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Optimizing Center Pivot Irrigation to Regulate Field Microclimate and Wheat Physiology under Dry-Hot Wind Conditions in the North China Plain

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Abstract: The dry-hot wind climate is one of the major agro-meteorological disasters associated with high temperature, low humidity, and specific wind forces, which seriously affects the yield of wheat in the North China Plain. A field experiment was conducted to investigate the field microclimate, net photosynthetic rate, chlorophyll content of flag leaves, grain filling rate, and wheat yield after sprinkler misting under the condition of a dry-hot wind climate in the 2018 and 2019 seasons. Two travel speeds, full and half speed, and the corresponding irrigation amounts of 2.5 and 5 mm were used by a center pivot irrigation system during dry-hot wind conditions. A treatment without irrigation was applied as a control. The results showed that the air temperature and relative air humidity were greatly improved within 60 min after irrigation, especially in the upper part of the canopy. The net photosynthetic rate of flag leaves under 5 mm irrigation was higher than that under 2.5 mm irrigation during the middle and late grain filling periods. The adverse effects of dry-hot wind on the chlorophyll content of the flag leaves were mainly concentrated in the late grain filling stage. In the two years of the experiment, the average 1000-grain weights of 5 and 2.5 mm of irrigation treatments were 4.3 and 2.8% higher, and the grain yields were 5.8 and 3.3% higher, respectively, than those of the non-irrigated yields. Overall, applying a small amount of water between 12:00–14:00 with a center pivot before the occurrence of dry-hot wind is an effective means to regulate the field microclimate and produce more yield in the North China Plain.

Keywords: sprinkler irrigation; dry-hot wind; winter wheat; grain yield; center pivot; microclimate

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1. Introduction

Global warming is causing an increasing amount of extreme weather and climate events, which seriously affects agroecosystems and causes increased instability in agricultural production [1]. According to records, the frequency of dry-hot wind occurrence has been increasing recently in China due to climate warming [2]. Dry-hot wind events are characterized by maximum day temperatures greater than 30 °C, relative humidity less than 30%, and a wind speed greater than 3 m s^{-1} at approximately 14:00 local time in the North China Plain [3,4]. The most concentrated period of dry-hot wind is from mid and late May to early June in the North China Plain, during which winter wheat (*Triticum aestivum* L.) is in the anthesis and filling stage [5]. Based on agronomic statistics over decades, dry-hot wind can cause a significant large-area yield reduction of 5–10%

in general years and up to 20–30% in seriously occurring years [6]. It is theoretically and practically necessary to study the damage mechanism and defense measures of dry-hot wind in the North China Plain.

In the past several decades, many studies have been conducted to investigate the effects of dry-hot wind on wheat physiological functions and disaster losses. Dry-hot wind stress affects the chlorophyll contents of wheat leaves, resulting in a sharp decrease in the photosynthesis process and impacting the normal function of the cell membrane system [7,8]. Furthermore, dry-hot wind stress has an adverse effect on the grain formation phase, root respiration, and water absorption capacity, which often directly affects the growth of grain weight, resulting in a reduction in 1000-grain weight [2,9,10].

In open fields, the evaporation of droplets and canopy interception during the sprinkler irrigation process enhance field humidity and decrease air temperature. Therefore, water spraying has become an effective way to regulate field microclimates [11]. By investigating the long-term effect of sprinkler irrigation on the microclimate in a winter wheat field, the reduction in the difference in air temperature values, vapor pressure deficiencies, and pan evaporation in the sprinkler-irrigated field in comparison with surface irrigated field was higher when it was hot, dry, and windy, with episodes of concentrated precipitation [12]. An increase in the photosynthesis rate and a reduction in the leaf respiration rate at night have also been found in sprinkler-irrigated areas [13,14]. Under dry-hot wind conditions, a study found that effectively applying approximately 1.0–1.5 mm of water for each event improves the field microclimate and regulates canopy temperature [15]. However, there is still a lack of research on temperature and humidity changes in the inner and upper canopies of wheat after sprinkler irrigation and its comprehensive effects on photosynthetic rate, chlorophyll, and grain filling rate under dry-hot wind conditions.

Among the common types of sprinkler irrigation systems, the center pivot irrigation system offers several advantages, such as a high degree of automation, high water application efficiency, and reduced environmental pollution [16,17]. Due to these factors, including the development of scaled agricultural production and land use intensification in China, the application of center pivot irrigation systems has been increasingly popularized [18,19]. Therefore, it is necessary to determine the most suitable irrigation amount, timing, and their impacts on wheat growth and yield using center pivots under dry-hot wind conditions.

The objectives of this field study were to (1) quantify the air temperature and relative air humidity regulation range in the inner and upper canopies of wheat after applying a small amount of water; (2) explore the effects of sprinkler misting on the leaf photosynthetic rate, chlorophyll content and grain filling rate under dry-hot wind conditions; and (3) determine the optimal irrigation amount and appropriate time under a center pivot irrigation system for higher grain yield of winter wheat.

2. Materials and Methods

2.1. Research Site

The experiment was conducted from May to June in 2018 and 2019 at the Tongzhou Experimental Station of China Agricultural University (Beijing, China; 39°41′59″ N, 116°41′01″ E; 21 m altitude), located in the North China Plain. The climate is a typical temperate continental semi-humid monsoon climate with a summer precipitation pattern. The mean annual temperature is 11.3 °C, and the average precipitation is 620 mm, mainly distributed from June to September. According to the USDA texture scheme, the soil type in the 0–100 cm profile is sandy loam. The average bulk density in the 0–20 cm profile measured using a 100 cm^3 ring was 1.45 g cm^{-3}, and the average field capacity measured by the in situ test was 0.31 cm^3 cm^{-3}. Prior to the 2018 season, the nutrient availability in the top 20 cm of soil with a pH of 8.2 contained 12.3 g kg^{-1} organic matter, 40.5 mg kg^{-1} available phosphorus, and 168.9 mg kg^{-1} available potassium. The soil in the experimental plot was homogeneous, and the land was leveled before sowing.

2.2. Experimental Design

Winter wheat (Nongda211) was sown on 3 October 2017, and 9 October 2018, using a wheat seeder machine with a row spacing of 15 cm. The harvest dates were 15 June 2018 and 16 June 2019. Cultivation practices, including controls of pests, crop diseases, and weeds, were similar to the normal practices in this region.

