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OPTIMIZED TIMING OF USING CANOPY TEMPERATURE TO SELECT HIGH-YIELDING CULTIVARS OF WINTER WHEAT UNDER DIFFERENT WATER REGIMES

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SUMMARY

Selecting high-yielding cultivars under drought is an important practice to improve crop production. Canopy temperature (T) shows a relative reliable association with grain yield. In this study, we compared the suitability of canopy T and other agronomic as well as physiological traits associated with grain yield under different water regimes. Field experiments over two seasons (2011–2012 and 2012–2013) were carried out under three water regimes, represented about 64, 76 and 89% of potential evapotranspiration, with 16 local winter wheat (*Triticum aestivum* L.) cultivars in each season. Results showed that cultivars with higher yield usually performed consistently lower canopy T under three water regimes, while the relationships of grain yield with other agronomic or physiological traits were more influenced by soil moisture. In addition, the relationship between canopy T and grain yield varied with different growth stages: From the time of heading to early grain filling stages, a more significant negative linear relationship ($p < 0.001$) existed under the three irrigation levels.

ABBREVIATIONS

LWP: leaf water potential; canopy T: canopy temperature; Kernel Δ^{13}C: kernel carbon isotope discrimination; Pn: flag leaf photosynthesis; LAI: maximum leaf area index; NCP: north china plain; ET_0: daily reference evapotranspiration; ET_p: crop potential evapotranspiration; ET: seasonal evapotranspiration; WUE: water use efficiency; SC: lower stomatal conductance; δ^{13}C: carbon isotope composition of plant dry matter; K_c: crop coefficient; IRC: infrared camera; SLA: specific leaf area; HI: harvest index.

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INTRODUCTION

In recent years, water shortages have become more severe, restricting agricultural development. Latiri *et al.* (2010) has proved that, after the yield increase in 1960s, the rate of yield increase has been slowing down, and wheat sensitivity to drought is one of the main limiting factors. Simulated with cropping systems simulation model, Jalota *et al.* (2014) find that in mid and end century time slice of the 21st century, environment temperature and drought would increase, while yields of rice and wheat would decrease owing to shortening of crop duration. Many researchers indicate that improving water use efficiency (WUE) during grain development is one of the most important methods to solve this problem (Mei *et al.*, 2013; Tallec *et al.*, 2013; Wang *et al.*, 2013; Zhang *et al.*, 2013). WUE increases have been associated with increased grain yield, which comes from breeding of new cultivars or improved management practices. However, the breading of new cultivars played a more important role in improving crop production. Zhang *et al.* (2013) reported that yields from new cultivars increased by approximately 24.7% during the 1990s and by 52.0% during the last 12 crop years compared to yields during the 1980s in the North China Plain (NCP). Selection of drought-resistant cultivars could provide more opportunities to secure a stable yield and high WUE, especially under water-limited conditions. Simple and reliable methods are needed to assess the performance of different cultivars under drought.

A number of physiological traits have been used to assess drought resistance of crops. These traits include specific leaf area (SLA), stem water soluble carbohydrate, anthesis date, leaf water potential, crop canopy T and yield performance (Fischer *et al.*, 1998; Lilley and Fukai, 1994; O'Toole and Moya, 1978; Pantuwan *et al.*, 2001a, b).

Compared with direct selection for grain yield and other traits in breeding programmes, canopy T has larger genetic value as an indirect index to select certain types of cultivars, which is achieved via higher narrow-sense heritability and genetic correlation with yield (Pierre *et al.*, 2010; Rebetzke *et al.*, 2013). In addition, cooler plant surfaces may reflect a high rate of evapotranspiration in canopy (Amani *et al.*, 1996), which would result from a high water uptake ability through roots (Zhang *et al.*, 2004). Wheat cultivars with cooler canopies have a high cytokinin level in flag leaf, which increases photosynthetic duration and drought (Fang *et al.*, 2012). These characteristics are all necessary to ensure a better crop yield under drought conditions.

Canopy T of wheat can be influenced by the existence or shortness of organs; wheat canopy T with spikes is 2 °C higher than those without panicles under well-watered conditions (Olivares-Villegas *et al.*, 2007). Changes of leaf shape and orientation result in diversification of thermal distribution in field microclimates (Bingham *et al.*, 2012; Zhang *et al.*, 2011).

Thermal imaging technology provides an easy way to detect canopy T, especially the IRC has the following advantages: (i) thermal images in a selected area can be stored in pictures, which enable crop temperatures to be analysed overall and partially without a significant loss of quality; (ii) rapid measurement in field experiment reduces the potential impact of environmental changes and increases observation frequency during the optimum period and (iii) the effects of low-speed crosswinds are less apparent. Moreover, the high resolution of infrared picture enables organ T to be measured. Thus, the objectives of this study were (i) to compare the canopy T to other crop traits in indicating yield performance of different winter wheat cultivars, (ii) to determine the optimized time of using canopy T to assess yield performance of wheat cultivars and (iii) to analyse temperature characters of plant organs and their relationship with yield performances under different soil water regimes.

