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# Luxury transpiration of winter wheat and its responses to deficit irrigation in North China Plain

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**ABSTRACT**

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Reducing crop luxury transpiration is an important step in improving water productivity; water shortage regions are potential hotspots for studying physiological water conservation. This study investigated the amount of luxury transpiration in winter wheat and its responses to different irrigation treatments in North China Plain. The results showed that luxury transpiration existed and increased with growth of winter wheat and after rainfall. In each sampling day, the amount of luxury transpiration under full irrigation was significantly higher than that under deficit irrigation. The average amount of luxury transpiration was 258.87 g/m$^2$ under full irrigation, and 125.18 g/m$^2$ under deficit irrigation during the experimental period. Although the amount of luxury transpiration was 2.09-fold higher under full irrigation than that in deficit irrigation, the water loss ratio due to luxury transpiration in deficit irrigation (8.13%) was significantly higher than that in full irrigation (6.75%). Furthermore, the ratio between luxury transpiration amount and crop daily transpiration was revealed in all sampling dates. Therefore, deficit irrigation should be generalized in the water shortage area, because it can save irrigation water and reduce the amount of luxury transpiration. Full irrigation should be carried out in the water abundant region mainly for higher production.

**Keywords**: *Triticum aestivum* L.; precipitation; photosynthesis; drought condition; water use efficiency

Transpiration, defined as the loss of water vapour from plants, is a physical process that is under control of both external physical and physiological factors (Pallardy 2008, Thapa et al. 2017). Transpiration helps maintain body temperature of the plant (Ayeneh et al. 2002), creates a negative pressure that aids in pulling the moisture and nutrients firmly held by soil particles (Collins et al. 2018), and maintains a favourable microclimate near the plant canopy (Reddy et al. 2015). However, significant amounts of water are withdrawn from the agroecosystems through transpiration. Water is necessary for plants, but only a small amount of water absorbed by the roots is used for growth and metabolism. The remaining 97–99.5% is lost by transpiration and guttation. High transpiration promotes plant morphogenesis and crop yield, but it also reduces crops water use efficiency and increases agricultural pressure on water use under water shortage conditions. In arid and semiarid regions, agriculture largely depends on irrigation due to insufficient precipitation. Preventing unnecessary (excessive) transpiration in crops and managing physiological water conservation is one of the effective ways to improve irrigation water use efficiency and realize efficient water use in agriculture in these areas.

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Both the photosynthetic rate and transpiration rate follow a parabolic curve (Wang and Liu 2003, Yang et al. 2006). Leaf photosynthesis and transpiration increase with increasing photosynthetic active radiation. While leaf photosynthesis plateaus at certain value, transpiration keeps increasing and crop luxury transpiration may occur (Ji et al. 2017). Luxury transpiration is part of water consumed by transpiration that exceeds the amount necessary for physiological processes, nutrient transport, photosynthesis and crop growth. Reducing crop luxury transpiration is important for decreasing the water loss in agroecosystems and improving the efficiency of water consumption (Kang et al. 2017). Many studies on luxury transpiration were carried out, but they offered only abstract description of luxury transpiration and failed to quantify. Quantifying the amount of luxury transpiration will help conserve physiological water and improve water use efficiency on farmlands.

North China Plain (NCP) is a key winter wheat production area in China (Zhou et al. 2011). One third of the wheat produced in China originates from this area, rendering this region particularly important contributor to food wealth in China. However, winter wheat production in this region is threatened by limited water resources, water contamination, and overexploited aquifers (Gao et al. 2014, Wang et al. 2016). The current water use efficiency of winter wheat is about 1.32 kg/m$^3$ in the region (Zhang et al. 2011), which is lower than that in most wheat production regions worldwide. Therefore, it is imperative to improve irrigation water productivity (Perry et al. 2009, Pereira et al. 2012, Kang et al. 2017) in order to save water resources and sustain winter wheat production in the NCP.

Physiological water conservation can be achieved by reducing luxury transpiration via optimization of irrigation practices. Therefore, this study aimed at quantifying the amount of luxury transpiration by studying the transpiration in irrigated winter wheat and compared the differences in luxury transpiration under different irrigation schedules.