The winter wheat was irrigated by a center pivot (Debont Irrigation Equipment Co., Ltd., Tianjin, China), which consisted of two spans of 43.3 and 37.5 m for the first and second spans, respectively, and an overhang with a length of 8.4 m. A Nelson P85A impact sprinkler with a nozzle diameter of 8.7 mm was installed as the end gun without a booster pump. All Nelson D3000 sprinklers were placed 1.6 m above the ground using polythene flexible drop pipes. A 15 psi (103 kPa) pressure regulator (Nelson Irrigation Corp., Walla Walla, Washington, DC, USA) was deployed upstream of each sprinkler. The maximum travel speed of the end tower was 2.78 m min^{-1} when the percent timer setting was 100%, and the corresponding irrigation depth was 2.5 mm. A solenoid valve (PGV, Hunter Industries Corp., San Marcos, CA, USA) was installed at the connection between each drop hose and the lateral pipe, and every four solenoid valves shared a valve controller (Intelirri (Beijing) Technology Co., Ltd., Beijing, China). A small program could independently control each solenoid valve on a display screen, thereby regulating the flow or pulsing rates through various sprinklers. During the experiment, the inlet pressure at the pivot point was 240 kPa, and the average inlet flow rate of the whole system was 24.7 $\text{m}^3\ \text{h}^{-1}$.

All fields were applied with 67.5 kg N ha^{-1},172.5 kg P_2O_5 ha^{-1}, 75 kg K_2O ha^{-1} in the 2017 sowing season and 67.5 kg N ha^{-1}, 172.5 kg P_2O_5 ha^{-1}, 52.5 kg K_2O ha^{-1} in the 2018 sowing season. Using a center pivot irrigation system, the remaining 207 kg N ha^{-1} was applied with irrigation water as a topdressing fertilizer. Urea (46% N) was used as a source of N fertigation and applied four times (regreening, jointing, anthesis, and filling stages) during the winter wheat growing season. The fertigation system consisted of a 2000 L fertilizer storage tank and a piston injection pump with a flow rate of 285 L h^{-1}. Irrigation in this study was scheduled based on soil water content which was determined using a gravimetric method. All plots received the same irrigation water during the whole growth period of wheat. The entire field was irrigated by the center pivot, with total irrigation amounts of 145 and 175 mm in 2018 and 2019, respectively.

In agricultural production, the most important concern is to adjust the appropriate irrigation before the occurrence of dry-hot wind to avoid its adverse effect on the growth of wheat. However, if the irrigation time is too early, the water will be wasted through evaporation and drift loss. In this study, irrigation was conducted one or two hours before the occurrence of dry-hot wind. The dry-hot wind was judged by comprehensive meteorological forecasts and information collected from field meteorological sensors. To evaluate the effects of applying a small amount of water during dry-hot wind conditions, the center pivot operated at full speed and half speed, and the corresponding irrigation amounts were 2.5 (W1) and 5 mm (W2), respectively. At the same time, non-irrigation regulation under dry-hot wind conditions was used as a control (CK). During the early stage, the amount of irrigation and fertilizer application in the control area was consistent with W1 and W2.

Experiments were conducted using a randomized complete block design with three replications, and each experimental plot size was 6 m × 10 m (Figure 1a). A set of field meteorological monitors was arranged in each experimental area.

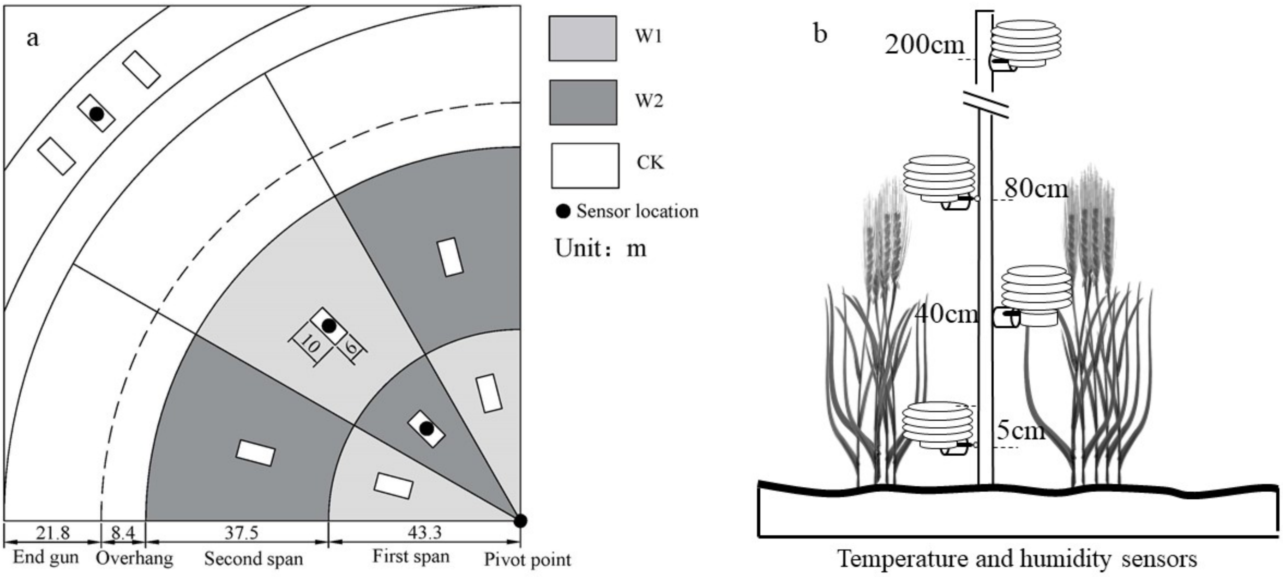


Figure 1. Schematic diagram of center pivot, layout of plots (**a**), and schematic diagram of temperature and humidity sensors (**b**). W1, W2 and CK represent 2.5 mm, 5 mm, and no irrigation treatments during dry-hot wind condition, respectively. Four sets of temperature and humidity sensors were installed at 5, 40, 80 and 200 cm from the ground surface.

2.3. Measurements

2.3.1. Meteorological Data

Meteorological data were measured with an automatic weather station (HOBO U30, Onset Computer Co., Bourne, MA, USA) near the experimental plots. Precipitation, air temperature, relative air humidity, wind speed, wind direction, and solar radiation were measured every 5 s, and the averages of 15 min were calculated and stored in a data logger. Three temperature and humidity probes (ZKYC-3A, Zhongkeyuanchuan Technology Co., Ltd., Beijing, China) were installed at 5, 40, 80, and 200 cm to measure the temperature and humidity at the bottom, middle, and top of the crop canopy, approximately 1.2 m above the canopy (Figure 1b).

2.3.2. Photosynthesis Parameters and Chlorophyll Content of Flag Leaves

The photosynthetic characteristics of the flag leaves were measured using a CI-340 Ultra-Light Portable Photosynthesis System (CID, Inc., Washington, DC, USA) from 9:00 to 11:00 a.m. (under natural light) during the filling days. Chlorophyll meter values (SPAD) of flag leaves were taken using a portable SPAD meter (Model SPAD-502, Minolta Camera Co., Osaka, Japan). The instrument measures transmission of red light at 650 nm, at which chlorophyll absorbs light, and transmission of infrared light at 940 nm, at which no absorption occurs. On the basis of these two transmission values, the instrument calculates a SPAD value that is well correlated with chlorophyll content.

