 CIMMYT 6703 (52) 3386 (71) 9615 CIMMYT 6218 (100) 3297 (86) | Xinchun29 Local 7635 (2) 3793 (21) 9629 CIMMYT 6703 (52) 3386 (71) 9615 CIMMYT 6218 (100) 3297 (86) | Xinchun29 Local 7635 (2) 3793 (21) 9629 CIMMYT 6703 (52) 3386 (71) 9615 CIMMYT 6218 (100) 3297 (86) | Xinchun29 Local 7635 (2) 3793 (21) 9629 CIMMYT 6703 (52) 3386 (71) 9615 CIMMYT 6218 (100) 3297 (86) | Xinchun29 Local 7635 (2) 3793 (21) 9629 CIMMYT 6703 (52) 3386 (71) 9615 CIMMYT 6218 (100) 3297 (86) |

Table 3. Mean grain yield of 152 genotypes under no-stress conditions (T1) and drought-stress conditions (T2) averaged over the two growing seasons.
Table 4. Screening of 24 genotypes with the highest drought yield index (DYI), water yield index (WYI) and yield high water use efficiency index (YH-WUEI) over 1.05 averaged over the two growing seasons

| Genotype | Origin     | Plant height, cm in T1 | Plant height, cm in T2 | GY in T1, kg/ha | GY in T2, kg/ha | DYI | WYI | YH-WUEI |
|----------|------------|------------------------|------------------------|----------------|----------------|-----|-----|---------|
| 9645     | CIMMYT     | 91.74                  | 71.64                  | 7995           | 3881           | 1.15| 1.24| 1.20    |
| Xinchen29| Local      | 84.67                  | 68.62                  | 7635           | 3793           | 1.13| 1.19| 1.16    |
| 9611     | CIMMYT     | 95.98                  | 67.76                  | 7622           | 3815           | 1.14| 1.18| 1.16    |
| 9650     | CIMMYT     | 95.15                  | 71.07                  | 7574           | 3873           | 1.15| 1.18| 1.16    |
| 9637     | CIMMYT     | 91.23                  | 72.82                  | 7573           | 3798           | 1.13| 1.18| 1.15    |
| 9692     | CIMMYT     | 85.18                  | 64.79                  | 7322           | 4124           | 1.23| 1.14| 1.18    |
| 9638     | CIMMYT     | 87.09                  | 64.86                  | 7315           | 3894           | 1.16| 1.14| 1.15    |
| 9655     | CIMMYT     | 91.69                  | 68.89                  | 7300           | 3704           | 1.10| 1.13| 1.12    |
| 9606     | CIMMYT     | 85.38                  | 71.68                  | 7267           | 3875           | 1.15| 1.13| 1.14    |
| Xinchen23| Local      | 89.61                  | 69.56                  | 7264           | 3621           | 1.08| 1.13| 1.10    |
| 9639     | CIMMYT     | 85.82                  | 67.04                  | 7259           | 3605           | 1.07| 1.13| 1.10    |
| Xinchen11| Local      | 74.61                  | 58.11                  | 7149           | 3591           | 1.07| 1.11| 1.09    |
| 9729     | CIMMYT     | 90.01                  | 75.29                  | 7103           | 4052           | 1.21| 1.10| 1.15    |
| 9746     | CIMMYT     | 83.90                  | 68.52                  | 7085           | 3577           | 1.06| 1.10| 1.08    |
| 9622     | CIMMYT     | 100.75                 | 81.98                  | 7071           | 3629           | 1.08| 1.10| 1.09    |
| 9730     | CIMMYT     | 88.87                  | 70.08                  | 7054           | 3808           | 1.13| 1.10| 1.11    |
| 9642     | CIMMYT     | 77.20                  | 64.32                  | 7050           | 4169           | 1.24| 1.09| 1.17    |
| 9688     | CIMMYT     | 88.26                  | 69.58                  | 7038           | 3553           | 1.06| 1.09| 1.07    |
| 9646     | CIMMYT     | 85.87                  | 73.90                  | 7000           | 4262           | 1.27| 1.09| 1.18    |
| 9698     | CIMMYT     | 88.63                  | 67.16                  | 6942           | 3901           | 1.16| 1.08| 1.12    |
| 9627     | CIMMYT     | 90.66                  | 65.97                  | 6926           | 3853           | 1.15| 1.08| 1.11    |
| 9636     | CIMMYT     | 86.39                  | 68.24                  | 6822           | 3574           | 1.06| 1.06| 1.06    |
| 9644     | CIMMYT     | 90.90                  | 74.93                  | 6816           | 3791           | 1.13| 1.06| 1.09    |
| 9725     | CIMMYT     | 80.22                  | 69.65                  | 6767           | 3758           | 1.12| 1.05| 1.08    |

Genotypes are listed according to their ranking for mean grain yield under no-stress conditions.

filling stage, SPAD was also positively correlated with thousand-grain weight, grain weight per spike and days to heading. Significant positive correlations were obtained between grain yield and the traits plant height, days to heading, spike length, spikelet number per spike, grain number per spike, grain weight per spike, grain plumpness and thousand-grain weight.

