Postprint: Effects of Drip Irrigation Amount on Field Microclimate and Yield of Winter Wheat

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Abstract

To optimize the irrigation quota of drip-irrigated winter wheat in northern Xinjiang and explore the relationship between different drip irrigation amounts and the field microclimate and yield of winter wheat, a field experiment was conducted under drip irrigation conditions using a single-factor randomized block design. The effects of three different irrigation amounts—3 000 m3 hm 2 (Treatment TA), 3 750 m3 hm 2 (Treatment TB), and 4 500 m3 hm 2 (Treatment TC)—on soil temperature at 15 cm depth, canopy temperature, humidity, flag leaf intercellular CO2 concentration (Ci), atmospheric CO2 concentration (Ca), inter-plant evaporation, and yield were studied. The results showed that: as irrigation amount increased, the cooling effect of irrigation on soil temperature in the late growth stage of winter wheat was enhanced, with soil temperature differences between treatments reaching 1.09 ℃ (TA vs. TB), 1.61 ℃ (TA vs. TC), and 0.52 ℃ (TB vs. TC). With increasing irrigation amount, canopy temperature decreased while humidity increased, with the maximum canopy temperature difference between treatments reaching 3.68 ℃. Both inter-plant evaporation and Ci first decreased and then increased with increasing irrigation amount. Throughout the entire growth period, Ca generally showed a gradual decreasing trend with increasing drip irrigation amount, while yield first increased and then decreased, reaching its maximum at an irrigation amount of 3 750 m3 hm 2, attaining 8 971.66 kg hm 2, which represented yield increases of 20.55% and 6.86% compared with the lower irrigation amount (TA) and higher irrigation amount (TC), respectively. Further correlation analysis between the above factors and yield/irrigation amount revealed that both soil temperature and canopy temperature had significant negative correlations with yield and irrigation amount, canopy humidity showed a highly significant positive correlation with irrigation amount, and intercellular CO2 concentration exhibited a highly significant negative correlation with yield. Under the conditions of this experiment, when the drip irrigation quota for winter wheat in northern Xinjiang was 3 750 m3 hm 2, the canopy temperature and humidity in the wheat field were appropriate, inter-plant evaporation was low, and yield was highest, providing a reference for field production practices.

Full Text

Effects of Drip Irrigation Amount on Field Microclimate and Yield of Winter Wheat

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Abstract

To optimize the irrigation quota for drip-irrigated winter wheat in northern Xinjiang and explore the relationship between different drip irrigation amounts and field microclimate and yield of winter wheat, a field experiment was conducted under drip irrigation conditions using a single-factor randomized block design. Three irrigation amounts were studied: 3,000 m^{3} · hm ^{2} (Treatment TA), 3,750 m^{3} · hm ^{2} (Treatment TB), and 4,500 m^{3} · hm ^{2} (Treatment TC). The effects on soil temperature at 15 cm depth, canopy temperature, humidity, intercellular CO concentration (Ci) of flag leaves, atmospheric CO concentration (Ca), soil evaporation, and yield were investigated. The results showed that as irrigation amount increased, the cooling effect on soil temperature during the late growth stage of winter wheat was enhanced, with temperature differences among treatments reaching 1.09 °C (between TA and TB), 1.61 °C (between TA and TC), and 0.52 °C (between TB and TC). With increasing irrigation amount, canopy temperature decreased while humidity increased, with the maximum canopy temperature difference among treatments reaching 3.68 °C. Both soil evaporation and Ci initially decreased then increased with irrigation amount. Throughout the entire growth period, Ca showed a gradual decreasing trend with increasing drip irrigation amount, while yield first increased then decreased, reaching its maximum of 8,971.66 kg · hm ^{2} at the irrigation amount of 3,750 m^{3} · hm ^{2}. This represented yield increases of 20.55% and 6.86% compared with the lower (TA) and higher (TC) irrigation amounts, respectively. Further correlation analysis between these factors and yield/irrigation amount revealed that soil temperature and canopy temperature were significantly negatively correlated with both yield and irrigation amount, canopy humidity was extremely significantly positively correlated with irrigation amount, and intercellular CO concentration was extremely significantly negatively correlated with yield. Under the conditions of this experiment, a drip irrigation quota of 3,750 m^{3} · hm ^{2} for winter wheat in northern Xinjiang resulted in suitable canopy temperature and humidity, low soil evaporation, and maximum yield, which can serve as a reference for field production practices.