2.3.3. Yield Measurements

The grain number per spike was determined by counting the grains in each spike from 60 randomly selected plants in each plot before harvesting. In each plot, wheat plants from a 1 m^2 area were harvested at maturity and threshed to determine grain yield. Actual grain yield was reported on a 13% moisture basis. The 1000-grain weight was calculated by weighing 1000 grains from each sample and averaging three replicates. The grain filling rate is the difference between the two 1000-grain weights and is divided by the number of days between two measurements.

2.3.4. Data Analysis

The photosynthetic rate and chlorophyll content of flag leaves, grain filling rate, and yield were recorded and sorted by Microsoft Excel 2016. The variance analysis (ANOVA) was performed by SPSS statistical software, and the drawing analysis was carried out with Origin 9.1 drawing software. Data are presented as the mean of three replicates, and bars represent the standard errors of the mean. ANOVA was used to establish significant differences, and treatment means were compared using the least significant difference (p = 0.05).

3. Results and Discussion

3.1. Climatic Condition

The filling period of winter wheat is a critical period that affects the final yield and quality of wheat, and any changes in meteorological factors can lead to fluctuations in total yield [20]. Figure 2 shows the trends of air temperature, relative air humidity, and precipitation during the grain filling period in 2018 and 2019. Except for the precipitation of 67.2 mm on 14 May 2018, three precipitation events occurred during the rest of the filling period in both 2018 and 2019, but the maximum precipitation was 7.4 mm. Despite 67.2 mm precipitation on 14 May 2018, the minimum relative air humidity was already less than 30% by 22 May. It is also evident that precipitation had difficulty effectively regulating field temperature and humidity throughout the filling period in 2018 and 2019. Thus, irrigation can help to mitigate the effects of insufficient precipitation during this period.

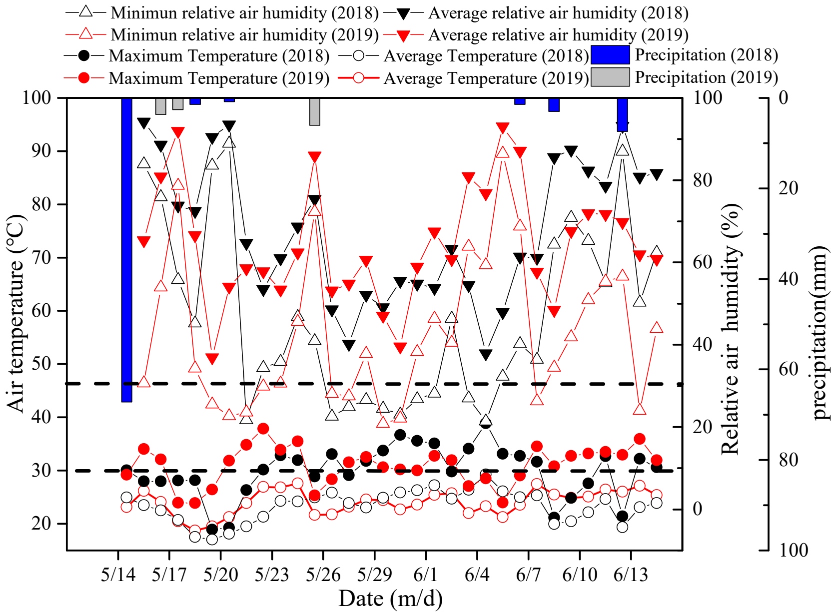


Figure 2. Air temperature, relative air humidity, and precipitation during the filling period of winter wheat in 2018 and 2019.

The dry-hot wind climate is considered to have occurred when the temperature exceeds 30 °C, the air relative humidity is lower than 30% and the wind speed is greater than 3.0 m s^{-1} at 14:00. Figure 3 shows the meteorological parameters with a date corresponding to the occurrence of dry-hot winds in 2018 and 2019. It can be seen that a dry-hot wind climate occurred on 27 May, 1 June, 4 June, and 5 June 2018, and on 21 May, 28 May, and 8 June 2019, respectively. Dry-hot wind occurred on 4 and 3 days during the wheat filling period in 2018 and 2019, respectively. This result was more consistent with the findings of a previous study that found light dry-hot wind in the North China Plain region occurred on average 2.9 days per year from 1961–2010 [5]. In addition, dry-hot winds occurred mainly in the middle of the filling period during the two years of the experiment. According to the classification of the disaster grades of dry-hot wind for wheat, the dry-hot winds that occurred on 5 June 2018 and 21 May 2019, belonged to severe and moderate grades, respectively, and the rest belonged to light grades [3]. The trends in air temperature, relative air humidity, and wind speed corresponding to the days when dry-hot wind occurred were similar in 2018 and 2019 (Figure 3). During the two years, the air temperature reached the minimum and maximum at 5:00 and 14:00, respectively. The air temperature ranged from 15.6 to 38.9 °C and 8.9 to 34.6 °C in 2018 and 2019, respectively. Contrary to the pattern of air temperature, the relative air humidity reached its maximum at 5:00 and minimum at 14:00. The relative air humidity ranged from 22.0 to 90.1% in 2018 and 23.1 to 97.4% in 2019. Meanwhile, the wind speed started to increase from approximately 7:00, reached its maximum at 14:00, and then gradually decreased. The wind speed at 14:00 ranged from 3.1 to 3.7 m s^{-1} in 2018 and 3.1 to 3.5 m s^{-1} in 2019. It can be seen from Figure 3 that the air temperature was higher than 30 °C, and the relative air humidity was lower than 30% during the day from 11:00 to 17:00. Therefore, sprinkler irrigation can be carried out during this time to regulate the field microclimate.