MATERIALS AND METHODS

Experimental site and design

Field experiments were conducted during the 2011–2012 and 2012–2013 growing seasons for winter wheat at the Luancheng Agro-Eco-Experimental Station of the Chinese Academy of Sciences, located in the NCP (37°53′ N latitude, 114°40′ E longitude, 50.1 m elevation). In each season, a total of 16 randomly selected winter wheat cultivars which had been released recently and purchased in local seed shops, were planted in plots under three irrigation applications. Five of the 16 cultivars were the same during the two seasons. 1 ha of uniform land was divided into three blocks for irrigation treatments. Each block was further divided into 64 plots with areas of 24 m^2. Wheat cultivars were randomly sown in the plots, with four replications. Three irrigation treatments were rain-fed treatment without irrigation during the growing period (W0), one irrigation treatment with 60 mm of water at the jointing stage (W1) and two irrigations treatment with 60 mm of water at the jointing stage and 65 mm of water at the anthesis stage (W2). These treatments were arranged to represent the deficit irrigated (W0), moderate deficit irrigated (W1) and full irrigated (W2) soil conditions that produced the maximum grain yield in a normal rainfall season in the NCP, based on the results from Zhang *et al.* (2008; 2013). The irrigation amount used in this study was to bring the top 1 m soil layer to 80–85% of field capacity.

Based on the definition of international soil classification system (Atterberg, 1905), soil at the station was a well-drained loamy soil with a deep soil profile that was considered highly suitable for crop production. In the 2 m profile, the average field capacity was 36% (v/v), and the wilting point was 11% (v/v). Cultivars were sown on October 1. Reviving began from the middle of March, jointing occurred at the beginning of April, and heading occurred near the end of April and the beginning of May. Harvests were in the middle of June. Plots were sown using a hand-operated seeder. Row spacing was 20 cm, and seeding rates were adjusted for each cultivar to achieve a density of 300 viable seeds m^{-2}. Fertilizer application was similar to the practices of local farmers. Before planting, diammonium phosphate at 450 kg ha^{-1}, urea at 150 kg ha^{-1} and potassium chloride at 150 kg ha^{-1} were broadcasted and incorporated. An additional 150 kg ha^{-1} of urea was top-dressed during the jointing stage in early April. Surface irrigation was applied using a low-pressure hose fitted with a flow metre to measure the volume of water applied to each plot.

Measurements

Weather conditions. Data of weather conditions came from an automatic weather station near the experimental field. Main weather factors, including air temperature, sunshine duration, humidity, wind speed, radiation and precipitation, were recorded every 5 minutes. Daily reference evapotranspiration (ET_0) was calculated with the crop–water programme developed with the FAO Penman–Monteith equation, which represented the definition of grass reference (albedo = 0.23, height = 0.12 m, surface resistance = 70 s m^{-1}) (Allen *et al.*, 1998) for winter wheat. Daily maximum temperature, minimum temperature, wind speed, radiation and relative humidity were main factors used in the calculation of ET_0. Crop potential evapotranspiration (ET_p) was calculated based on the equation of $ET_0 \times K_c$, where K_c was crop coefficient and its value was obtained from Liu *et al.* (2002). ET_p represented the crop water use under sufficient water supply.

Canopy and organ temperatures. For the replications of each treatment, thermal imaging was taken with a Thermo Shot F30 IRC (NEC Avio Technologies Co., Tokyo, JPN). Temperature measurements, which began at heading and ended at late grain filling, were taken daily from 11:00–12:00 local time on sunny days with an emissivity of 0.98 for the IRC. IRC was placed 50 cm above canopy at an angle of 30° to the horizon and 2.5 m away to obtain a view of the entire plot, which only took 3 seconds to make a thermal image. For all the replicates in this study, temperature investigation can be completed within 20 minutes, which minimized impacts of environmental changes.

Thermal images were analysed with assistant software (InfReC Analyzer NS9500 Lite software, NEC Avio Technologies Co., Tokyo, JPN), and temperature value for each cultivar under different irrigation treatments was averaged from four replications. Organ temperatures (T) of spike, flag leaf and pedicel were separately obtained from thermal images. At the late grain filling stage, thermal images included both canopy and soil temperatures due to leaf senescence. Bare soil and other non-plant parts were significantly hotter than vegetation (Luquet *et al.*, 2003). To separate the soil areas from those covered by plants, threshold values were determined visually by observed inflection points in the temperature density curves. The areas covered by plants were selected on the basis of the thresholds visualized.

Carbon isotope discrimination ($\Delta^{13}C$) in kernels and flag leaves. All the cultivars under three irrigation treatments were sampled for kernel $\Delta^{13}C$ at harvest using an Isotope Ratio Mass Spectrometer (Iso-prime 100 IRMS, Isoprime Co., UK) for both seasons. In the 2012–2013 season, flag leaves of all the cultivars under different treatments were also collected at early grain filling for $\Delta^{13}C$ analysis. Samples were oven-dried at 70 °C to constant weight and then pulverized into powder. Ground grains (1–2 mg) were passed through a mesh sieve with a particle size of 380 μm, packed with tin silver paper and then placed in the sample tray. Samples were sent to the Key Laboratory of Agricultural Water Resources, Chinese Academy of Sciences for $\delta^{13}C$ analysis. The $\Delta^{13}C$ values were expressed with the Pee Dee Belemnite international standards (Mohammadi *et al.*, 2012).

Agronomic and physiological traits. Dates at which 20, 50 and 80% of each crop reached certain morphological stages, especially the heading and anthesis stages, were recorded. Plant density was regularly measured. Physiological traits were assessed from heading to early grain filling. Leaf water potential, stomatal conductance (SC) and leaf photosynthetic rate were measured at midday on sunny days. Four flag leaves from each plot were sampled to measure leaf water potential with a ZLZ5 pressure chamber (produced by Lanzhou University, Lanzhou, China). The SC and photosynthetic rate (Pn) of four flag leaves were separately measured using a porometer (SC-1, Decagon Devices Co., USA) and gas exchange system (LI-6400, LI-COR Inc., USA). Dry matter accumulation and leaf area index (LAI) was investigated at over-wintering, jointing, booting, anthesis and mature stages for all cultivars. Thirty flag leaves were collected from each plot and their leaf area was measured using a leaf area meter (Li-3100C, LI-COR Inc., USA). Leaves were then oven-dried, and the dry weights were recorded. The ratio of leaf area to dry weight was calculated (SLA). At maturity, 80 plants from each plot were randomly selected, cut at the base and gathered to measure the seed numbers per spike, seed weight and harvest index (HI). Every plot was harvested with a plot combine harvester (NM-ELITE, Wintersteiger Inc., AT). The kernels were air-dried to the moisture content of 13%, and the weight was recorded.