## MATERIAL AND METHODS

**Experimental sites**. The field experiment was conducted at the experimental station of the Farmland Irrigation Research Institute, Chinese Academy of Agricultural Sciences (35°19'N, 113°53'E, 73.2 m a.s.l.), located in the central part of the NPC. The site has annual precipitation of 582 mm, annual mean temperature of 14.1°C, annual sunshine duration of 2497 h, a frost-free period of 220 days, and potential evaporation (measured with 20 cm pan) of 2000 mm. The soil type is sandy loam with mean bulk density of 1.35 g/cm$^3$, mean field capacity of 24% (gravitational content) and mean permanent wilting point of 8% (gravitational content) in the 0–100 cm profile. Soil available N, P and K contents were 72, 17.8 and 100 mg/kg, respectively. Soil organic carbon content was 6.04 g/kg and soil pH was around 8.2.

**Experimental design**. The experimental sites consisted of two sections. The first section, which was irrigated at a rate traditionally employed by local farmers to winter wheat, was used to determine the pattern of luxury transpiration. The second section was irrigated at two different rates to explore the effects of irrigation schedule on crop luxury transpiration. The two irrigation rates comprised a high irrigation rate (lower limit of soil moisture set at 70% of field capacity; HI) as the full irrigation treatment, and a low irrigation rate (lower limit set at 55% of field capacity; LI) as deficit irrigation treatment. The stage in early spring when wheat accelerates its growth with increasing temperatures was known as re-greening stage. In the re-greening stage of winter wheat, HI and LI sections were irrigated on the same day (5 March, 2016), when the soil water content in both reached about 55% of field capacity. The irrigation amounts in HI and LI treatments were determined by the lower limits of soil water content. The irrigation method was surface irrigation, and a precision flow meter (Shanghai Water Meter Manufacturing Factory, Shanghai, China) was used to measure and control the irrigation amount. The irrigation scheduling and the amount for treatments are shown in Table 1.

The tested cultivar of winter wheat was Xinmai 26. Seed beds were prepared by ploughing to a depth of 20 cm using a tractor-drawn rotary cultivator, larger soil clods were smoothed using a harrow to ensure a completely flat bed (Jha et al. 2017). Winter wheat was sown on 16 October 2015 and harvested on 1 June 2016. Other management practices were consistent with standard local practice. All the treatments were conducted in triplicates. Each experimental plot was 72 m$^2$ (6 m × 12 m), with 1 m wide buffers between the

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Table 1. Irrigation schedules and the amount of water (mm) used for the two treatments

| Treatment | Date of irrigation | | | | | Total amount |
|---|---|---|---|---|---|---|
| | 5 March | 23 March | 7 April | 23 April | 5 May | |
| Full irrigation | 30 | 30 | 30 | 30 | 30 | 150 |
| Deficit irrigation | 30 | – | – | 30 | – | 60 |

plots. Plots were surrounded by 10 cm high ridges to prevent runoff.

**Physiological parameters, luxury transpiration and transpiration**. Leaf transpiration ($T_r$) and photosynthetic rate ($P_n$) were measured using a LI-COR 6400 portable photosynthesis system (LI-COR, Inc., Lincoln, USA) as described in Ji et al. (2017). In each plot, transpiration rate and photosynthetic rate were measured on four fully developed upper leaves randomly selected from healthy plants. The measurements were conducted using the sensor head of the LI-COR 6400 portable photosynthesis system every hour from 7:00 to 18:00 of the sampling day. The mean value of the measurements for the four leaves represented the value of a plot.

Luxury transpiration amount was calculated as referenced by Wang and Liu (2003), Yang et al. (2006) and Ji et al. (2017). First, the photosynthetic rate was simulated as a quadratic curve (Bemis et al. 1998). When the hourly mean photosynthetic rate, 2 h smoothed, remained constant over time, it was defined that point in time as $t_1$. Second, the symmetrical points of $t_1$ were defined in the simulation quadratic curves of the photosynthetic rate as $t_2$. Third, the second quadratic curves were generated using the measured transpiration rate. The arch area enclosed by the fitting transpiration curves and a straight line by the two corresponding points (*a* and *b*) in the fitting transpiration curves from the time points ($t_1$ and $t_2$) were shown. Amount of luxury transpiration was determined by integrating the arch area (Figure 1). The dual crop coefficient method was used to estimate crop transpiration on a sampling date as referenced by Kang et al. (2000) and Gong et al. (2017).

**Data analysis**. Analysis of variance (ANOVA) was used to test the effects of the irrigation amounts on luxury transpiration by sampling date. The biomass, yield, and ratio luxury transpiration/irrigation amount were investigated using a one-way ANOVA and the least significant difference test. The data were analysed using SPSS 22.0 (SPSS Inc., Chicago, USA) and plotted with SigmaPlot 12.5 (Systat Software Inc., San Jose, USA).