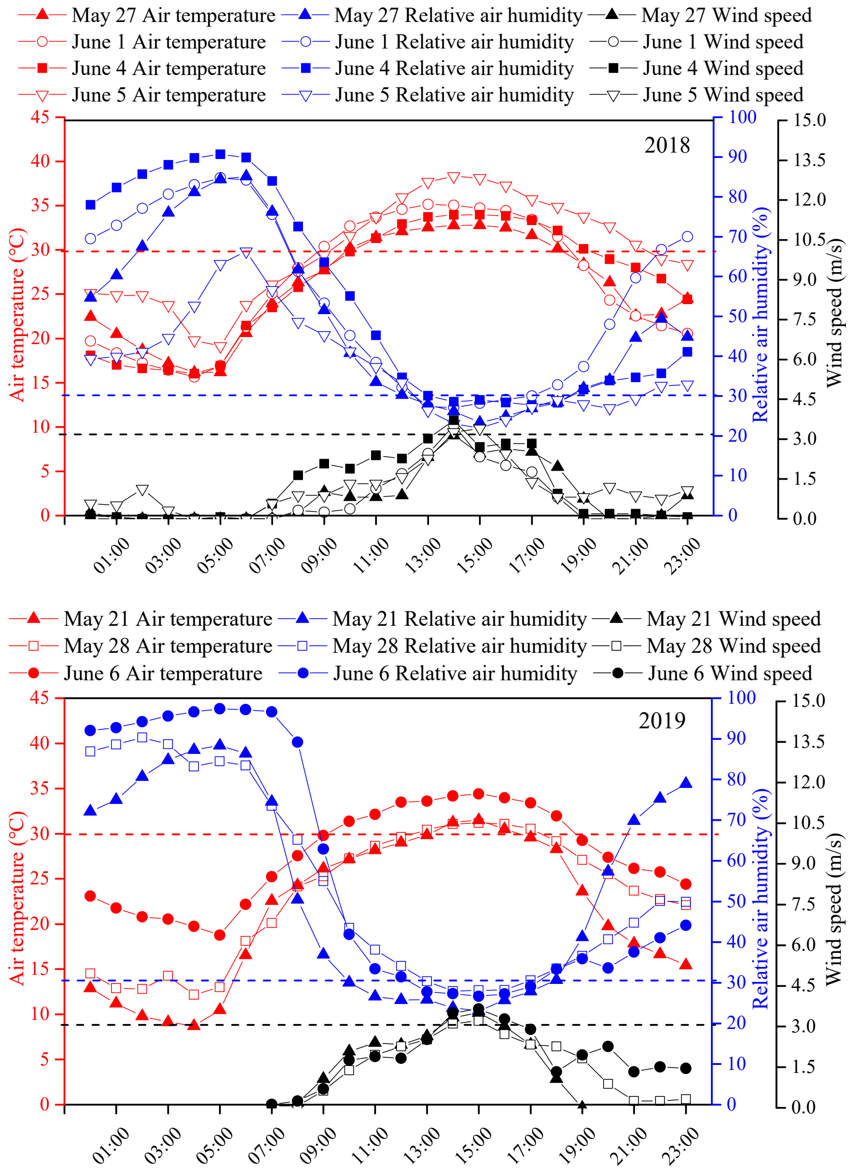
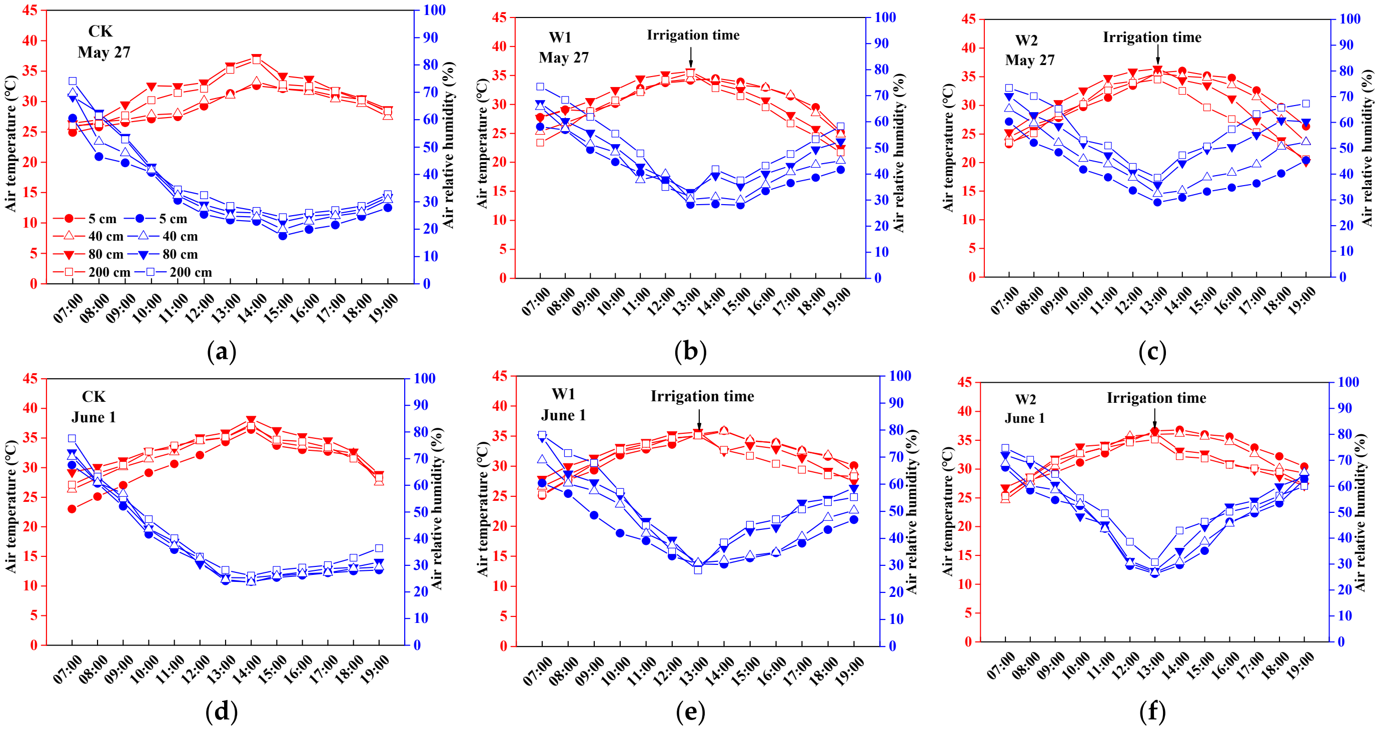


Figure 3. Air temperature, relative air humidity, and wind speed corresponds to the days when dry-hot wind occurred in the 2018 and 2019 seasons.