Soil moisture and water use efficiency (WUE). Soil volumetric water contents were monitored every 10 days in 20 cm increments to a depth of 2 m using a neutron metre (503 DR, CPN International Inc., USA). The access tubes were installed in the centre of six plots for each irrigation level to monitor soil water dynamics. Soil moisture remained the same at sowing for all treatments. At harvest, three plots for each cultivar under each irrigation treatment were sampled by taking soil cores to assess soil water depletion down to 2 m. The total water use (seasonal evapotranspiration, ET) for wheat was calculated under different irrigation treatments as the initial soil water content minus the final soil water content (ΔW), precipitation (P), irrigation (I), runoff (R), drainage (D) and capillary rise (CR) using the following equation: $ET = P + I + \Delta W - R - D + CR$. Runoff and drainage were zero because the irrigation and rainfall amounts were small during the growing season of winter wheat. Capillary rise was negligible due to the deep groundwater level (40 m below soil surface). WUE was defined as crop yield divided by total water use.

Statistical analysis

Data for each cultivar was statistically analysed with ANOVA by the general linear model procedure to calculate the effects of water regime on the studied parameters. Least significant differences (LSD) test ($p < 0.05$) was calculated. A correlation analysis was conducted to relate the grain yield and canopy T using the SPSS statistical package (Version 13, IBM Co., USA) and Microsoft Office Excel 2007 software.

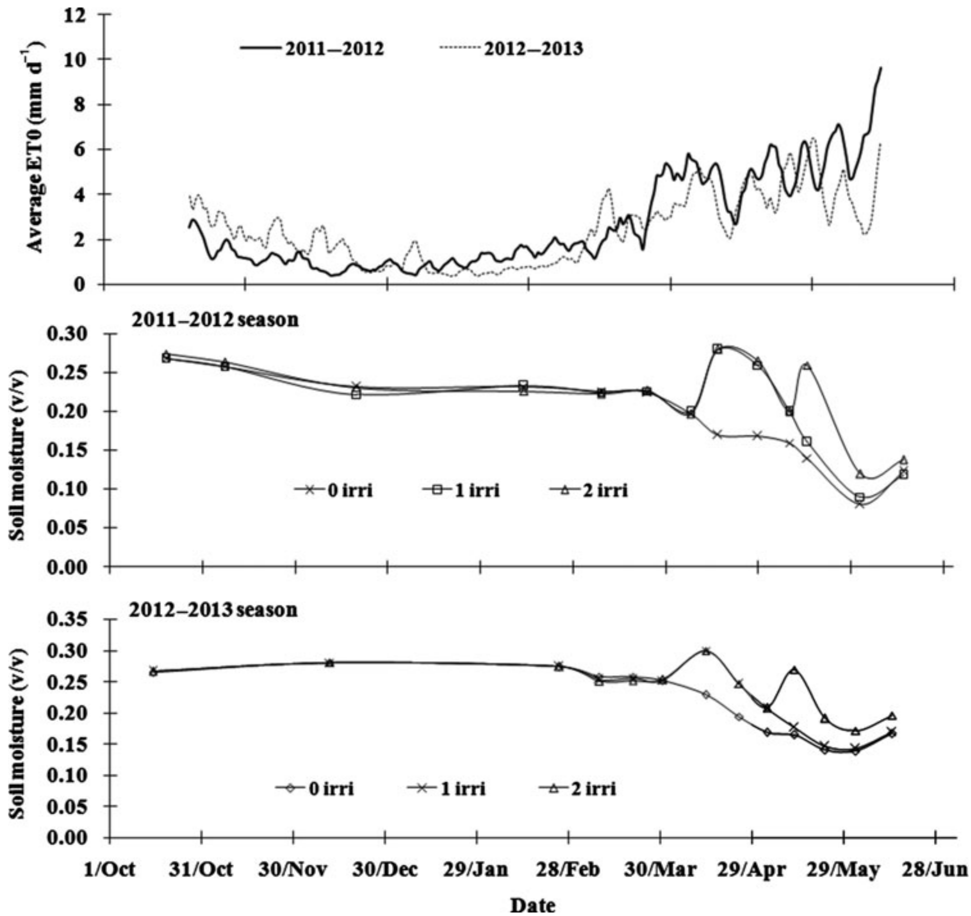

Figure 1. The 5 days' average daily atmospheric evaporation demand (ET_0) and average soil water contents for the top 1 m soil profile during the two growing seasons of winter wheat.

RESULTS

Soil moisture change and seasonal crop ET during the two growing seasons

Before sowing, soil moisture was usually good in the NCP due to rainfall in the summer season. Winter wheat used little soil moisture during its earlier growing stages (Figure 1). When wheat entered the rapid growing stage from jointing to early grain filling (from the beginning of April to the middle of May), canopy size as well as atmospheric evaporation increased greatly. The increased crop water use and evaporation resulted in a sharp decrease in soil moisture (Figure 1). So water deficits in the NCP usually occur at the rapid growth stages for winter wheat (Zhang *et al.*, 2013).

