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

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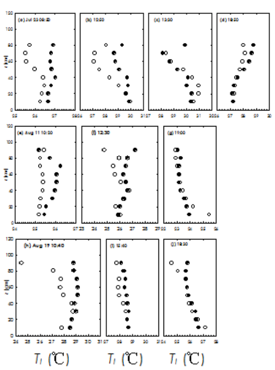
Graphical abstract



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_1) 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 expended to 2 m × 2 m (Plot A_2) 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. 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 ℃, 5.5 ℃ lower than T_l and T_p outside the plot, respectively. T_p was 6.6 ℃ 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 ℃, 3.4 ℃ 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

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 ℃ 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 (T_l) and panicle temperatures (T_p) were different from air temperature (T_a) under different climatic conditions. In 2005, Oue *et al*. reported that T_p would reach to 33.5 ℃ if T_a was 35.0 ℃ under elevated CO_2 condition [24]. In 2007, Matsui *et al*. reported that the T_p was 6.0 ℃ lower than T_a under dry and windy conditions in New South Wales, Australia [9]. In 2010, Tian *et al*. reported that T_p was higher than T_a 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.

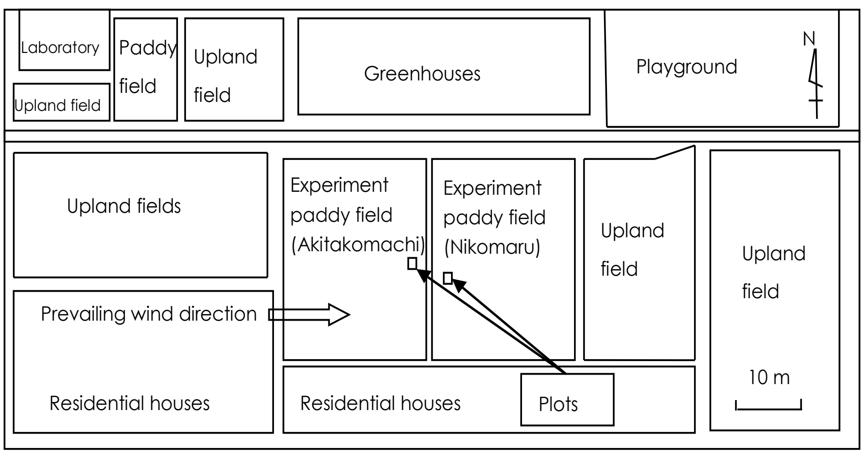


Figure 1 The schematic arrangement of observation site and its surroundings

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 (T_a) 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 A_1) 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 expended to 2 m × 2 m (Plot A_2) 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_l 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_l was measured from July 9th to September 8th, 2014. And T_p was measured from July 31st to September 8th, 2014. In the second experimental paddy field, T_l and T_p were measured from September 9th to 30th, 2014. T_l 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 St was 262.50 W m^{-2}. The average T_a was 24.73 ℃. And the highest air temperature was 34.64 ℃ on July 26th, 2014. The average RH was 80.57, and average u 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.

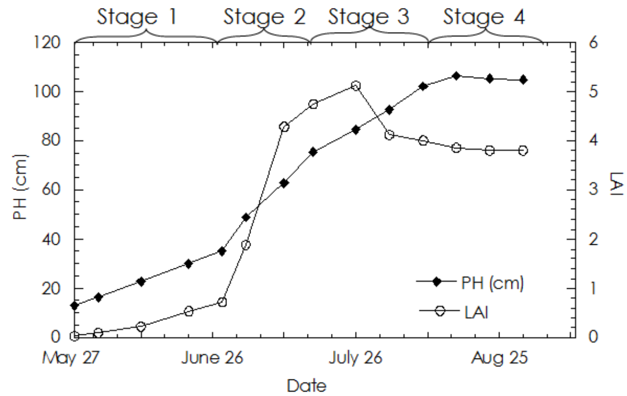


Figure 2 Variations through the growing season of plant height (PH), leaf area index (LAI) from May 27th to August 29th, 2014 in the first experimental paddy field

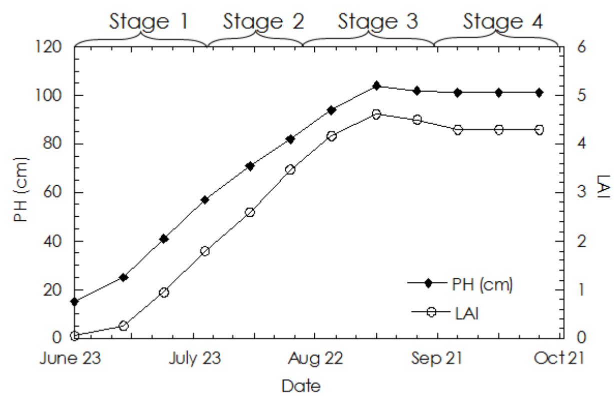


Figure 3 Variations through the growing season of plant height (PH), leaf area index (LAI) from June 23rd to October 15th, 2014 in the second experimental paddy field