3.2. Air Temperature and Relative Air Humidity Changes

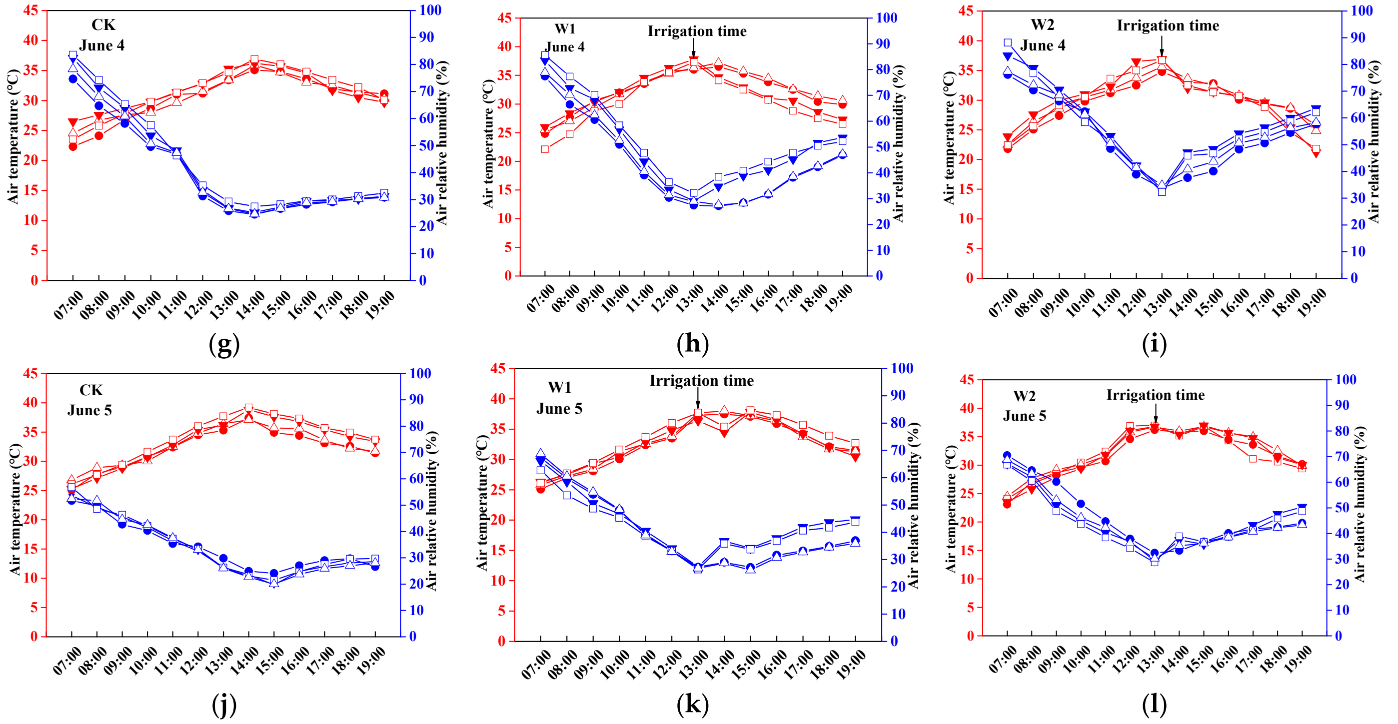
The time course of air temperature and relative air humidity with different irrigation amounts corresponding to the days when dry-hot wind occurred in 2018 and 2019 are shown in Figures 4 and 5. For the W1 treatment, air temperature was significantly affected by sprinkler misting for approximately one hour after the sprinkler was applied at 80 and 200 cm above the ground during the 2018 and 2019 winter wheat seasons. The air temperature at 80 and 200 cm decreased by 2 to 4 °C after sprinkler irrigation at 2.5 mm. However, the decrease in air temperature at 5 and 40 cm was less than that at 80 and 200 cm. In addition, the air temperature dropped rapidly within 1 h after irrigation stopped and then began to rise, which was close to the findings of previous findings [15]. In 2018 and 2019, the air temperature of each layer decreased under the W2 treatment, particularly at 80 and 200 cm above the ground surface, which was considerably noticeable. Under the 5 mm irrigation regulation, the average air temperature of each layer decreased by 2 to 5 °C. Approximately 50 to 60 min after sprinkler irrigation, the air temperature in the sprinkled field was approximately the same as that in the non-sprinkled field. Although the air temperature at different heights began to decrease after the irrigation of 2.5 and 5 mm, most of the air temperature at 14:00 was still higher than 30 °C. These results showed that when dry-hot wind occurred, a small amount of irrigation had a limited regulation range for air temperature. The ranges of air temperature dropped in this study were slightly lower than those of previous findings [21] and slightly higher than the studies of [22] due to the difference in the applied irrigation amount. However, few studies have focused on the changes in air temperature at the bottom and middle of the wheat canopy. This study found that the increase in air temperature at 5, 40, 80, and 200 cm away from the surface before irrigation was essentially the same, but that the air temperature reduced to 5 and 40 cm after irrigation and was lower than that at 80 and 200 cm (Figures 4 and 5). The reason for this drop might be related to the poor air movement in the bottom and middle of the wheat canopy.



(**a**) (**b**) (**c**)

(**d**) (**e**) (**f**)

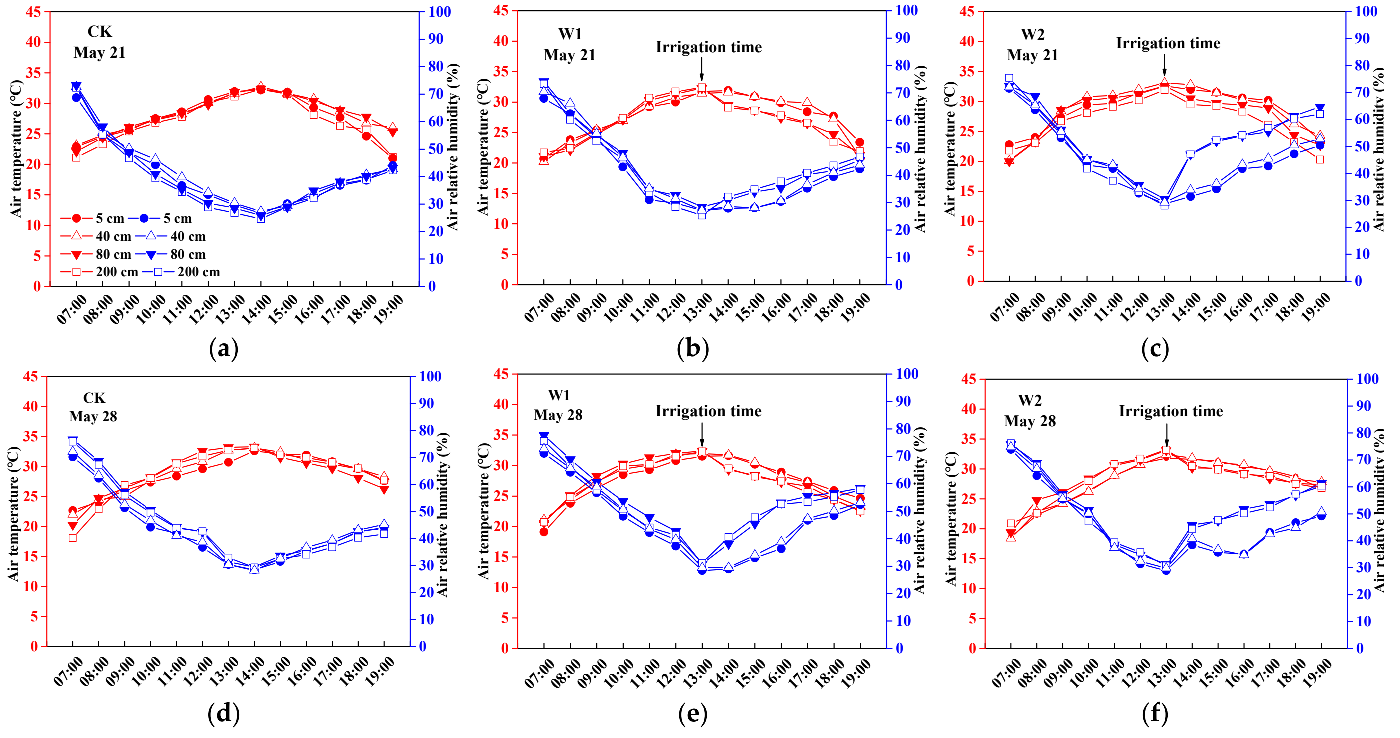
Figure 4. *Cont.*



(**g**) (**h**) (**i**)