The average seasonal ET_p was 490 mm in 2011–2012 and 436 mm in 2012–2013. The average seasonal ET was 317.9 mm for W0, 389.4 mm for W1 and 445.1 mm for W2 in 2011–2012. Average ET was 277.7 mm for W0, 320.9 mm for W1 and

Table 1. Average seasonal evapotranspiration (ET) under three irrigation treatments for wheat cultivars during the two growing seasons†.

	2011–2012 season		2012–2013 season	
Irrigation treatments	ET (mm)	ET/ET_p	ET (mm)	ET/ET_p (%)
W0	317.9±27.8	64.9%	277.7±14.6	63.7%
W1	389.4±20.2	79.5%	320.9±15.4	73.6%
W2	445.1±22.4	90.8%	381.2±15.0	87.4%

†ET_p was the potential evapotranspiration calculated based on the reference ET multiplied by crop coefficient (ET_p = 490 mm in 2011–2012 and ET_p = 432 mm in 2012–2013). Values after '±' were the deviation in ET among the 16 cultivars of each season.

381.2 mm for W2 in 2012–2013 (Table 1). During the two seasons, rainfall and stored soil moisture before sowing accounted for 65–67% of the ET_p under W0. Adding one irrigation increased seasonal ET to 74–80% of the ET_p under W1, and adding one more irrigation increased seasonal ET to 87–90% of the ET_p under W2 find that the highest yield of winter wheat can be achieved under a ratio of ET/ET_p around 0.86 in the NCP (Zhang *et al.*, 2008). Therefore, W2 treatment was considered as full irrigated with the highest grain yield in the NPC.

Grain yield and WUE of different cultivars under three water regimes

Grain yield for wheat cultivars was shown in Figure 2. The average yields of cultivars in 2011–2012 were 4611.9 for W0, 5775.6 for W1 and 6180.3 kg ha^{-1} for W2. In the 2012–2013 season, average yields were 4566.0 for W0, 5174.4 for W1 and 6381.6 kg ha^{-1} for W2. There were significant yield increases in W1 and W2 treatments. One irrigation improved yield by 25% in 2011–2012 and 7% in 2012–2013. Two irrigations increased the yield by 13% in 2011–2012 and 23.3% in 2012–2013. Due to the seasonal difference in rainfall distribution, the one irrigation in the 2011–2012 season substantially increased the grain yield more than two irrigations. However, in the 2012–2013 season, the second irrigation improved grain yield more than the first irrigation did.

In the 2011–2012 season, the average WUE of wheat were 1.45 for W0, 1.49 for W1 and 1.40 kg m^{-3} for W2, which were lower than the average values of 1.65, 1.62 and 1.68 kg m^{-3} for the 2012–2013 season under three irrigation treatments. The results showed that winter wheat consumed more water in seasons with a higher atmospheric evaporation demand, as ET_p was 490 mm in 2011–2012 while 436 mm in 2012–2013 season. The higher atmospheric evaporation demand usually resulted in lower WUE.

In Figure 2, the yield differences among cultivars were up to 33% under W0, 35% under W1 and 31% under W2, which showed the importance of selecting a high-yielding cultivar adapted to drought. Figure 2 also showed that wheat responses to irrigation slightly varied by cultivars. Some cultivars produced relative greater grain yields under rain-fed conditions and showed no significant improvements under irrigation, such as cultivar S15 in 2011–2012, while other cultivars performed better

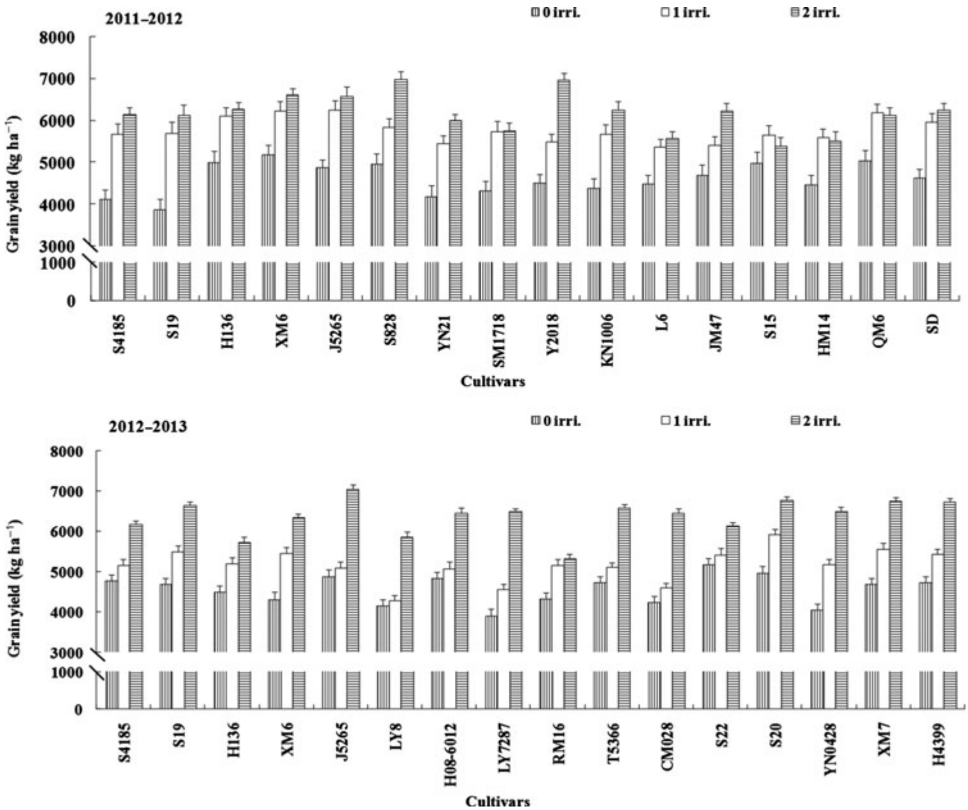

Figure 2. Grain yield of different winter wheat cultivars under three irrigation treatments in two growing seasons.