## RESULTS AND DISCUSSION

**The amount of luxury transpiration quantified**. As shown in Figure 2, parabolic curve fitted the data for the photosynthetic rate and transpiration of winter wheat under the local traditional irrigation practice model ($P < 0.001$). The levels of luxury transpiration were calculated from the fitted $P_n$ and $T_r$ parabolic curve (Table 2). The luxury transpiration existed at all sampling days, and increased with time, peaking at 177.01 g/m$^2$ and 476.83 g/m$^2$ on 27 April and 9 May 2016, respectively. Previous studies have confirmed the presence of the luxury transpiration (Kang et al. 2000, Kang and Zhang 2004, Kaman et al. 2006, Ji et al. 2017), but the present study quantifies the amount of luxury transpiration for the first time. Understanding the processes underlying the luxury transpiration was the basis for studying physiological water conservation in crops.

**Luxury transpiration under different irrigation treatments**. The dynamics of the luxury transpiration in HI and LI treatments is shown in Figure 3. Irrigation schedules had a significant effect on the luxury transpiration amount ($P < 0.001$). The luxury transpiration amount under the full irrigation treatment was significantly greater than that under the deficit irrigation treatment. The average

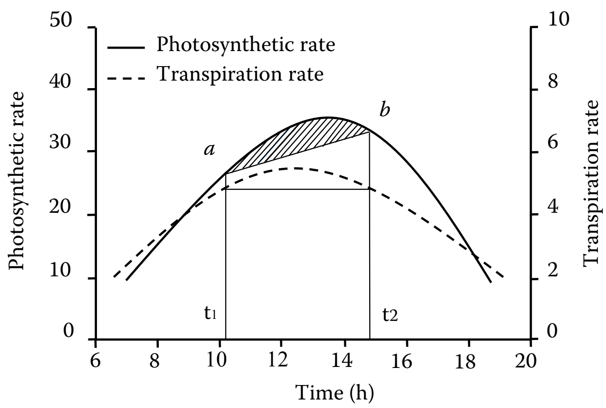


Figure 1. The diagram of luxury transpiration calculations ($t_1$ – starting time of luxury transpiration; $t_2$ – ending time of luxury transpiration)

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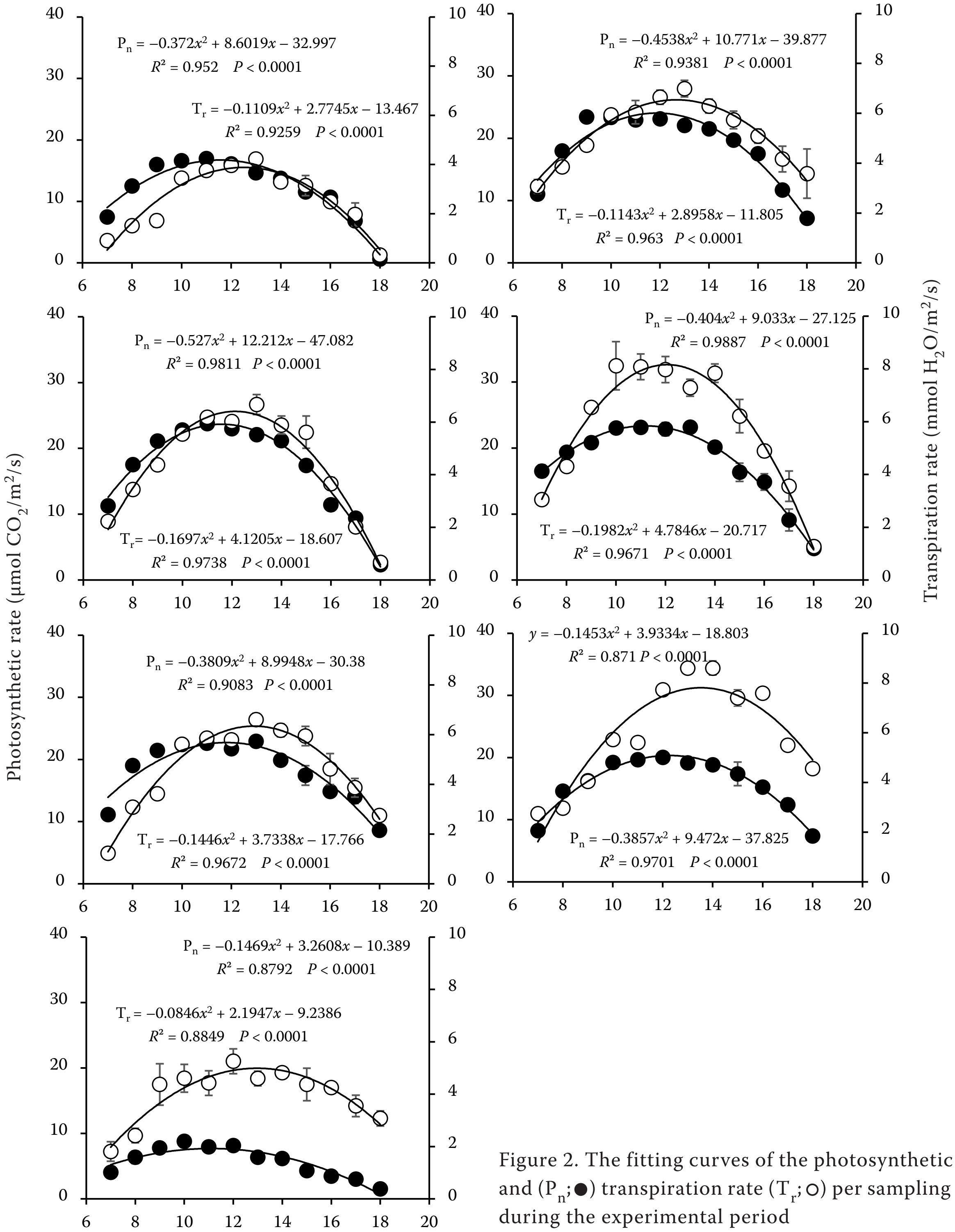