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 ($T_{l(in)}$) 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 $T_{l(in)} < T_{l(out)}$ was the largest at 13:00 mostly. And it could be as large as 95.0 % meaning $T_{l(in)}$ 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 δW 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).

$$Rn = H + LE + G + \delta W \quad (1)$$

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}).

$$\delta W = C_w d_w \frac{T_{w(t+1)} - T_{w(t)}}{\Delta t} \quad (2)$$

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

July 25th and August 19th were selected to show the influence of δW on T_l and T_p in the plot (as shown in Table 1). From July 22nd to 31st, 2014, with the increase of T_w in the morning, δW 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, δW 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 δW 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 cases of $T_{l(in)} < T_{l(out)}$ from August 1st to 20th, 2014 was higher.

Table 1 Change of stored heat energy of water (δW), leaf temperature (T_l) and panicle temperature (T_p) in and outside the plot A1 on July 25th and August 19th, 2014

Date	Time	T_a (℃)	$T_{w(in)}$ (℃)	$T_{w(out)}$ (℃)	$\delta W_{(in)}$ (W m^{-2})	$\delta W_{(out)}$ (W m^{-2})	$T_{l(in)}$ - $T_{l(out)}$ (10-40 cm) (℃)	$T_{l(in)}$ - $T_{l(out)}$ (50-90 cm) (℃)	$T_{p(in)}$ - $T_{p(out)}$ (50-90 cm) (℃)
July 25th	10:40	32.14	29.76	30.05	284.24	25.08	-0.23	-0.18	-
July 25th	13:50	33.52	35.45	33.61	-106.59	-36.23	0.44	-0.75	-
July 25th	16:10	34.23	33.54	30.91	-75.24	-9.75	0.06	-0.12	-
Aug. 19th	10:40	33.02	27.64	28.56	242.44	37.27	-0.28	-1.77	-1.79
Aug. 19th	15:40	33.12	29.14	28.96	-34.14	-19.06	-0.11	-0.40	-0.21
Aug. 19th	18:30	28.23	27.87	26.92	-36.784	-21.25	0.04	-0.38	-0.29

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

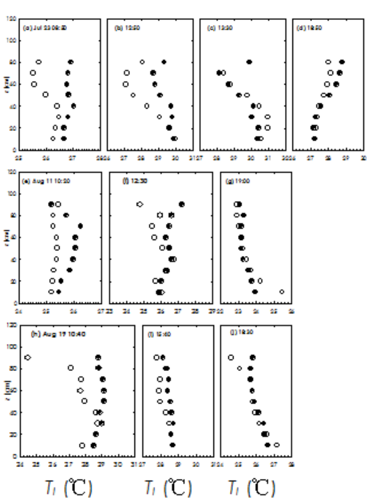


Figure 4 Leaf temperature (T_l) in the first experimental paddy field (○; T_l in the plot, ●; outside the plot): July 23rd (a-d), August 11th (e-g) and August 19th (h-j)

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

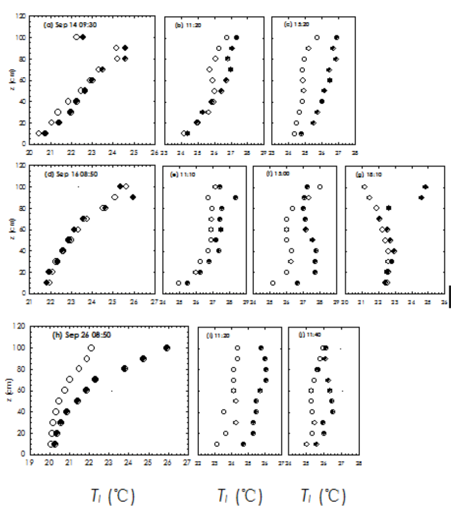


Figure 5 Leaf temperature (T_l) in the second experimental paddy field (○; T_l in the plot, ●; outside the plot): September 14th (a-c), September 16th (d-g) and September 26th (h-j)

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

In the second experimental paddy filed, at largest, $T_{l(in)}$ was 3.6 ℃ lower than $T_{l(out)}$ (18:10, September 16th).

