EFFECTS OF WATER PONDING ON DECREASING LEAF AND PANICLE TEMPERATURE IN RICE PADDY FIELDS

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Graphical abstract

Abstract

Several studies have suggested the spikelet fertility would be significantly damaged if the air temperature ($T_a$) was high at heading and flowering stage. In this study, we evaluated the effect of water ponding in two paddy fields to decrease leaf temperature ($T_l$) and panicle temperature ($T_p$) during the 2014 growing season. Within the first conventionally water managed paddy field (cultivar Akitakomachi), we set 1 m × 1 m experiment plot (Plot A\textsubscript{1}) from July 8\textsuperscript{th} to August 24\textsuperscript{th}, and water was put in 15 cm depth in the morning at 8:30. For expecting larger difference of leaf and panicle temperature between in and outside the plot, the plot was expended to 2 m × 2 m (Plot A\textsubscript{2}) from August 25\textsuperscript{th} to September 8\textsuperscript{th}, 2014, and water was put in 15 cm depth at noon. This method was also used in the plot B (2 m ×2 m) which was installed in another conventionally water managed field (cultivar Nikomaru) from September 9\textsuperscript{th} to 30\textsuperscript{th}, 2014. $T_l$ and $T_p$ were measured every two or three hours during daytime in every 10 cm canopy layer in and outside plots. In the first experimental paddy field, at largest, $T_l$ and $T_p$ in the plot were 4.3 °C, 5.5 °C lower than $T_l$ and $T_p$ outside the plot, respectively. $T_p$ was 6.6 °C lower than $T_a$ under low relative humidity condition. In the second experimental paddy field, $T_l$ and $T_p$ in the plot were 3.6 °C, 3.4 °C lower than $T_l$ and $T_p$ outside the plot, respectively. It revealed water ponding was a useful method to decrease leaf and panicle temperature under larger solar radiation, higher air temperature and lower relative humidity conditions at heading and flowering stage.

Keywords: Leaf temperature, panicle temperature, air temperature, water ponding

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1.0 INTRODUCTION

Rice (Oryza sativa L.) is a staple food for nearly half the world’s population [1], and highly adaptive to a range of environments from temperate to tropical climates [2].

In recent years, many occurrences of floret sterility have been reported [3], [4], [5]. It has been proved that floret sterility induced by high temperature during anthesis can decrease the yield of rice, and it may become a problem under global warming, even in the temperate regions such as Japan [6], [7], [8], [9]. In Japan, the heading and flowering stage of rice occurs in hot summer, mostly in July and August. In China Yangtze River Basin, floret sterility has begun to appear since 1990 [10].

High temperature can impair pollen activity, pollen germination on the stigma and pollen tube growth, which might cause sterility [11], [12], [13]. In grain-filling process, it can hinder photosynthetic transportation to grain, and shorten effective grain filling stage, and reduce endosperm cell division and elongation, thus decreasing grain plumpness [13][14]. For the entire growth stage of rice, heading and flowering stage is the most sensitive stage to high temperature. Some studies have suggested that the spikelet fertility will be significantly damaged if the air temperature exceeds 35.0 °C at heading and...
flowering stage [15], [16], [17], [18]. And even slight difference in heat tolerance among ecotypes and cultivars could be critical [19], [20], [21]. In order to alleviate the high-temperature damage, researchers have done a lot of exploration in sowing adjustment, breeding, fertilizer treatment, but using water ponding to decrease the canopy and panicle temperature is rare.

Measuring canopy temperature to determine the crop’s capability to avoid dehydration under stress is gaining acceptance as a potential selection tool [22], [23]. Some authors have reported the leaf temperature (Tl) and panicle temperatures (Tp) were different from air temperature (Ta) under different climatic conditions. In 2005, Oue et al. reported that Tp would reach to 33.5 °C if Ta was 35.0 °C under elevated CO2 condition [24]. In 2007, Matsui et al. reported that the Ta was 6.0 °C lower than Tp under dry and windy conditions in New South Wales, Australia [9]. In 2010, Tian et al. reported that Tp was higher than Ta under humid windless conditions in Jianghan Basin, China [25].