Figure 2. The fitting curves of the photosynthetic rate and ($P_n$; ●) transpiration rate ($T_r$; ○) per sampling date during the experimental period

luxury transpiration rate under the HI treatment was 258.87 g/$m^2$, 2.09-fold higher than that in the LI treatment. The results indicated that sufficient water supply increases the stomatal opening and speeds up water transport, thereby increasing the luxury transpiration amount (Changhai et al. 2010). Deficient water supply reduces stomatal opening and water transpiration, thus decreasing the luxury transpiration. The results of the ANOVA indicated that sampling times and interactions between irrigation schedule and sampling times had significant effects on the luxury transpiration amount.

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Table 2. Fitting equations and the amount of luxury transpiration in winter wheat fields subjected to traditional irrigation practice

| Date (2017) | Fitting equation for photosynthesis ($P_n$) | Starting time ($t_1$) | Ending time ($t_2$) | Fitting equation for transpiration ($T_r$) | Amount of luxury transpiration (g/m$^2$) |
|---|---|---|---|---|---|
| 2 April | $P_n = -0.37T^2 + 8.60T - 33.00$ | 10.00 | 13.12 | $T_r = -0.11T^2 + 2.77T - 13.47$ | 36.57 |
| 12 April | $P_n = -0.45T^2 + 10.77T - 39.88$ | 10.00 | 13.72 | $T_r = -0.11T^2 + 2.90T - 11.81$ | 63.62 |
| 20 April | $P_n = -0.53T^2 + 12.21T - 47.08$ | 10.00 | 13.17 | $T_r = -0.17T^2 + 4.12T - 18.61$ | 58.58 |
| 27 April | $P_n = -0.40T^2 + 9.03T - 27.13$ | 9.00 | 13.36 | $T_r = -0.20T^2 + 4.76T - 20.72$ | 177.01 |
| 4 May | $P_n = -0.38T^2 + 9.00T - 30.38$ | 10.00 | 13.61 | $T_r = -0.14T^2 + 3.73T - 17.77$ | 73.54 |
| 9 May | $P_n = -0.39T^2 + 9.47T - 37.83$ | 9.00 | 15.53 | $T_r = -0.15T^2 + 3.93T - 18.80$ | 476.83 |
| 17 May | $P_n = -0.15T^2 + 3.26T - 10.39$ | 9.00 | 13.18 | $T_r = -0.085T^2 + 2.20T - 9.24$ | 67.03 |