with more irrigation applications than they did without irrigation. However, the significant positive relationship ($p < 0.01$) for grain yield in the 2012–2013 season showed that cultivars giving a higher yield under rain-fed conditions usually produced higher yields under irrigation and vice versa (Figure 3). This result was similar in 2011–2012 season. In Figure 2, five cultivars (S4185, S19, H136, XM6, J5265) were used during the two seasons. J5265 showed a higher yield above 4900 kg ha^{-1} under irrigation as well as no irrigation in two seasons, while the yield performances of S4185 and S19 changed greatly under different irrigation treatments and growing seasons. This result enabled the selection of a better cultivar that would give a constant yield performance with or without irrigation in the NCP.

Agronomic and physiological traits associated with grain yield of different cultivars

Correlation analysis of the grain yield with the yield components showed that seed number per spike and HI played an important role in the yield performance of wheat cultivars (Table 2). Biomass and seed weight were only related to the yield under relatively good soil moisture conditions ($p < 0.05$). Therefore, to ensure better yields of winter wheat in the NCP under water stress conditions, cultivars with greater seed

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Table 2. The average values of agronomic traits of wheat cultivars and their relationship with grain yield in two growing seasons.

Seasons	Treatments	1000 seed weight (g)	Seed numbers per spike	Spikes m^{-2}	Biomass per plant (g)	Harvest index (HI)
2011–2012 Season	W0	33.44	22.91*	850.9*	173.6	0.421**
	W1	34.31	23.54*	1075.7	180.23	0.418*
	W2	36.42*	23.22*	1099.8	189.88*	0.442*
2012–2013 Season	W0	24.79	22.92*	773.7	87.19	0.351*
	W1	24.96	24.11*	794.4*	90.50*	0.336*
	W2	29.22*	26.49*	770.9	120.17*	0.391*

*significant at $p < 0.05$; **significant at $p < 0.01$; not specified: no significant relationship.

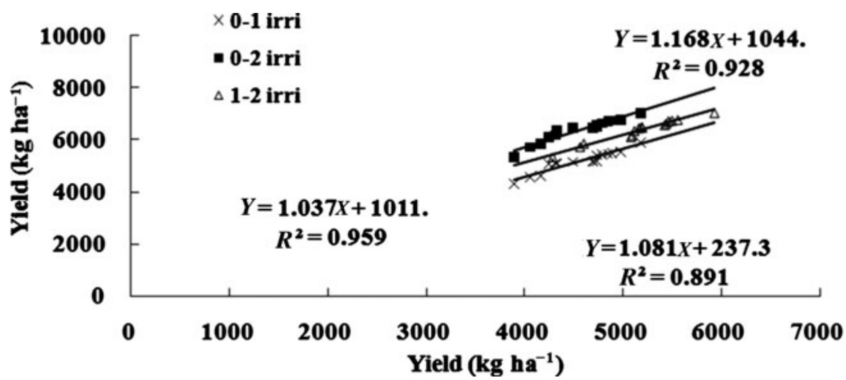

Figure 3. The relationship of grain yield of the 16 cultivars under different irrigation treatments in 2012–2013 season (0–1 irri was the yield relation of no irrigation with one irrigation, 0–2 irri was no irrigation with two irrigations and 1–2 irri was one irrigation with two irrigations).

numbers per spike and higher HI value should be given top priority. A significant positive relationship between HI and WUE was also found, indicating that cultivars with higher HI value also used water more efficiently. This could be a good trait for selecting cultivars adapted to drought stress.

In Table 3, the results showed that under dry conditions (i.e., without irrigation), cultivars with larger LAI values and canopy sizes tended to produce higher yields, while under relatively good soil moisture conditions, the canopy size may not be a limiting factor, and other physiological features were more important. In Figure 4, a similar relationship was found between kernel $\Delta^{13}C$ and the average soil moisture condition for the two growing seasons, as the kernel $\Delta^{13}C$ increased with the increase of irrigation, and a higher kernel $\Delta^{13}C$ was related to a higher yield of cultivars. Table 3 showed that $\Delta^{13}C$ had a strong relationship with grain yield under much drier conditions (W0), while the relationship disappeared as the irrigation amount and frequency increased. Further analysis of cultivars' agronomic and physiological traits showed that, no consistent relationship under the three irrigation strategies existed between the yield performances and leaf water potential, Pn, LAI, SLA, kernel and leaf $\Delta^{13}C$ or the anthesis date (Table 3). Only canopy T after heading had a constant

Table 3. Correlation analysis of some agronomic and physiological traits with the final grain yield of winter wheat cultivars in two seasons†.

Seasons	Treatments	LWP	Tc	Leaf $\Delta^{13}C$	Kernel $\Delta^{13}C$	Pn	LAI	Anthesis date	SLA
2011–2012 Season	W0	NS	**		*	NS	**	*	NS
	W1	NS	**		NS	*	NS	NS	NS
	W2	*	**		NS	*	NS	NS	NS
2012–2013 Season	W0	*	**	**	**	NS	*	NS	NS
	W1	*	**	*	*	*	NS	NS	NS
	W2	*	**	NS	NS	*	NS	*	NS

†LWP: leaf water potential; Tc: average canopy temperature; Kernel $\Delta^{13}C$: kernel carbon isotope discrimination; Pn: flag leaf photosynthesis; LAI: maximum leaf area index; SLA: specific leaf area; *significant at $p < 0.05$; **significant at $p < 0.01$; NS: no significant relationship. Tc and Pn were taken during heading stage.

significant relationship with the grain yield under three irrigation treatments in 2011–2012 and 2012–2013.