In this study, leaf temperature and panicle temperature in every 10 cm canopy layer were investigated at heading and flowering stage under different water depth in the experimental paddy fields.

2.0 MEASUREMENTS AND METHODS

2.1 Study Site

Two experiments were conducted to study the influence of high temperature on grain sterility at heading and flowering stage of two Japonica type, Akitakomachi and Nikomaru cultivars in two paddy fields located in the Ehime University Senior High School, Matsuyama, Japan (33°50′N, 132°47′E). The schematic arrangement of observation site and its surroundings is shown in Figure 1.

![Figure 1 The schematic arrangement of observation site and its surroundings](image)

The area of two conventionally water managed paddy fields was both 0.16 ha. Two paddy fields were parallel, and the paddy field (cultivar Nikomaru) was in the east of the other paddy field (cultivar Akitakomachi). The two fields were surrounded by upland fields, greenhouses and residential houses. The fetch of the paddy field (cultivar Akitakomachi) in the prevailing wind direction was about 50.0 m.

The cultivar Akitakomachi was transplanted on May 27th and harvested on September 9th, 2014. Nikomaru was transplanted on June 23rd and harvested on October 17th, 2014.

2.2 Microclimate Measurement

The global solar radiation (St), downward longwave radiation (Ld) and upward longwave radiation (Lu) were observed by CNR-4 (Kipp & Zonen, Netherland) at 2.0 m. Air temperature (Ta) and relative humidity (RH) were measured by psychrometers HMP-45A (Vaisala Inc., Helsinki, Finland). Thermometers and hygrometers were set at 0.6 m and 1.0 m on June 1st, and they were lifted to 1.0 m and 1.5 m, respectively on July 28th, 2014. Horizontal wind speeds were observed within and above the canopy by three-cup anemometers 014A (MetOne, USA) mounted at 0.6 m, 1.0 m and 2.0 m, respectively. Water temperature was measured by thermocouple sensor. All the data were sampled every 10 s, and averaged and recorded every 10 min by a data logger CR23x (Campbell Scientific Inc., Logan, UT, USA).

Plant height and leaf area index (LAI) were measured by means of three destructive samplings at interval of one week.

2.3 Experiments in the Plots

Within the first conventionally water managed paddy field (cultivar Akitakomachi), we set 1 m × 1 m experiment plot (Plot A1) from July 8th to August 24th, and water was put in 15 cm depth in the morning at
8:30. For expecting larger difference of leaf and panicle temperature between in and outside the plot, the plot was expanded to 2 m × 2 m (Plot A2) from August 25th to September 8th, 2014, and water was put in 15 cm depth at noon. This method was also used in the plot B (2 m × 2 m) which was installed in another conventionally water managed field (cultivar Nikomaru) from September 9th to 30th, 2014.

At heading and flowering stage, irrigation was conducted outside the plot (means natural condition) at 5 days interval. And 8 cm depth irrigated water decreased to 0 by evaporation and infiltration within one and half days. Except the water depth, other conditions outside the plots are the same with conditions in the plots.

\( T_i \) and \( T_p \) were measured every two or three hours during daytime in every 10 cm canopy layer in and out of plots by an infrared thermometer THI-500 (Tasco, Japan). In the first experimental paddy field, \( T_i \) was measured from July 9th to September 8th, 2014. And \( T_p \) was measured from July 31th to September 8th, 2014. In the second experimental paddy field, \( T_i \) and \( T_p \) were measured from September 9th to 30th, 2014. \( T_i \) and \( T_p \) data were recorded in ZR-RX 20 portable multi-logger (Omron, Japan).

3.0 RESULTS

3.1 Microclimate

In the first experimental paddy field, during the whole measurement period, the daily average \( S_i \) was 262.50 W m\(^{-2}\). The average \( T_d \) was 24.73 °C. And the highest air temperature was 34.64 °C on July 26th, 2014. The average RH was 80.57, and average \( v \) at 100 cm was 0.54 m s\(^{-1}\).