Multiple linear regression analysis indicated that grain yield was significantly (p < 0.001) related to grain weight per spike, plant height and grain plumpness under the no-stress conditions (Fig. 2A). The three principal factors, grain weight per spike (r = 0.318; p < 0.001), plant height (r = 0.549; p < 0.001) and grain plumpness (r = 0.172; p < 0.001) explained 61.8% of the total phenotypic variation in grain yield under no-stress conditions in 2011 and 2012. Multiple linear regression analysis also found significantly (p < 0.001) relationships between grain yield and CT, plant height and grain plumpness under drought-stress conditions (Fig. 2B). The three principal factors, CT at the grain filling stage (r = 0.244; p < 0.001), plant height (r = 0.244; p < 0.001) and grain plumpness (r = 0.239; p < 0.001) together explained 44.8% of the total phenotypic variation in grain yield under drought-stress conditions in 2011 and 2012.

Discussion

CIMMYT hexaploid spring wheat germplasm has played a global role in assisting wheat breeding with respect to high yield potential and quality improvement (Bhatia et al. 2018, Wang et al. 2009, Zhang et al. 2011). We evaluated the drought-stress response of a set of WPHYSGP lines, introduced from CIMMYT, under the two different irrigation regimes during the 2011 and 2012 growing seasons. Based on yield, DYI, WYI, and YH-WUEI, 24 elite genotypes with high and stable yield under drought-stress and no-stress conditions were identified. In view of the demand for varieties of appropriate suitable plant height, 10 of these genotypes can be recommended as core parents for breeding for improved drought response in Xinjiang, China. The DYI, WYI and YH-WUEI were shown to be very useful for evaluating drought tolerance and to be powerful in identifying genotypes with high yield potential and high water-use efficiency as well (Li et al. 2006, Wu et al. 2005). Interestingly, three out of seven (43%) locally bred varieties were included in the 10 selected superior lines, compared with seven out of 145 (4.8%) CIMMYT lines.