Keywords: Drip irrigation amount; Winter wheat; Canopy temperature;

Canopy humidity; Soil evaporation; Yield

1.1 Study Site Description

The field experiment was conducted in 2014 at the Yining County Agricultural Science and Technology Demonstration Park in Ili Kazakh Autonomous Prefecture, Xinjiang (44°N, 81°E, altitude 813 m). Located in the central Ili River Valley, the experimental area features a mid-temperate arid inland mountain climate with annual sunshine hours of 2,800–3,000 h, a frost-free period of 169–175 days, and multi-year average precipitation of 257 mm. During the winter wheat growth period (October 20, 2013 to July 10, 2014), rainfall totaled 237.2 mm. The nutrient content in the 0–20 cm soil layer was: organic matter 15.6 g · kg ^{1}, alkaline hydrolysis nitrogen 69.6 mg · kg ^{1}, available phosphorus 2.5 mg · kg ^{1}, and available potassium 78.5 mg · kg ^{1}. The previous crop was spring maize.

1.2 Field Experimental Design

A single-factor randomized block design was employed. The winter wheat cultivar tested was 'Yinong 20' , a locally common variety. Before sowing, diammonium phosphate was applied as base fertilizer at 270 kg · hm ^{2}. After sowing, 300 m^{3} · hm ^{2} of water was applied uniformly to ensure consistent emergence, with no irrigation before the jointing stage. After jointing, three drip irrigation amount treatments were established based on winter wheat water requirements and local climate conditions : 3,000 m^{3} · hm ^{2} (Treatment TA), 3,750 m^{3} · hm ^{2} (Treatment TB), and 4,500 m^{3} · hm ^{2} (Treatment TC), each replicated four times. Each plot covered 30 m^{2} (5 m × 6 m), with water meters controlling irrigation amounts at plot inlets. One-meter-wide isolation strips were installed between plots to prevent water seepage. Nitrogen fertilizer (urea) was applied with irrigation water in all treatments through four applications during the grain-filling stage, totaling 225 kg · hm ^{2} of nitrogen.

1.3.1 Soil Temperature Measurement

Before applying the first drip irrigation at the jointing stage, MicroLite-U disk temperature loggers (Israel) with a measurement precision of 0.3 °C were buried at 15 cm depth between winter wheat rows in two plots per treatment to measure soil temperature, with automatic recordings every 30 minutes until wheat maturity.

1.3.2 Canopy Temperature and Humidity Measurement

Using Lascar EL-USB-2 temperature and humidity loggers (UK), five representative winter wheat plants with uniform growth were selected in each treatment starting from the heading stage. Measurements were taken approximately every 7 days on clear, windless days at the 2/3 canopy height position, avoiding bare ground effects, with recording times from 10:00 to 20:00 Beijing time until 26 days after anthesis.

1.3.3 Flag Leaf Intercellular CO Concentration and Atmospheric CO Concentration Measurement

Starting from the flag leaf stage, five uniformly growing winter wheat plants were randomly selected and marked in each plot of each treatment. A CARIS-2 portable photosynthesis system (PP Systems, UK) was used to measure intercellular CO concentration (Ci) of flag leaves and atmospheric CO concentration (Ca) on clear days between 11:00–13:00 at the booting, anthesis, grain-filling, and dough stages.