(**j**) (**k**) (**l**)

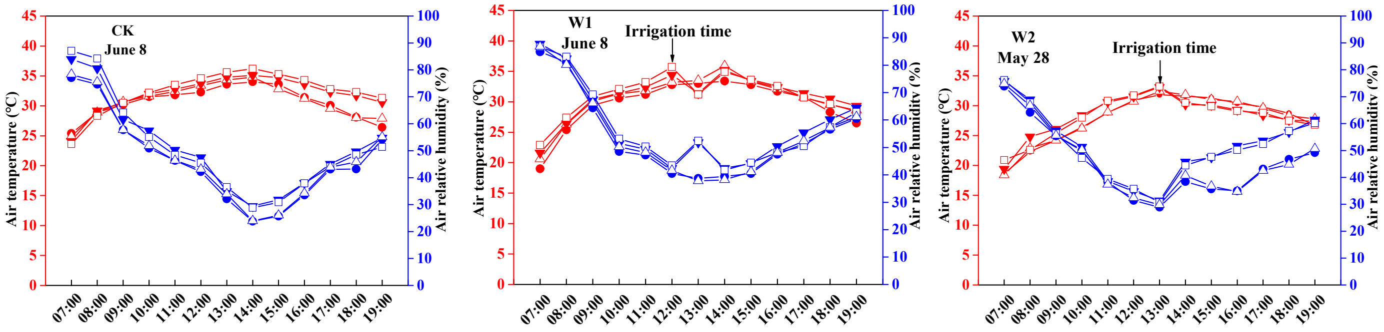
Figure 4. Time course of air temperature and air relative humidity with (**a**) CK, (**b**) W1, (**c**) W2 treatments on 27 May, (**d**) CK, (**e**) W1, (**f**) W2 treatments on 1 June, (**g**) CK, (**h**) W1, (**i**) W2 treatments on 4 June, and (**j**) CK, (**k**) W1, (**l**) W2 treatments on 5 June when dry-hot wind occurred in 2018, respectively. W1, W2, and CK represent 2.5 mm, 5 mm, and no irrigation treatments during dry-hot wind condition, respectively.



(**a**) (**b**) (**c**)

(**d**) (**e**) (**f**)

Figure 5. *Cont.*



(**g**) (**h**) (**i**)

Figure 5. Time course of air temperature and air relative humidity with (**a**) CK, (**b**) W1, (**c**) W2 treatments on 21 May, (**d**) CK, (**e**) W1, (**f**) W2 treatments on 28 May, and (**g**) CK, (**h**) W1, (**i**) W2 treatments on 8 June when dry-hot wind occurred in 2019, respectively. W1, W2, and CK represent 2.5 mm, 5 mm, and no irrigation treatments during dry-hot wind condition, respectively.

The trends of relative air humidity at 5, 40, 80, and 200 cm above the ground under different treatments are shown in Figures 4 and 5. For the CK treatment, the relative air humidity of each layer started to drop at 07:00, reached the lowest value at 14:00, and then gradually rose in two years. The relative air humidity of each layer began to rise under the W1 treatment, and the increase at 80 and 200 cm was higher than that at 5 and 40 cm. The increase in the relative air humidity at the crop canopy and above the crop canopy was lower than that observed by the studies of [23], likely because a single irrigation of not less than 18.8 mm was applied in their study. For the W2 treatment, the relative air humidity at all four heights increased after sprinkler irrigation. This might be because the irrigation amount of W2 enabled more water to pass through the canopy to the surface, resulting in more evaporation of surface water.

We observed that when irrigation started at 12:00 on 8 June 2019, the relative air humidity at 80 and 200 cm under the W1 treatment began to rise, while at 5 and 40 cm, it continued to decline. However, after W2 irrigation, the relative air humidity of both layers began to rise. The increase in relative air humidity lasted for 1 to 2 h both after the W1 and W2 irrigation events finished in our study, which was similar to that found by the studies of [11,21]. Therefore, a sprinkler irrigation time is recommended between 12:00 and 14:00. Overall, the relative air humidity at 14:00 was higher than 30% after the W1 and W2 irrigation regulations, indicating that a small amount of irrigation has a significant regulatory effect on the relative air humidity [15,23].

3.3. Photosynthetic Characteristics and Chlorophyll Content of Flag Leaves

3.3.1. Photosynthetic Characteristics

The net photosynthetic rate of flag leaves during the whole filling period of winter wheat went through three stages: steady decline, rapid decline, and slow decline stage (Figure 6). The significant ($p < 0.05$) differences in the net photosynthetic rate corresponding to the three treatments were mainly concentrated in the rapid and slow decline stages. In 2018, the net photosynthetic rate of the W2 treatment was 5.1 and 10.8% higher than that of W1 and CK on 29 May, respectively. After 31 May, the net photosynthetic rate of the W2 and W1 treatments was significantly higher than that of the CK treatment. This may be due to a severe grade of dry-hot wind that occurred on 27 May, which damaged the flag leaves of wheat to varying degrees and then affected the photosynthetic rate of the flag leaves [24].

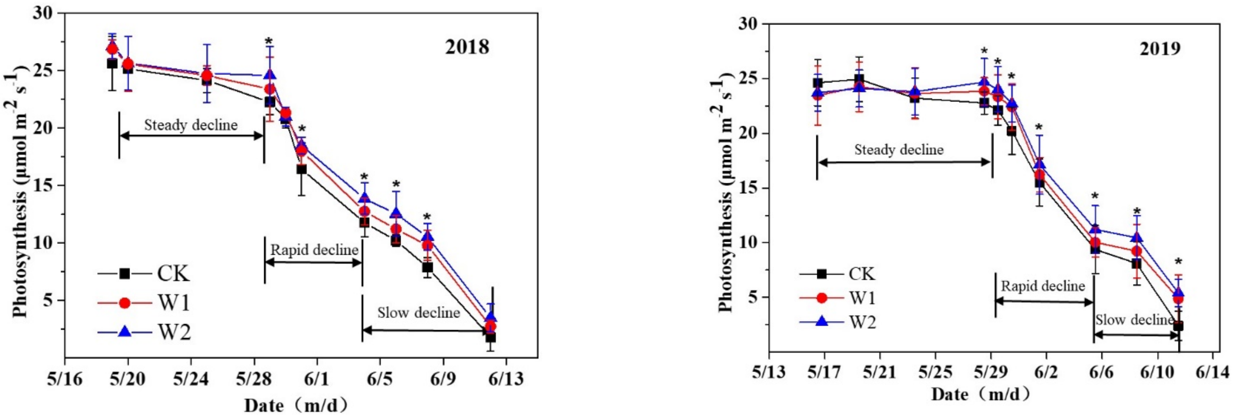


Figure 6. The photosynthetic rate during the grain filling stage under different treatments in 2018 and 2019. The values are the mean ± standard error ($n = 3$). * = significant at a probability level of $p < 0.05$ according to the Least Significant Difference test. W1, W2, and CK represent 2.5 mm, 5 mm, and no irrigation treatments during dry-hot wind condition, respectively.