**Accumulation of luxury transpiration calculated**. The accumulative amount of luxury transpiration in HI and LI treatments was 11.61 mm and 5.56 mm, respectively, accounting for 6.75% and 8.13% of crop transpiration during the experiment period (Figure 4) in the full irrigation treatment and deficit irrigation treatment, respectively. The ratio of daily luxury transpiration and crop daily transpiration under the traditionally irrigated treatment in different sampling dates were not high, the mean value was 6.76% and the maximum ratio of 9.44% appeared on 9 May 2018 (Figure 5). Although the amount of luxury transpiration in deficit irrigation treatment was reduced, the ratio between the amount of luxury transpiration and crop daily transpiration was higher when compared with the treatment that followed the traditional irrigation practice (6.76%). However, the ineffective transpiration rate was also higher under deficit irrigation when compared with those obtained by full irrigation.

To the best of our knowledge, this field experimental research on the quantification of luxury transpiration under different irrigation schedules is the first study of this type conducted on irrigated winter wheat agricultural systems in the NCP. Our results revealed a low ratio between luxury transpiration amount and crop daily transpiration (< 10%). Although there may be some disputes in the calculation or simulation process above, this is the first step in quantifying luxury transpiration research.

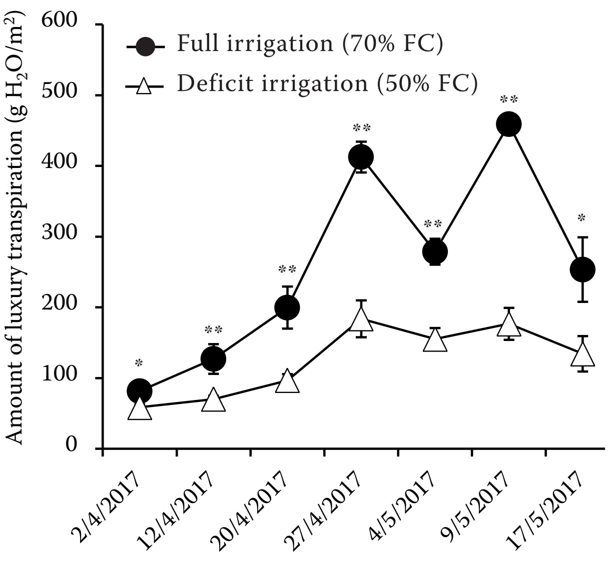


Figure 3. The amount of luxury transpiration under different irrigation schedules. *$P$ < 0.05; **$P$ < 0.01; FC – field capacity

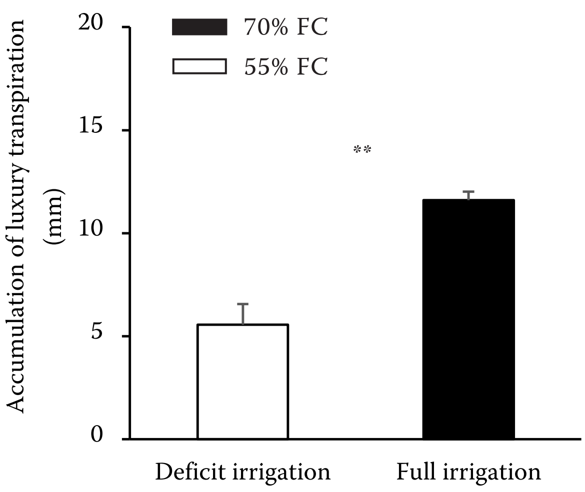


Figure 4. Accumulation of luxury transpiration under different irrigation schedules. **$P$ < 0.01; FC – field capacity

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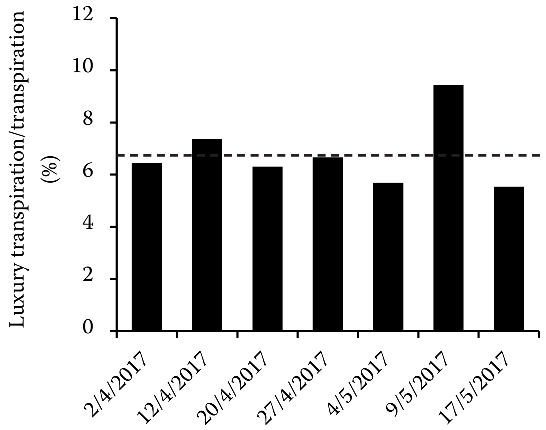


Figure 5. The ratio of daily luxury transpiration to crop daily transpiration at different sampling dates under the traditional irrigation practices. The dotted line represents the average daily luxury transpiration amount

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