3.4 Panicle Temperature (T_p)

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

In the first experimental paddy field, at largest, $T_{p(in)}$ was 5.5 ℃ lower than $T_{p(out)}$ and it occurred on August 11th at 12:30. During that time, it was sunny with 29.0 ℃, and relative humidity was 64.8 %, and wind speed was 0.8 m s^{-1}. Under the T_a condition of 30.9 ℃, $T_{p(in)}$ was controlled to be 25.7 ℃, while $T_{p(out)}$ was 28.9 ℃ (10:50, August 18th). And under the T_a condition of 33.0 ℃, $T_{p(in)}$ was controlled to be 26.4 ℃, while $T_{p(out)}$ was 30.8 ℃ (10:40, August 19th), meaning that $T_{p(in)}$ was 6.6 ℃ lower than T_a. At that time, solar radiation (*St*) 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, $T_{p(in)}$ was 3.4 ℃ lower than $T_{p(out)}$ under the T_a condition of 27.1 ℃, and $T_{p(in)}$ was controlled to be 22.9 ℃, while $T_{p(out)}$ was 26.3 ℃ (11:20, September 26th). While under the T_a condition of 27.5 ℃, $T_{p(in)}$ was controlled to be 25.8 ℃, and $T_{p(out)}$ was 27.7 ℃ (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.

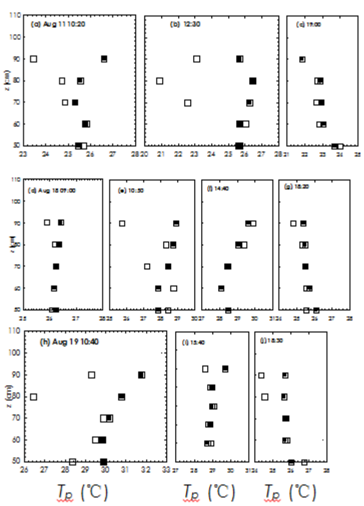


Figure 6 Panicle temperature (T_p) in the first experimental paddy field (□; T_p in the plot, ■; T_p outside the plot): August 11th (a-c), August 18th (d-g) and August 19th (h-j)

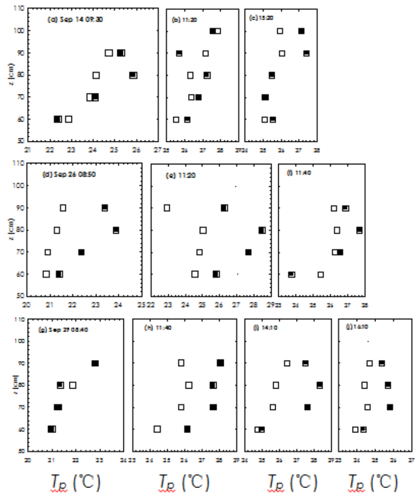


Figure 7 Panicle temperature (T_p) in the second experimental paddy field (□; T_p in the plot, ■; T_p outside the plot): September 14th (a-c), September 26th (d-f) and September 29th (g-j)

4.0 DISCUSSION

Climate factors, such as *St*, T_a, *RH* and *u* have influence on $T_{l(out)} - T_{l(in)}$ and $T_{p(out)} - T_{p(in)}$. Table 2 shows R-square (R^2) results of *St*, T_a, *RH* and *u* on $T_{l(out)} - T_{l(in)}$ and $T_{p(out)} - T_{p(in)}$ 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 *St* and higher T_a conditions, $T_{l(out)} - T_{l(in)}$ and $T_{p(out)} - T_{p(in)}$ were larger. And under lower *RH* condition, $T_{l(out)} - T_{l(in)}$ and $T_{p(out)} - T_{p(in)}$ were larger. Since the R^2 results of *u* and $T_{l(out)} - T_{l(in)}$ and $T_{p(out)} - T_{p(in)}$ were low, *u* had almost no influence on the difference of T_l and T_p between in and outside the plot.

Table 2 R-square (R^2) results of *St*, T_a, *RH* and *u* on $T_{l(out)} - T_{l(in)}$ and $T_{p(out)} - T_{p(in)}$ in the two experimental paddy fields

Item	Akitakomachi		Nikomaru	
	$T_{l(out)}$-$T_{l(in)}$	$T_{p(out)}$-$T_{p(in)}$	$T_{l(out)}$-$T_{l(in)}$	$T_{p(out)}$-$T_{p(in)}$
St (W m^{-2})	0.427	0.471	0.135	0.272
T_a (℃)	0.548	0.242	0.450	0.292
RH (%)	0.690	0.311	0.373	0.338
u (m s^{-1})	0.299	0.243	0.142	0.033

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.

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 *St* (=668.4 W m^{-2}), T_a (=29.5 ℃) and *RH* (=63.1) conditions, $T_{l(out)}$ - $T_{l(in)}$ and $T_{p(out)}$ - $T_{p(in)}$ on September 5th were 2.82 ℃, 2.02 ℃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, $T_{p(in)}$ was lower than T_a mostly. And $T_{p(in)}$ was 6.6 ℃ lower than T_a 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 ℃ on July 26th, 2014. So we could not observe T_l and T_p higher than 35.0 ℃, 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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