The relationship of grain yield with canopy T among the cultivars

The relationship between canopy T and grain yield under different irrigation strategies. A significant negative linear relationship was found between the canopy T and grain yield under all treatments, as shown in Figure 5. Without irrigation, canopy T increased significantly from heading to anthesis and then slightly increased again at late grain filling (Figure 5a). Rapid decrease in soil moisture reduced the transpiration rate, and hence the canopy T increased. With the irrigation application in Figure 5b, canopy T increased gradually from heading to late grain filling as the atmospheric T increased. Figure 5a and Figure 5b also showed that the relationship between canopy T and grain yield was similar at heading, anthesis and grain filling stages with and without irrigation. Canopy T could be used as an indicator of grain yield for wheat cultivars under different water conditions.

The timing of canopy T measurement to assess the performance of winter wheat. Canopy T was affected not only by the soil water availability but also by the atmospheric conditions. Under low atmospheric T and good soil moisture conditions, canopy T was usually lower and the difference among cultivars was smaller. Figure 5d showed that around the jointing stage in 2012–2013, the canopy T was similar for all the cultivars, and no relationship existed between the canopy T and grain yield. It was only around the heading stage that significant relationship between the canopy T and yield occurred. Figure 5c showed that in the 2011–2012 season, cultivars' canopy T differences existed around the heading stage, and the significant differences also occurred later. This result was mainly because during reviving and jointing, the atmospheric temperature and ET_0 were lower, which meant the transpiration rate was smaller. Figure 1 showed that from reviving to jointing, the soil moisture conditions were relatively good for these irrigation treatments and canopy T values were similar among the cultivars. As the ET_0 and crop transpiration rate increased, decreased soil water content resulted in

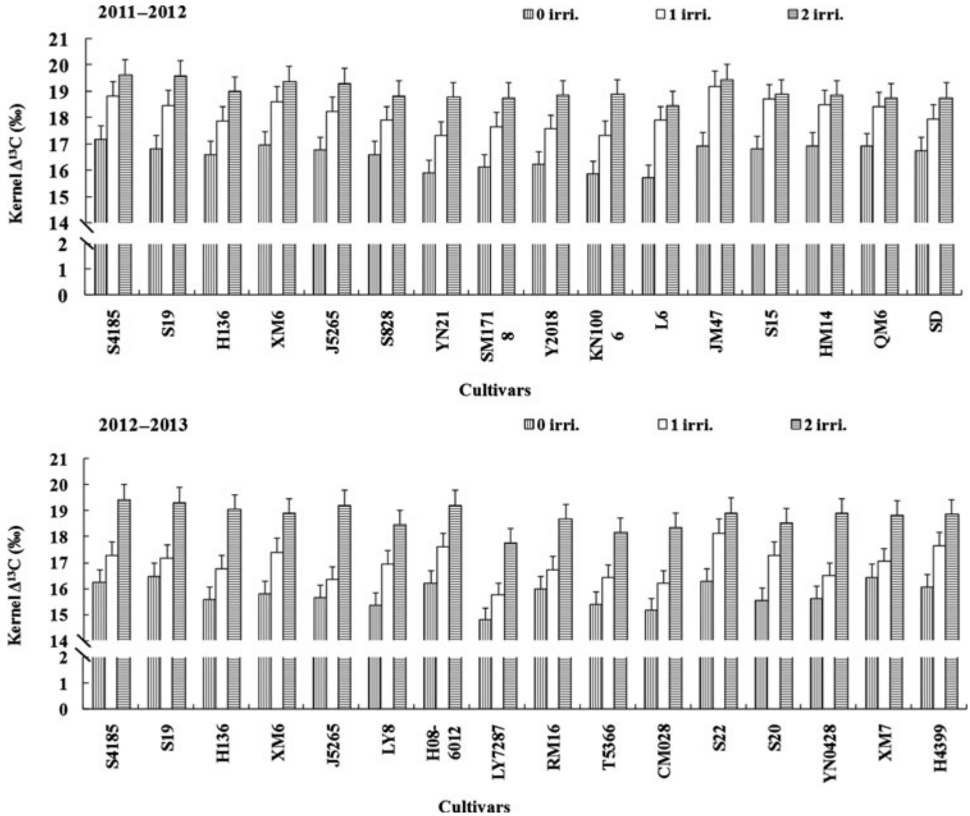

Figure 4. Kernel carbon isotope discrimination (Kernel $\Delta^{13}C$) of different winter wheat cultivars under three irrigation treatments in two growing seasons.