The total precipitation was 670.0 mm and the total evapotranspiration was 566.74 mm meaning the daily evapotranspiration was 5.45 mm d\(^{-1}\).

3.2 Plant Height (PH) and Leaf Area Index (LAI)

The variations through the growing season of plant height (PH) and leaf area index (LAI) from May 27th to August 29th, 2014 in the first experimental paddy field, and PH, LAI from June 23rd to October 15th, 2014 in the second experimental paddy field are shown in Figure 2 and Figure 3, respectively.

The total growth period can be divided into four stages according to the LAI observations. And the four stages are: (1) the early stage of reproductive growth, (2) the early stage of reproductive growth phase, (3) the heading and flowering stage and (4) the ripening stage.

In the first experimental paddy field, on the transplanting day, PH was 13.0 cm, and LAI was around 0. Before it was harvested, PH was around 105.0 cm, and LAI was 3.8. The heading and flowering stage started from July 22nd to 26th, and the largest LAI was 5.1 on July 25th, 2014.

In the second experimental paddy field, LAI was 4.6 at heading and flowering stage starting from August 28th to September 2nd, 2014.

3.3 Leaf Temperature (\( T_l \))

Water status and transpiration play a major role in controlling temperature as stress develops [22][23][26][27]. Transpiration cooling is the main driver of the difference between panicle and air temperature [28].

After water ponding in the plot, leaf temperature in the plot \( (T_{l(out)}) \) was lower than leaf temperature outside the plot \( (T_{l(out)}) \) mostly.

Based on all the measurements in the first experimental paddy field, the percentage of the cases of \( T_{l(out)} < T_{l(out)} \) was the largest at 13:00 mostly. And it could be as large as 95.0 % meaning \( T_{l(out)} \) was almost always lower than \( T_{l(out)} \) at that time.

Water ponding made the water depth \( (d_{w}) \) different in and outside the plot, which resulted in the different \( \Delta W \) meaning the change of stored heat energy of water based on the energy balance in the paddy field as shown in eq. (1) and (2).
\[ Rn = H + LE + G + \delta W \]

where \( Rn \) is net radiation (W m\(^{-2}\)), \( H \) is sensible heat flux (W m\(^{-2}\)), \( LE \) is latent heat flux (W m\(^{-2}\)), \( G \) is soil heat flux (W m\(^{-2}\)).

\[
\delta W = C_w d_w \frac{T_{w[l]} - T_{w[h]}}{\Delta t}
\]

where \( C_w \) is water heat capacity (4.18 J m\(^{-3}\) K\(^{-1}\)), \( T_w \) is water temperature (K) and \( \Delta t \) is time period (s).

July 25\(^{th}\) and August 19\(^{th}\) were selected to show the influence of \( \delta W \) on \( T_l \) and \( T_p \) in the plot (as shown in Table 1). From July 22\(^{nd}\) to 31\(^{st}\), 2014, with the increase of \( T_w \) in the morning, \( \delta W \) was positive, meaning the water body absorbed the energy, and it could cool rice plant, so \( T_{l(in)} \) was lower than \( T_{l(out)} \). In the afternoon, since \( T_w \) decreased gradually, \( \delta W \) was negative meaning the water body released energy to the rice plant, so the high \( T_w \) could make \( T_{l(in)} \) higher under short plant height (10-40 cm). And it led to the low percentage of cases of \( T_{l(in)} < T_{l(out)} \) at 10-40 cm. In the upper canopy layer (50-90 cm), transpiration was promoted by sufficient water, so \( T_{l(in)} \) was lower, which made the percentage of cases of \( T_{l(in)} < T_{l(out)} \) higher.