In 2019, although a dry-hot wind event occurred on 21 May, there was no significant ($p > 0.05$) difference in the net photosynthetic rate among the three treatments before 29 May. The reason may be due to the occurrence of 6 mm of rainfall on 26 May, which increased the soil surface moisture and thus slowed down the adverse effects of dry-hot wind on photosynthetic rates. Significant ($p < 0.05$) differences were found among the three treatments on 29 May, in which the net photosynthetic rate of W2 was 3.8 and 8.3% higher than those of W1 and CK, respectively. After 29 May, the net photosynthetic rate of the W2 and W1 treatments was significantly ($p < 0.05$) higher than that of the CK treatment. The difference in the net photosynthetic rate among the three treatments was the largest on 9 June, and the net photosynthetic rate of the W2 treatment was 14.1 and 29.6% higher than that of the W1 and CK treatments, respectively. Studies have found that photosynthesis can be significantly stressed by dry-hot wind and more significantly stressed by severe dry-hot wind [25]. In this study, the photosynthetic rates of both the W1 and W2 treatments were higher than those of CK after the occurrence of dry-hot wind, indicating that a small amount of irrigation regulation improved the photosynthetic rates of flag leaves. Furthermore, the net photosynthetic rate of the flag leaf corresponding to the W2 treatment was higher than that of the W1 treatment, showing that irrigation of 5 mm has a significant impact on photosynthesis regulation.

3.3.2. Chlorophyll Content of Flag Leaves

The trends of SPAD among the three treatments in the early filling stage were almost the same during in the two years, but a significant ($p < 0.05$) difference appeared in the late stage of filling, which agreed with the result observed by the previous studies [7]. In 2018, the SPAD in the W2 treatment was significantly ($p < 0.05$) higher than that in the W1 and CK treatments after 3 June and persisted until the end of the filling period. Similarly, in 2019, a significant ($p < 0.05$) difference in SPAD among the three treatments occurred after 4 June (Figure 7). These results showed that the adverse effects of dry-hot wind on chlorophyll content in the flag leaves were mainly concentrated in the late filling stage. The reason could be the high SPAD and water content in wheat leaves during the prefilling period, which has a certain resistance and self-healing capacity to adversity stress [8]. At the same time, it can be seen that W2 and W1 treatment can delay leaf senescence especially for W2 treatment when dry-hot wind occurs, and scholars have confirmed this finding using foliar spraying of different nutritional mixtures under dry-hot wind stress [26].

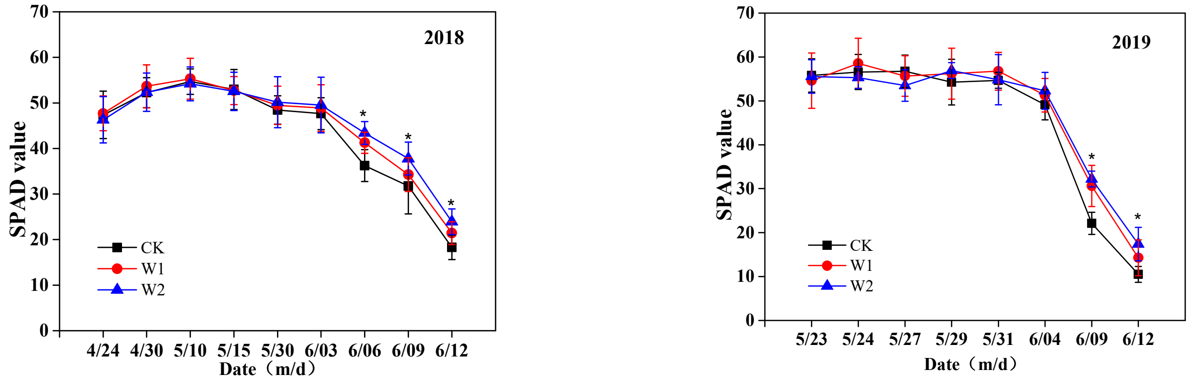


Figure 7. Relative content of chlorophyll of flag leaves during the grain filling stage under different treatments in 2018 and 2019. The values are the mean ± standard error ($n = 3$). * = significant at a probability level of $p < 0.05$ according to the Least Significant Difference test. W1, W2, and CK represent 2.5 mm, 5 mm, and no irrigation treatments during dry-hot wind condition, respectively.

3.4. Grain Filling Rate and Grain Yield

3.4.1. Grain Filling Rate

The grain filling rate of the two years can be divided into four stages: rapid rise, slow rise, rapid decline, and slow decline stages (Figure 8). In 2018, there were no significant ($p > 0.05$) differences in the grain filling rate among the three treatments before 30 May. It was found that dry-hot wind in the early stage of grain filling would cause some damage to the physiological function of winter wheat, but the damage could recover quickly because the plant was still in the vigorous growth period [27]. It can be seen from Figure 8 that from 1 June to 7 June the CK treatment had significantly ($p < 0.05$) lower values of grain filling rate than W1 and W2, but the difference between W1 and W2 was not significant ($p > 0.05$). After 7 June, the differences in grain filling rate values between the three treatments CK, W1 and W2 were not significant. It can be concluded that both W1 and W2 irrigation regulation had a significant effect on the grain filling rate during the rapid decline period compared to the non-irrigation regulation treatment in 2018.

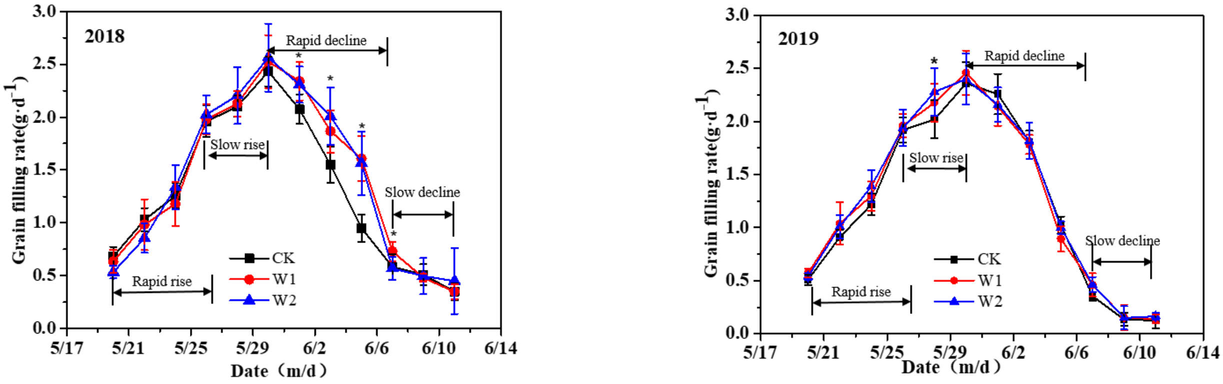


Figure 8. Grain filling rate during the grain filling stage under different treatments in 2018 and 2019. The values are the mean ± standard error ($n = 3$). * = significant at a probability level of $p < 0.05$ according to the Least Significant Difference test. W1, W2, and CK represent 2.5 mm, 5 mm, and no irrigation treatments during dry-hot wind condition, respectively.