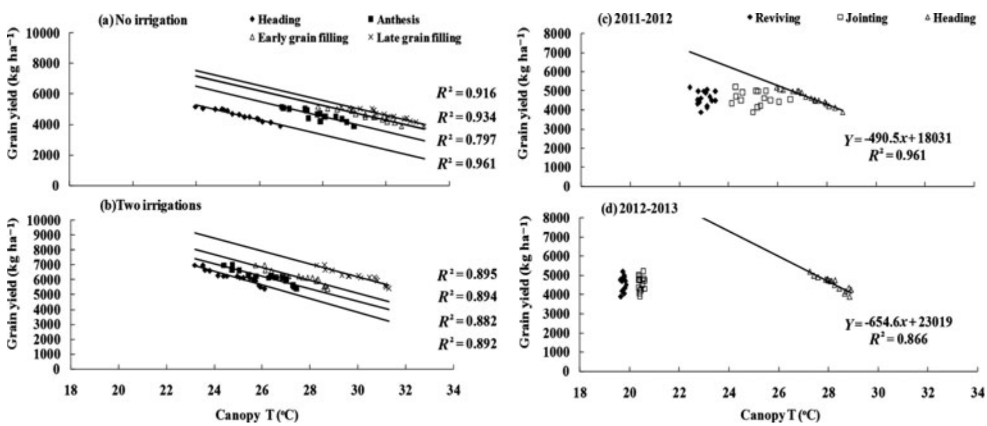

Figure 5. The relationship of canopy temperature (T) measured at heading, anthesis, early grain filling and late grain filling stages with the grain yield of wheat cultivars under no irrigation (a) and two irrigation (b) conditions in 2011–2012 season; the relation of canopy T with grain yield at reviving, jointing and heading stages during 2011–2012 (c) and 2012–2013 (d) seasons under no irrigation condition.

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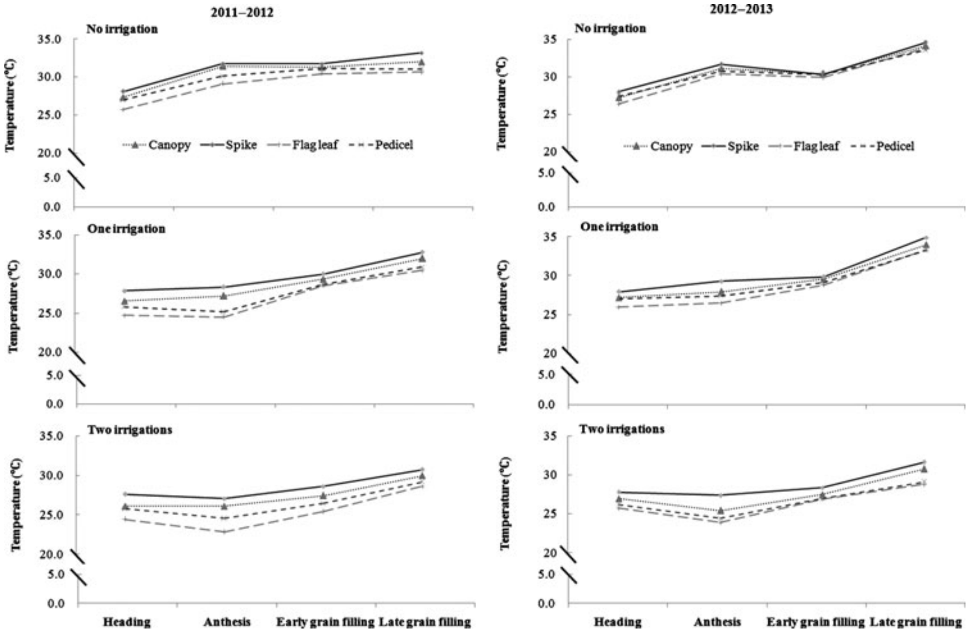

Figure 6. Temperature (T) of canopy and individual organs for wheat cultivars at four growing stages in 2011–2012 and 2012–2013 seasons (T was the average value of wheat cultivars measured during mid-day in sunny days).

drought stress. As a result, some cultivars showed different ability to maintain relatively high transpiration rates and, subsequently, relatively higher leaf photosynthesis rate. For these cultivars, there existed a significant relationship between canopy T and grain yield from the heading stage, so the optimized timing of canopy T measurement was also important. Therefore, the heading or early grain filling stage might be a good time of using canopy T to assess cultivars' yield performance.

Relationship of organ temperatures with grain yield. Figure 6 showed that differences among the temperatures (T) of flag leaf, spike and pedicel were large. The flag leaf T was always the lowest, while the spike T was the highest with or without irrigation, indicating that leaves transpired more water and thereby reduced their T values. The T of flag leaf and pedicel were similar under the W0 and W1 treatments, while the difference was apparent under W2. Canopy T was higher than the T of flag leaf and pedicel.

Since there was a significant temperature difference in organs, their relationships with grain yield were different too (Figure 7). Under no irrigation treatment (Figure 7a), the relationship between canopy T and grain yield was the strongest ($R^2 = 0.9618$), followed by the flag leaf T ($R^2 = 0.5706$). No significant relationship was found between grain yield and pedicel or spike T. However, both the canopy and organs T under relatively good water conditions had strong relationships with the grain yield (Figure 7b). These results indicated that plant organs responded to water stress differently, and water stress affected the spike or pedicel T less than leaf T. Given