After heading and flowering stage, since water surface was largely covered with rice plant, and the change of \( T_w \) was lower, so \( \delta W \) was smaller, which meant less energy was released to the rice plant. And the promoted transpiration made \( T_{l(in)} \) and \( T_{p(in)} \) lower. Therefore, the percentage cases of \( T_{l(in)} < T_{l(out)} \) from August 1\(^{st}\) to 20\(^{th}\), 2014 was higher.

### Table 1
<table>
<thead>
<tr>
<th>Date</th>
<th>Time</th>
<th>( T_0 )</th>
<th>( T_{l(in)} )</th>
<th>( T_{w(out)} )</th>
<th>( \delta W_{l(in)} )</th>
<th>( \delta W_{w(out)} )</th>
<th>( T_{l(in)} - T_{l(out)} )</th>
<th>( T_{l(in)} - T_{l(out)} )</th>
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<td>10:40</td>
<td>32.14</td>
<td>29.76</td>
<td>30.05</td>
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<td>25.08</td>
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<td>-0.18</td>
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<td>13:50</td>
<td>33.52</td>
<td>35.45</td>
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<td>-36.23</td>
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<tr>
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<td>34.23</td>
<td>33.54</td>
<td>30.91</td>
<td>-75.24</td>
<td>-9.75</td>
<td>0.06</td>
<td>-0.12</td>
</tr>
<tr>
<td>Aug. 19(^{th})</td>
<td>10:40</td>
<td>33.02</td>
<td>27.64</td>
<td>28.56</td>
<td>242.44</td>
<td>37.27</td>
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<td>33.12</td>
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<tr>
<td>Aug. 19(^{th})</td>
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<td>26.92</td>
<td>-36.784</td>
<td>-21.25</td>
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<td>-0.38</td>
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</table>

Examples of \( T_l \) in the two experimental paddy fields under clear conditions are shown in Figure 4 and Figure 5.

**Figure 4** Leaf temperature \( (T_l) \) in the first experimental paddy field \( (\circ) \); in the plot, ●; outside the plot: July 23\(^{th}\) (a-c), August 11\(^{th}\) (d-g) and August 19\(^{th}\) (h-j)

Water ponding could decrease \( T_l \) consistently in the plot during daytime as a whole.

In the first experimental paddy filed, at largest, \( T_{l(in)} \) was 4.3 °C lower than \( T_{l(out)} \) (10:40, August 19\(^{th}\)).

In the second experimental paddy filed, at largest, \( T_{l(in)} \) was 3.6 °C lower than \( T_{l(out)} \) (18:10, September 16\(^{th}\)).
3.4 Panicle Temperature ($T_p$)

After water ponding, $T_p$ was also mostly lower than $T_p$. Based on all the measurements in the first experimental paddy field, the percentage of cases of $T_p$ < $T_p$ ranged from 52.5% to 93.8%, meaning that water ponding could make panicle temperature lower.

In the first experimental paddy field, at largest, $T_p$ was 5.5°C lower than $T_p$ and it occurred on August 11th at 12:30. During that time, it was sunny with 29.0°C, and relative humidity was 64.8%, and wind speed was 0.9 m/s. Under the $T_a$ condition of 30.8°C, $T_p$ was controlled to be 25.7°C, while $T_p$ was 28.9°C (10:50, August 18th). And under the $T_a$ condition of 33.0°C, $T_p$ was controlled to be 25.4°C, while $T_p$ was 30.8°C (10:40, August 19th), meaning that $T_p$ was 6.6°C lower than $T_a$. At that time, solar radiation ($S_l$) was large, while relative humidity ($RH$) and wind speed ($u$) were low.

In the second experimental paddy field, because of low $T_a$ in September, $T_p$ was lower than $T_p$ in the first experimental paddy field. After water ponding, at largest, $T_p$ was 3.4°C lower than $T_p$ under the $T_a$ condition of 27.1°C, and $T_p$ was controlled to be 22.9°C, while $T_p$ was 26.3°C (11:20, September 26th). While under the $T_a$ condition of 27.5°C, $T_p$ was controlled to be 25.8°C, and $T_p$ was 27.7°C (11:40, September 29th).