1.3.4 Soil Evaporation Measurement

Soil evaporation was measured using micro-lysimeters constructed from PVC pipes (10 cm inner diameter, 5 mm wall thickness, 15 cm height). During each soil sampling, these were vertically pressed into the soil between the first and second rows beside the drip irrigation tape in each plot, with two micro-lysimeters deployed per plot. The top surface was leveled with the ground surface to collect undisturbed soil, sealed at the bottom with ziplock bags, and placed inside an outer PVC pipe sleeve (12 cm inner diameter) fixed between rows with its surface level with the surrounding soil to avoid disturbing the soil structure during operation. Weighing with an electronic balance (precision 0.01 g) was conducted every two days at 11:00 Beijing time, with the weight difference representing evaporation. To maintain measurement accuracy and ensure soil moisture consistency between the lysimeter and surrounding soil, the internal soil core was replaced every 3–5 days, and immediately after rainfall or irrigation.

1.3.5 Yield Measurement

At winter wheat maturity, three points with uniform growth were randomly selected in each treatment for harvest measurement in a 1.11 m × 0.6 m area. Additionally, 10 representative wheat plants from the same side of the drip tape in each plot were harvested for indoor analysis of yield components, including spike length, kernels per spike, and thousand-kernel weight.

1.4 Data Analysis

Microsoft Excel 2010 and DPS 6.5 software were used for data statistics and analysis, with LSD method applied for variance analysis.

2.1 Changes in 15 cm Soil Temperature and Canopy Temperature/Humidity of Winter Wheat Under Different Drip Irrigation Amounts

2.1.1 Dynamic Changes in 15 cm Soil Temperature of Winter Wheat

As shown in [Figure 1: see original paper], soil temperature under all irrigation treatments showed consistent overall trends from jointing to maturity, fluctuating upward. Influenced by plant growth status, ground cover, and air temperature, soil temperature increased substantially during the late growth stage, reaching a maximum of 25.0 °C. Different irrigation treatments affected soil temperature at 15 cm depth differently. As winter wheat grew, soil temperature showed an increasing trend in the early stage and decreasing trend in the late stage, with this cooling effect being more pronounced during the late growth period. With increasing irrigation amount, soil temperature at 15 cm depth followed the pattern TA > TB > TC, with significant differences between TA and both TB and TC ($P < 0.05$). From anthesis to maturity, the maximum temperature difference between treatments reached 2.98 °C (between TA and TC). Pairwise comparisons between treatments showed temperature differences of 1.09 °C (TA vs. TB), 1.61 °C (TA vs. TC), and 0.52 °C (TB vs. TC), demonstrating that increasing irrigation amount effectively reduced soil temperature during the late growth stage of winter wheat, which has positive effects on preventing yield loss caused by excessively high temperatures during the grain-filling period.

2.1.2 Dynamic Changes in Canopy Temperature and Humidity of Winter Wheat

Comparing average canopy temperature values across different water supply levels, canopy temperature under all irrigation treatments generally increased with growth progression from heading stage onward [FIGURE:2A–E], reaching a maximum average canopy temperature of 37.28 °C at 26 days after anthesis. Diurnal variation analysis of canopy temperature at each growth stage showed a convex pattern peaking around 16:00, with daily averages following the pattern TA > TB > TC and a maximum temperature difference of 3.68 °C among treatments, demonstrating a trend of decreasing canopy temperature with increasing drip irrigation amount. Further analysis of diurnal canopy humidity variation revealed that from heading to post-anthesis, daily average humidity values showed an overall increasing then decreasing trend across all treatments. However, at each growth stage, diurnal canopy humidity variation showed an opposite pattern to canopy temperature, presenting a concave shape with a trough around 16:00. Diurnal canopy humidity variation among treatments increased with irrigation amount. These results indicate that irrigation effectively regulates canopy temperature and humidity, and that appropriately increasing irrigation amount during the late growth stage of winter wheat can mitigate yield loss caused by hot, dry winds.