In 2019, there was no significant ($p > 0.05$) difference in grain filling rate among the three treatments during the whole filling period, except on 29 May. Overall, dry-hot wind had a greater adverse effect on grain filling rates in 2018 than in 2019. In 2018, the adverse effects of dry-hot wind on the filling rate mainly appeared in the middle and late filling periods, while the difference in filling rate among different treatments in 2019 was not significant. This was related to the occurrence frequency of dry-hot wind in 2018 being greater than that in 2019, and the daily maximum temperature at the time of dry-hot wind was higher than that in 2019, which was consistent with related research results [28].

3.4.2. Grain Yield and Yield Components

The grain yield and yield components under different treatments in 2018 and 2019 are shown in Table 1. There was no significant ($p > 0.05$) difference in the spike number among the different treatments during in the two years of the experiment. Similarly, there was no significant ($p > 0.05$) difference in the number of grains per spike among the three treatments both in 2018 and 2019. It can be seen that the mean number of grains per spike in 2019 was 29.9% higher than that in 2018. This was due to the fact that the smaller number of spikes in 2019 promoted the increase in the number of grains. Due to the various effects of meteorological conditions during different periods on the grain filling process, the effects of dry-hot wind on the final 1000-grain weight of wheat were distinct, which agreed with the studies of [29,30]. In 2018, the 1000-grain weights of W1 and W2 were 3.3 and 4.9%, respectively, which were significantly ($p < 0.05$) higher than that of CK. In 2019, there was no significant ($p > 0.05$) difference in 1000-grain weight among the three treatments, but the 1000-grain weights of W1 and W2 were 2.2 and 3.6% higher than that of CK, respectively. For wheat not regulated by irrigation water, the different degrees of dry-hot wind disasters could cause a reduction in 1000-grain weight after the middle stage of grain filling [7]. On the contrary, for irrigation-regulated wheat, the increase in field relative humidity and the decrease in air temperature were able to slow down the physiological functions of wheat affected by dry and hot winds. The grain yield of W2 was 2.0 and 6.3% higher than that of W1 and CK in 2018, respectively. Meanwhile, the yield of W2 was 2.9 and 5.3% higher than that of W1 and CK in 2019, respectively. Overall, W2 and W1 increased by 5.8 and 3.3%, respectively, on average compared with CK during in the two years, and these findings are in line with previous research [15]. It was also observed that both W2 and W1 irrigation regulation increased wheat yields to some extent compared to wheat yields without irrigation regulation, especially in 2018, when dry-hot winds occurred more frequently. The adverse effects of dry-hot wind on grain yield can be reduced by spraying a small amount of water to adjust the field temperature and humidity when dry-hot wind occurs.

Table 1. Grain yield and yield components under different treatments in 2018 and 2019.

Years	Treatments	Spike Number (10^4 ha^{-1})	Grains per Spike	1000-Grain Weight (g)	Yield (kg ha^{-1})
2018	CK	599.9 ± 2.9 a	32.6 ± 0.1 a	44.9 ± 0.5 b	8776.7 ± 128.9 b
	W1	603.2 ± 3.0 a	32.7 ± 0.7 a	46.4 ± 0.6 a	9141.1 ± 237.5 ab
	W2	600.5 ± 13.9 a	33.0 ± 0.9 a	47.1 ± 0.4 a	9328.0 ± 189.0 a
	Mean	601.2	32.8	46.1	9081.9
	ANOVA	NS	NS	*	NS
2019	CK	454.3 ± 2.3 a	42.3 ± 0.5 a	41.1 ± 0.7 a	7893.1 ± 57.0 a
	W1	453.0 ± 9.9 a	42.4 ± 1.8 a	42.0 ± 0.3 a	8076.2 ± 226.9 a
	W2	453.7 ± 3.7 a	43.0 ± 0.9 a	42.6 ± 1.6 a	8310.5 ± 402.6 a
	Mean	453.7	42.6	41.9	8093.3
	ANOVA	NS	NS	NS	NS

Notes: Mean ± standard error ($n = 3$) followed by different lowercase letters are significantly different at $p < 0.05$. NS = not significant at a probability level of $p < 0.05$, * = significant at a probability level of $p < 0.05$. W1, W2, and CK represent 2.5 mm, 5 mm, and no irrigation treatments during dry-hot wind condition, respectively.

The strength of a two-year field study was successfully optimized by center pivot irrigation to regulate field microclimate and wheat physiology under dry-hot wind conditions in the North China Plain. We evaluated the effects of two irrigation levels on the field microclimate, net photosynthetic rate, and chlorophyll content of flag leaves, grain filling rate, and yield based on field experiments. To our knowledge, there have been few studies examining the coupling effects of optimized irrigation-based field microclimate and wheat physiology on wheat yield in irrigated regions. Despite the success demonstrated in the current study, a considerable limitation of the field study is that it is mainly focused on the effects of irrigation levels on wheat in one climatic zone where the study area is located. However, dry-hot winds behave differently in different year types. There is still room for improvement in optimizing irrigation water for winter wheat under various dry-hot wind climatic conditions. Therefore, prospective field studies are needed to confirm our results under other climatic zones in this area.

4. Conclusions

The results of this study have shown that a small amount of sprinkler irrigation 1–2 h before the occurrence of dry-hot wind strongly modifies the field microclimate of winter wheat for a short period after the irrigation event is finished. The most significant changes in air temperature and relative air humidity were observed at 80 and 200 cm above the ground after 2.5 mm of irrigation, but significant changes in air temperature and relative air humidity were observed in all layers after 5 mm of irrigation. The net photosynthetic rate of flag leaves under 5 mm irrigation was higher than that under 2.5 mm irrigation during the middle and late filling periods. The adverse effects of dry-hot wind on chlorophyll content in flag leaves were mainly concentrated in the late filling stage. During the two years of the experiment, the 1000-grain weights of 5 and 2.5 mm of irrigation before the occurrence of dry-hot wind were on average 4.3 and 2.8% higher than those of non-irrigation, and the yield was 5.8 and 3.3% higher than non-irrigation, respectively. It is recommended that a small amount of sprinkler irrigation 1–2 h before the occurrence of dry-hot wind to adjust the wheat field microclimate in the North China Plain.

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