In the present study, drought-stress was associated with a noticeable decrease in grain yield, plant height, grain number per spike, grain weight per spike, thousand-grain weight, grain plumpness, NDVI at the flowering and grain filling stages and chlorophyll content at the grain filling stage, and to an increase in CT and chlorophyll content at the flowering stage. Plant height and grain weight per plant generally exhibit above-average heritability and have been shown to be very sensitive to drought-stress, so could be recommended as selection criteria for drought-response improvement (Chen et al. 2012, Christopher et al. 2016). However, another study also showed that the yield components number of kernels per spike and thousand-grain
|       | GY       | TGW     | SPS     | SL      | SPAD-GF | SPAD-F | GP      | PH      | NDVI-GF | NDVI-F | NDVI-E | HD    | GWPS   | GNPS   |
|-------|----------|---------|---------|---------|---------|--------|---------|---------|---------|--------|--------|-------|--------|--------|
| **A** |          |         |         |         |         |        |         |         |         |        |        |       |        |        |
| TGW   | 0.450*** |         |         |         |         |        |         |         |         |        |        |       |        |        |
| SPS   | 0.512*** | NS      |         |         |         |        |         |         |         |        |        |       |        |        |
| SL    | 0.602*** | 0.229** | 0.824***|         |         |        |         |         |         |        |        |       |        |        |
| SPAD-GF | NS     | 0.284***| NS      |         |         |        |         |         |         |        |        |       |        |        |
| SPAD-F | NS      | 0.301***| NS      | 0.469***|         |        |         |         |         |        |        |       |        |        |
| GP    | 0.413*** | 0.546***| NS      | NS      | NS      |        |         |         |         |        |        |       |        |        |
| PH    | 0.740*** | 0.389** | 0.651***| 0.703***| NS      | 0.354***|        |         |         |        |        |       |        |        |
| NDVI-GF | 0.249** | NS      | NS      | NS      | NS      |        |         |         |         |        |        |       |        |        |
| NDVI-F | 0.543***| NS      | 0.658***| NS      | NS      | 0.645***| 0.440***|         |         |        |        |       |        |        |
| NDVI-E | 0.551***| 0.282***| NS      | 0.576***| NS      | 0.604***| NS      | 0.637***|         |        |        |       |        |        |
| HD    | 0.541*** | NS      | 0.700***| NS      | 0.734***| NS      | 0.728***| 0.339***| 0.770***| 0.639***|        |       |        |        |
| GWPS  | 0.567*** | 0.397***| NS      | 0.642***| 0.734***| 0.162* | 0.171*  | NS      | 0.512***| NS      | 0.471***| 0.382***| 0.491***|        |
| GNPS  | 0.316*** | -0.198* | 0.691***| 0.683***| NS      | -0.1791*| 0.342***| NS      | 0.409***| NS      | 0.238** | 0.509***| 0.716***|        |
| CT-GF | -0.440***| NS      | -0.424***| -0.477***| -0.209**| NS      | -0.532***| -0.275***| -0.535***| -0.439***| -0.512***| -0.291***| -0.222***|        |
| **B** |          |         |         |         |         |        |         |         |         |        |        |       |        |        |
| TGW   | 0.379*** |         |         |         |         |        |         |         |         |        |        |       |        |        |
| SPS   | 0.301*** | 0.369***|         |         |         |        |         |         |         |        |        |       |        |        |
| SL    | 0.300*** | 0.462***| 0.863***|         |         |        |         |         |         |        |        |       |        |        |
| SPAD-GF | 0.173* | 0.519***| 0.396***| 0.270***|         |        |         |         |         |        |        |       |        |        |
| SPAD-F | NS      | NS      | -0.242**| -0.251**| NS      |         |         |         |         |        |        |       |        |        |
| GP    | 0.489*** | 0.698***| 0.219***| 0.2448***| 0.388***| NS      |         |         |         |        |        |       |        |        |
| PH    | 0.494*** | 0.334***| 0.440***| 0.447***| NS      | -0.241**| 0.386***|         |         |        |        |       |        |        |
| NDVI-GF | 0.222** | 0.348***| NS      | 0.468***| NS      | 0.387***| NS      |         |         |        |        |       |        |        |
| NDVI-F | 0.442***| 0.492***| 0.542***| 0.539***| 0.369***| -0.287***| 0.417***| 0.426***| 0.474***|         |        |       |        |        |
| NDVI-E | 0.255***| 0.484***| 0.524***| 0.582***| 0.264***| NS      | 0.300***| 0.436***| NS      | 0.506***|        |       |        |        |
| HD    | 0.321*** | 0.562***| 0.735***| 0.687***| 0.503***| -0.2759*| 0.436***| 0.335***| 0.378***| 0.631***| 0.560***|        |       |        |
| GWPS  | 0.482*** | 0.463***| 0.590***| 0.634***| 0.385***| NS      | 0.411***| 0.252***| 0.249***| 0.424***| 0.252***| 0.435***|        |        |
| GNPS  | 0.268*** | -0.189* | 0.427***| 0.377***| NS      | NS      | NS      | NS      | NS      | NS      | NS      | NS      | 0.650***|        |
| CT-GF | -0.494***| -0.290**| -0.492***| -0.393***| -0.265**| NS      | -0.228**| -0.274**| -0.276**| -0.476**| -0.309**| -0.471**| -0.393***| -0.294***|

* Significant at the 0.05 probability level.
** Significant at the 0.01 probability level.
*** Significant at the 0.001 probability level.
NS, non-significant at the 0.05 probability level.
Phenotyping and evaluation of wheat under two irrigation regimes

Many studies have reported that chlorophyll content (measured here as SPAD) was positively correlated with yield under drought-stress conditions (Hamblin et al. 2014, Yıldırım et al. 2010). In our study, chlorophyll content at the grain filling stage was positively associated with yield under drought-stress conditions but not under no-stress conditions. Furthermore, chlorophyll content at the flowering stage was not associated with grain yield under either irrigation regime. The reason for this may be the result of the SPAD measurement affected by leaf glaucousness.

Cooler canopies have been associated with increased stomatal conductance and increased grain yield under irrigated conditions (Fischer et al. 1998) and with increased rooting depth and greater ability to extract moisture from deeper soil profiles under drought-stress conditions (Lopes and Reynolds 2010, Rutkoski et al. 2016). CT, dry weight stem⁻¹, grains spike⁻¹ and water-soluble carbohydrate concentration had high mean heritability and were recommended for use in selection for stress tolerance in plant breeding programs (Rattey et al. 2011, Stallmann et al. 2018). Lower CT was a trait that was proposed for breeding and early-stage selection, aimed at increasing genetic gain for grain yield in water-limited environments (Reynolds et al. 2009, Rutkoski et al. 2016). Our study confirmed that CT was negatively associated with grain yield under well-watered conditions as well as under drought-stress conditions. CT, especially at the grain filling stage, plant height and grain plumpness were the three principal factors associated with grain yield under drought-stress conditions.