2.2 Changes in Flag Leaf Intercellular CO Concentration (Ci) and Atmospheric CO Concentration (Ca) of Winter Wheat Under Different Drip Irrigation Amounts

As shown in [Figure 3: see original paper], with advancing growth progression, intercellular CO concentration of flag leaves under all treatments showed an overall increasing trend, while atmospheric CO concentration first increased then decreased, peaking at the anthesis stage across all treatments. At each growth stage, flag leaf intercellular CO concentration under different treatments first decreased then increased with increasing irrigation amount, with extremely significant differences between TA and both TB and TC. Meanwhile, except at the dough stage, atmospheric CO concentration showed a continuous decreasing trend with increasing irrigation amount, with significant or extremely significant differences among treatments. This may be because increasing irrigation amount enhanced the photosynthetic rate of the winter wheat canopy, which absorbed surrounding CO more rapidly, thereby reducing atmospheric CO concentration. These findings indicate that both low and high irrigation amounts are unfavorable for leaf CO assimilation, while appropriate irrigation enhances the capacity for CO assimilation and improves photosynthetic rate, which benefits photosynthate accumulation.

2.3.1 Daily Changes in Farmland Evapotranspiration and Winter Wheat Soil Evaporation

Analysis of daily changes in farmland evapotranspiration and soil evaporation under different treatments after winter wheat regreening [Figure 4: see original paper] showed that both evapotranspiration and soil evaporation increased after irrigation or rainfall events. Evapotranspiration peaked in early grain-filling (around June 4) with a daily value up to 6.39 mm · d^{1}, while soil evaporation reached its maximum in mid-grain-filling with an average daily value of 0.93 mm · d^{1}, accounting for 33.63% of farmland evapotranspiration during this period. Among different irrigation treatments, before the booting stage (May 11), soil evaporation was primarily affected by leaf area index, showing the pattern TC > TB > TA with increasing irrigation amount. From heading (May 12) to early grain-filling (June 4), the pattern was TA > TC > TB because when leaf area index was larger, better canopy closure reduced soil evaporation. During this period, increasing irrigation amount reduced canopy temperature and maintained higher canopy humidity, relatively suppressing or weakening soil evaporation and thereby reducing ineffective water loss.

2.3.2 Diurnal Variation of Soil Evaporation in Winter Wheat

As shown in [Figure 5: see original paper], diurnal variation of soil evaporation under different irrigation amounts at different growth stages showed a single-peak pattern, with peaks occurring between 14:00–16:00. At the jointing, grain-filling, and dough stages, soil evaporation followed the pattern TC > TB > TA, while at booting and anthesis stages it showed TA > TC > TB. This occurred because leaf area index was smaller in the early growth stage and leaves withered and fell in the late stage with fewer functional leaves, resulting in less plant shading and more exposed soil. During these periods, soil evaporation was mainly affected by surface soil water content, which increased with irrigation amount. However, at booting and anthesis stages when winter wheat growth was vigorous with large leaf area index and good shading effect, soil evaporation was relatively small. These results indicate that maintaining reasonable leaf area index, appropriately reducing irrigation amount during early and late growth stages, and scheduling irrigation after 18:00 when evaporation is lower can all reduce soil evaporation.

2.4 Correlation Between Soil Temperature, Canopy Temperature/Humidity, Soil Evaporation and Winter Wheat Yield

As shown in Table 2, winter wheat yield and its components under different irrigation amounts showed a trend of first increasing then decreasing with irrigation amount. Both effective spike number and yield showed extremely significant differences among treatments. With increasing irrigation amount, kernels per spike increased significantly by an average of 4 kernels per spike, but further increasing irrigation amount did not produce significant increases. The highest yield of 8,971.66 kg · hm ^{2} was achieved at the irrigation amount of 3,750 m^{3} · hm ^{2}, representing yield increases of 20.55% and 6.86% compared with the lower and higher irrigation amounts, respectively. Further correlation analysis between these factors and yield/irrigation amount revealed that soil temperature and canopy temperature were significantly negatively correlated with both yield and irrigation amount, canopy humidity was extremely significantly positively correlated with irrigation amount, and intercellular CO concentration was extremely significantly negatively correlated with yield. No significant correlations were found between other factors and yield or irrigation amount. These results demonstrate that irrigation can modify soil temperature and canopy temperature/humidity, thereby affecting leaf and atmospheric CO concentration to coordinate their relationships with yield and achieve water-saving and yield-increasing effects.