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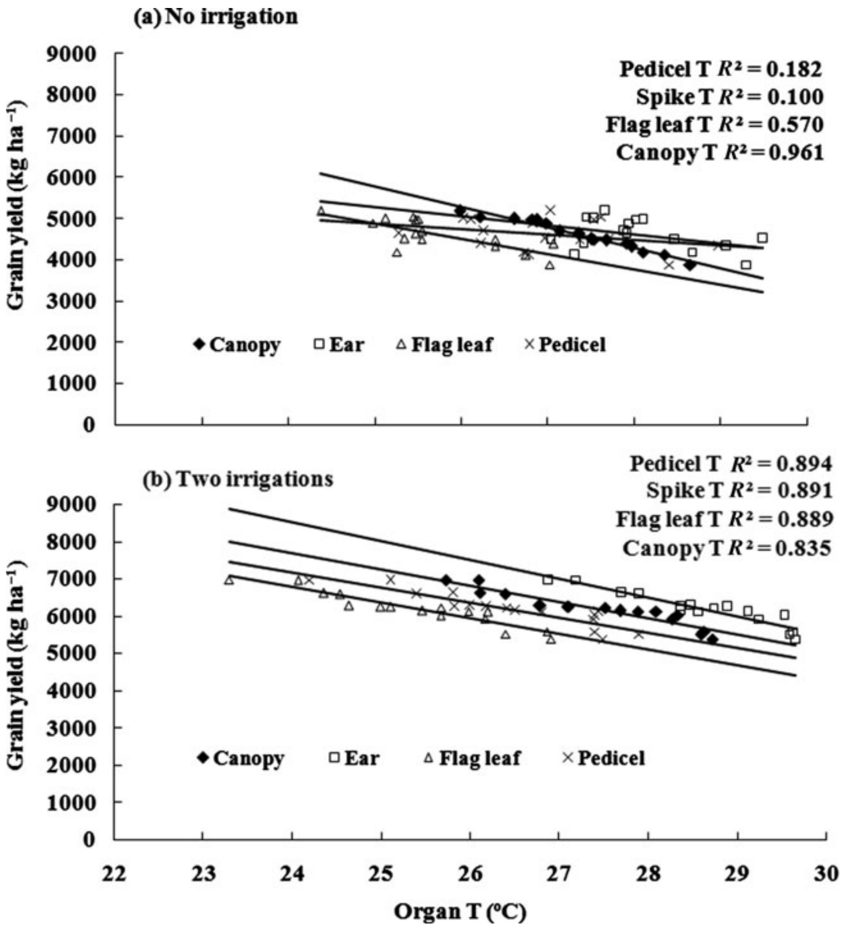

Figure 7. The relationship between organ temperature (T) at heading (flag leaf, spike, pedicel and canopy T) and the grain yield of wheat cultivars under no irrigation (a) and two irrigation (b) applications in 2011–2012 season.

the varying responses of different cultivars to water stress, canopy T as the average T of organs was more reliable. Thus, under different water regimes, canopy T was a better indicator of yield performance.

DISCUSSION AND CONCLUSIONS

Improving genetic potential is essential to further yield increase (Rijk *et al.*, 2013). Results showed yield differences of up to 33% among winter wheat cultivars tested in this study. Therefore, selecting certain cultivars adapted to local environment could increase yield potential of farmland. Singh *et al.* (2014) find that varieties released by plant breeders are most productive under ideal conditions, while they are often not suitable for marginal farm conditions. Compared with the direct selection for grain yield alone in breeding programmes, canopy T has larger genetic value as an indirect index to select certain types of cultivars, which could be achieved via

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higher narrow-sense heritability and genetic correlation with yield (Rebetzke *et al.*, 2013).

Results showed that high yields were correlated with high photosynthetic rates as well as leaf water potentials under irrigated conditions, while the relationship was much weaker under water deficit conditions. In contrast, the grain yield under rain-fed conditions was more strongly correlated with canopy size trait (LAI), because cultivar differences in canopy structure could be neglected if the soil water content was sufficient during the fast-growth stage, whereas drought stress could restrict the canopy development of drought sensitive cultivars.

In addition, physiological traits such as Pn, leaf water potential and LAI did not show such constant relationships with grain yield. Some traits were only related to yield under certain drought conditions; for example, the leaf and kernel $\Delta^{13}C$ were only related to grain yield under no irrigation treatment. This relationship disappeared as the soil water conditions improved. Previous studies have found that a decrease in the $\Delta^{13}C$ can be explained by a greater photosynthetic capacity (Pn), a lower SC or a combination of the two factors (Condon *et al.*, 2004; Farquhar *et al.*, 1989). Under serious drought conditions, higher SC indicated that plant could absorb soil water more effectively, and hence $\Delta^{13}C$ was positively related to the grain yield. While under good soil moisture conditions, increases in Pn and SC both resulted in a decrease in productivity and an increase in $\Delta^{13}C$. Thus, the relationship between $\Delta^{13}C$ and grain yield was not significant.

Previous studies have shown weak crop genotype differences for canopy T under full water supply conditions (Hede *et al.*, 1999; Mahan *et al.*, 2012; Rehman *et al.*, 2011). For spring wheat, there is a significant relationship between the canopy T and yield under moisture-stress conditions (Rashid *et al.*, 1999), which is in accordance with the results of Ayeneh *et al.* (2002) and Balota *et al.* (2007; 2008).

Results from this study showed that canopy T was significantly correlated with the grain yield of different cultivars with or without irrigation. This relationship was stable and consistent after heading. However, during the earlier growing period of winter wheat, no significant relationship was found between the canopy T and grain yield. This result was mainly attributed to the relatively good soil moisture conditions, low atmospheric T and leaf transpiration rates before heading, which resulted in less cultivar difference in canopy T. From heading to late grain filling, the high atmospheric evaporation demand and limited soil water supply resulted in different canopy T performances. A significant relationship between canopy T and yield was found at this period, which also reflected their resistance to drought stress.

By analysing thermal images, this study analysed organ T distribution and the relationship with yield performance, especially under different soil water conditions. The results also proved the differences among canopy T and organ T. Plant leaf usually had a lower T than other organs due to its high transpiration rate. Under no irrigation treatment, there was a significant relationships between canopy T and grain yield. Under relatively good soil moisture conditions, there was a significant relationship of grain yield with organ T, similar to canopy T. Thus, canopy T can be considered as representation of all the organs and should be used to assess the performance of different breeding lines.

Based on the more stable association between canopy T and grain yield, this study confirmed canopy T as a suitable selection index for winter wheat cultivars in field conditions. Under sufficient water supply, plant organ T was also significantly correlated with grain yield. In addition, this research confirmed that canopy T measurement should be taken during the reproductive growth stages rather than vegetative growth period to increase the accuracy of assessment.

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