NDVI has been used as a criterion to estimate relative biomass before heading (Reynolds et al. 2007) and the relative character of “stay-green” after flowering (Christopher et al. 2014). “Stay-green” traits may provide cumulative effects, together with other traits, which improve adaptation under stress conditions (Christopher et al. 2016, Lopes and Reynolds 2012). NDVI showed a positive relationship with

| Variables                | 95% CI          | P Value |
|--------------------------|-----------------|---------|
| TGW, g                   | 6.25-13.87      | 0.009   |
| Grain plumpness          | 0.25-3.68       | <0.001  |
| CT – grain filling, °C    | -64.70-24.37    | 0.374   |
| NDVI jointing stage      | 538.68-1839.56  | <0.001  |
| NDVI flowering           | 170.13-2822.54  | 0.026   |
| NDVI mid-grain filling   | 2015.86-3412.11 | <0.001  |
| SPAD flowering           | -16.45-21.24    | 0.002   |
| SPAD mid-grain filling   | -20.60-9.15     | 0.443   |
| Spike length, cm         | -16.33-2.56     | 0.153   |
| Spikelet per spike       | -6.89-7.77      | 0.101   |
| Grains number per spike  | -1.07-3.51      | 0.047   |
| Grain weight per spike   | -76.71-609.52   | <0.001  |
| Days to heading          | -70.66-37.70    | 0.001   |
| Plant height, cm         | 14.22-37.35     | <0.001  |

Fig. 2. Regression analysis between grain yield and other traits under no-stress (A) and drought-stress (B) in 2011 and 2012.

weight, and especially grain yield were even more sensitive to drought-stress than was plant height (Denečić et al. 2000, Mwadzingeni et al. 2016). Improvements in grain yield in recent years were often accompanied by increased thousand-grain weight (Feng et al. 2018, Singh et al. 2007, Stallmann et al. 2018). Our study showed that grain weight per spike, grain yield, NDVI at the flowering and grain filling stages, grain plumpness, grain number per spike, thousand-grain weight, plant height and CT were more sensitive to drought-stress than were NDVI at the jointing stage, spikelet number per spike, spike length and days to heading. Plants were watered at both jointing and heading stages of drought-stress, and spike development was completed before the heading stage, so drought-stress had little effect on NDVI at the jointing stage, spikelet number per spike, spike length and days to heading. The drought stress affected the growth of wheat after flowering stage, especially grain filling, thereby resulting in more change in grain weight per spike, grain yield, NDVI at the flowering and grain filling stages, grain plumpness, grain number per spike, thousand-grain weight, plant height and CT. Grain yield was negatively correlated with CT and positively correlated with plant height, grain number per spike, grain weight per spike, thousand-grain weight, grain plumpness, and NDVI. Low CT and high NDVI reflected better growth potential. The grain number per spike, grain weight per spike, thousand-grain weight and grain plumpness all reflected results of grain filling, so they were positively correlated with grain yield. We also found that grain weight per spike, plant height and grain plumpness were the three principal factors related to yield and could explain 61.8% of the total phenotypic variation of grain yield under no-stress conditions, so that grain weight per spike and grain plumpness could be used as selection indicator for high yield under stress conditions wheat breeding. Plant height was a key parameter affecting lodging and thus grain yield and grain quality, so the appropriate plant height was an important indicator for wheat breeding.

Many studies have reported that chlorophyll content (measured here as SPAD) was positively correlated with yield under drought-stress conditions (Hamblin et al. 2014, Yıldırım et al. 2010). In our study, chlorophyll content at the grain filling stage was positively associated with yield under drought-stress conditions but not under no-stress conditions. Furthermore, chlorophyll content at the flowering stage was not associated with grain yield under either irrigation regime. The reason for this may be the result of the SPAD measurement affected by leaf glaucousness.
grain yield under well-irrigated condition, with an even stronger association with grain yield under drought conditions (Christopher et al. 2016). In the present study, we found that NDVI in the jointing stage, the flowering stage and the mid-grain filling stage were all significantly positively correlated with yield under both no-stress and stress conditions.

Wheat drought tolerance is a complex quantitative trait and it is difficult to identify a single trait index which reflects both wheat yield potential and drought tolerance (Chen et al. 2012). Based on our study, plant height, grain number per spike, grain weight per spike, thousand-grain weight, grain plumpness, NDVI and CT could be recommended as indicators of drought tolerance improvement in spring wheat. Especially when breeding for improved varieties for cultivation in irrigated regions, more attention should be paid to screening for low values of CT and high values of grain weight per spike and grain plumpness, in combination with appropriate plant height in spring wheat breeding programs.

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