3 Discussion and Conclusion

Soil temperature directly affects soil water movement and crop water uptake, ultimately influencing crop yield. Numerous studies have shown that mulching practices can regulate farmland soil temperature to varying degrees, mitigating damage from high or low temperatures on crop growth and development. However, few studies have clarified the relationship between irrigation and soil temperature. This study demonstrates that irrigation can also effectively regulate soil temperature. Under drip irrigation conditions, appropriately increasing irrigation amount showed obvious cooling effects during the late growth stage of winter wheat, helping to reduce high-temperature damage from anthesis to grain-filling and thereby increasing kernels per spike and grain weight. This study found that with increasing irrigation amount, the average cooling amplitude reached 1.07 °C and yield increased by 635.96 kg · hm ^{2}.

Canopy temperature is closely related to winter wheat growth and development, with genetic correlation coefficients with yield exceeding 0.8. Studies have shown that under flood irrigation conditions, each 1 °C increase in canopy temperature during mid-to-late grain-filling decreased yield by 280 kg · hm ^{2}. Additionally, the negative correlation between canopy temperature during grain-filling and yield gradually increased with grain-filling progression. In this experiment, the correlation coefficient between yield and canopy temperature was -0.753, showing a significant negative correlation that further validates these conclusions and demonstrates that canopy temperature is greatly affected by irrigation quota regardless of irrigation method. Other research indicates that high canopy humidity helps alleviate photosynthetic "midday depression" in rice and enhances photosynthetic capacity, with irrigation being the most direct and effective way to regulate canopy humidity. Among the three irrigation treatments in this study, the irrigation amount of 3,750 m^3 · hm ^{2} maintained relatively high canopy humidity while also producing the strongest capacity for leaf CO assimilation, enabling rapid absorption and utilization of atmospheric CO and laying a good foundation for high yield.

Soil evaporation is a major component of farmland evapotranspiration and represents ineffective water consumption, making it an important indicator of field microclimate. Research results show that under surface irrigation conditions, soil evaporation accounts for about 30% of total water consumption during the entire winter wheat growth period. Therefore, reducing soil evaporation is important for improving farmland water use efficiency and saving water. This study found that soil evaporation did not always increase with irrigation amount. Affected by both winter wheat canopy coverage and surface soil water content, when canopy closure was good, appropriately increasing irrigation amount actually suppressed soil evaporation due to higher canopy humidity. However, when irrigation amount was excessive, ineffective water loss remained high.

Different crop growth microenvironments affect crop development and consequently yield. This study indicates that irrigation effectively regulates soil temperature and canopy temperature/humidity, thereby affecting soil evaporation and yield. Different irrigation amounts had different regulatory effects on the winter wheat growth microenvironment: larger irrigation amounts produced more obvious cooling effects on soil and canopy temperatures and increased canopy humidity, but soil evaporation and yield did not continue to increase with irrigation amount. Appropriately increasing irrigation amount could improve canopy humidity to relatively suppress ineffective water loss while enhancing leaf CO assimilation capacity, positively promoting yield formation.

The results of this study show that when the irrigation amount was 3,750 m^3 · hm ^{2}, field microclimate conditions were suitable and yield was highest, providing a reference for field production practices. Since this study did not involve farmland latent heat flux and turbulent heat flux, more in-depth comparative analysis could not be conducted, which will be improved in future work. Additionally, the results show that larger irrigation amounts decreased canopy temperature and increased humidity, where factors suppressing and promoting soil evaporation coexisted. Therefore, further investigation into the relationship between soil evaporation and crop canopy temperature/humidity, and how to coordinate and balance these relationships, remains to be studied.

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