Examples of $T_p$ in the two experimental paddy fields under clear conditions are shown in Figure 6 and Figure 7.

### 4.0 DISCUSSION

Climate factors, such as $S_l$, $T_a$, $RH$ and $u$ have influence on $T_l$ and $T_p$. Table 2 shows R-square ($R^2$) results of $S_l$, $T_a$, $RH$ and $u$ on $T_l$ and $T_p$ in the two experimental paddy fields.

Under the same $T_a$ condition, $T_l$ was lower than $T_p$ because of larger transpiration of a leaf than a panicle. Under larger $S_l$ and higher $T_a$ conditions, $T_l$ and $T_p$ were larger. And under lower $RH$ condition, $T_l$ and $T_p$ were larger. Since the $R^2$ results of $u$ and $T_l$ and $T_p$ were low, $u$ had almost no influence on the difference of $T_l$ and $T_p$. These results have shown that water ponding was effective to decrease leaf and panicle temperature under larger solar radiation, higher air temperature and lower relative humidity conditions.

![Figure 7 Panicle temperature ($T_p$) in the second experimental paddy field (where $T_p$ in the plot, $T_p$ outside the plot): September 14th (a-c), September 26th (d-f) and September 29th (g-i)](image)

![Figure 6 Panicle temperature ($T_p$) in the first experimental paddy field (where $T_p$ in the plot, $T_p$ outside the plot): August 11th (a-c), August 18th (d-g) and August 19th (h-j)](image)

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<th>Nikomaru</th>
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</thead>
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<td>0.135</td>
</tr>
<tr>
<td>$T_p$ (°C)</td>
<td>0.242</td>
<td>0.272</td>
</tr>
<tr>
<td>$RH$ (%)</td>
<td>0.311</td>
<td>0.450</td>
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<tr>
<td>$u$ (m/s)</td>
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</tbody>
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5.0 CONCLUSION

In this study, we evaluated the effect of water ponding in two paddy fields (cultivar Akitakomachi and Nikomaru) to decrease leaf temperature \( T_l \) and panicle temperature \( T_p \) at heading and flowering stage. Compared with water ponding in the plot \( A_1 \) (1 m × 1 m) in the morning at 8:30 from July 8th to August 24th, water ponding in the plot \( A_2 \) (2 m × 2 m) plot at noon from August 25th to September 8th made the larger difference of \( T_l \) and \( T_p \) between in and outside the plot. For example, on August 11th and September 5th at 15:00, under similar SI \( (=688.4 \ \text{W m}^{-2}) \), \( T_a \) \( (=29.5 \ \text{°C}) \) and RH \( (=63.1 \ \%\) conditions, \( T_{\text{in}} - T_{\text{in}} \) and \( T_{\text{out}} - T_{\text{out}} \) on September 5th were 2.82, 2.02 °C larger, respectively. So this method was also used in the plot \( B \) (2 m × 2 m) which was installed in another conventionally water managed field (cultivar Nikomaru) from September 9th to 30th, 2014.

In our experimental paddy fields, because of water ponding, \( T_{\text{in}} \) was lower than \( T_{\text{out}} \) mostly. And \( T_{\text{in}} \) was 6.8 °C lower than \( T_{\text{out}} \) under high solar radiation, high air temperature and low relative humidity conditions.

Our hypothesis was that ponding water could cool leaves and panicles under extremely hot temperature. But from July to September, 2014, the monthly air temperature was lower than the 10-year average temperature in Matsuyama based on the data from Japan Meteorological Agency. At heading and flowering stage, the highest temperature was 34.64 °C on July 26th, 2014. So we could not observe \( T_l \) and \( T_p \) higher than 35.0 °C, and we could not confirm our hypothesis for extreme temperature.

Our results have demonstrated that water ponding was a useful method to decrease leaf and panicle temperature under larger solar radiation, higher air temperature and lower relative humidity conditions.

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References


