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Effects of Elevated Air Temperature on Yield and Yield Components of Rice

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온도 상승 조건이 벼의 수량 및 수량구성요소에 미치는 영향

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ABSTRACT

High temperature stress would affect rice production in the future as heat wave is expected to occur frequently under climate change conditions. The objective of this study was to obtain rudimentary information to assess the impact of heat stress on rice yield and its yield component in Korea. Two rice cultivars "Hwaseongbyeo" (Japonica) and "Dasanbyeo" (Tongil-type) were grown at different nitrogen fertilization levels in two seasons. These cultivars were grown in 1/5000a Wagner pot placed within four plastic houses where temperature was controlled at ambient, ambient+1.5°C, ambient+3°C and ambient+5°C throughout the rice growing season in Suwon (37°16'N, 128°59'E), Korea. The degree of temperature change affected grain yield whereas the level of nitrogen had little impact on grain yield. The number of panicle per pot and spikelet per panicle were not significantly different among temperature treatments in both cultivars tested. In contrast, 1000-grain weight and ripened grain ratio were decreased significantly under the treatments raising the air temperature to the level of 5.0°C and 1.5°C above the ambient air temperature in Dasanbyeo and Hwaseongbyeo, respectively. Reduction of 1000–grain weight and ripened grain ratio under the temperature treatments of 3.0°C and 5.0°C above the ambient air temperature resulted in significantly less grain yield for Dasanbyeo and Hwaseongbyeo, respectively. The greater sensitivity of grain yield to temperature increase in Dasanbyeo was attributable to the sharp decrease of 1000-grain weight and ripened grain ratio with the temperature rise above 23°C during ripening period. On the other hand, Hwaseongbyeo had little variation of them in the temperature range of 23-27°C. These results suggested that grain yield would decrease under future climate conditions due to grain weight decreased by shorter grain filling period as well as the ripened grain ratio reduced by spikelet sterility and early abortion of rice kernel development. Thus, it would be essential to use cultivars tolerant to heat stress for climate change adaptation, which merits further studies for developing varieties that have traits to avoid spikelet sterility and early abortion of rice kernel, e.g., early morning flowering, under heat wave.

***Key words*: High temperature, Yield, Yield components, Rice**

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I. Introduction

Global warming is unequivocal and becomes accelerated recently. Projections to the end of this century suggest that mean global temperature will increase by 1.0-3.7°C, depending on representative concentration pathways scenario (IPCC, 2014). The projected climate change characterized by the increase in both frequency and intensity of high temperature along with its large variability is expected to become a major detrimental factor to rice production not only in sub-topical and tropical regions of the world where most of rice is grown presently and temperature is above optimum for rice production, but also even in temperate region in the future climate.

The optimum temperature for the normal development of rice ranges from 27 to 32°C (Yin *et al*., 1996). High temperature affects almost all the growth stages of rice, i.e. from emergence to ripening and harvesting (Shah *et al*., 2001). The developmental stage at which the plant is exposed to heat stress determines the severity of the possible damage to the crop (Wahid *et al*., 2007).

Plant growth period can be divided into two developmental stages: vegetative growth period and reproductive growth period. Generally, high temperature accelerates and low temperature delays heading by reducing and lengthening the vegetative period, respectively (Ahn and Vergara, 1969; Hosoi and Tamagata, 1973). However, supra-optimal high temperature delays heading (Asakuma and Iwashita, 1961; Azmi, 1969). Generally, high temperature stress effect on grain yield is greater during reproductive stage than during vegetative stage (Yoshida, 1981).

High temperature during vegetative period affects grain yield mainly through the effects on tillering and eventually on panicle number. Tillering increases with rising temperature in the range of 15 to 33°C, and temperature above 33°C is unfavorable for tillering (Chaudhary and Ghildyal, 1970). And Yoshida (1973) also reported that higher temperatures increased tiller numbers but at 3-5 weeks after sowing, temperature only slightly affected the tillering rate and the relative growth rate except at the lowest temperature (22°C) tested. After the active tillering stage, high temperature decreases the number of panicles (Yamamoto *et al*., 1985).

High temperature during reproductive stage would result in decrease of grain yield by less number of spikelets produced per unit dry weight or nitrogen absorbed (Yoshida, 1983), lower spikelet fertility (Satake and Yoshida, 1978; Tashiro and Wardlaw, 1991; Kim *et al.*, 1996a; Kim *et al*., 1996b; Matsui *et al.*, 1997), and accelerated panicle senescence of grain (Kim *et al*., 2011). High temperature-induced spikelet sterility has decreased rice yield in tropical Asia (Osada *et al.*, 1973) and Africa (Matsushima *et al*., 1982). Sterility induction by high temperature is most sensitive at flowering time and next most sensitive at meiotic stage of spikelet (Satake and Yoshida, 1978). During microsporogenesis the processes close to the meiotic stage are most sensitive to high temperature (Yoshida, 1981). A significant decrease in pollen production was found at 5°C above ambient temperature (Prasad *et al*., 2006) that was attributed to impaired cell division of pollen mother cell (Takeoka *et al*., 1992). The varietal differences in the tolerance to high temperature induced sterility during flowering has been well documented (Osada *et al*., 1973; Satake and Yoshida, 1978; Yoshida, 1981; Jagadish *et al*., 2007; Matsui *et al*., 2001) For instance, Matsui *et al*. (2001) reported a 3°C difference in critical temperature causing 50% spikelet sterility between the tolerant variety "Akitakomatch" (40°C) and the susceptible variety "Hinohikari" (37°C).

Yoshida and Hara (1977) and Oh-e *et al*. (2007) observed that the rate of grain growth was faster and the grain-filling period was shorter at higher temperatures. High temperatures above 30°C are generally not favorable for ripening (Osada *et al*., 1973). Morita *et al*. (2004) reported that the final grain weight which is the product of the rate and duration of grain growth is affected by high temperatures which increase growth rate in the early ripening period but reduce the duration of grain growth and ultimately result in decreases in final grain weight. The length of the ripening period is inversely correlated with daily mean temperature and, therefore, grain filling is poor when temperature is above optimum, although a rise in temperature increases the rate of grain filling. The duration of grain filling, defined as the number of days required to reach maximum weight, was found to be 13 days at a mean temperature of 28°C, and 33 days at 16°C for cultivar IR20, an *indica* rice. But, the cultivar Fujisaka 5, a *japonica* rice, took a little longer to ripening: 18 days at a mean temperature of 28°C and 43 days at 16°C (Oh-e *et al*., 2007). The reduced grain filling period due to high temperature is ascribed to the accelerated panicle senescence rather than the earlier shortage of assimilate due to leaf senescence (Kim *et al*., 2011).

In mid-to high-latitude regions, moderate to medium increases in temperature can have small beneficial impacts on the main cereal crops like rice at local scale (IPCC, 2007). However, even moderate temperature increases are likely to have negative yield impacts for major cereal crops in low-latitude regions. For temperature increases of more than 3°C, average impacts are stressful to all crops and to all regions that encompass the majority of global cereal production area. The ongoing climate change in Korea also is projected to decrease rice yield and deteriorate grain quality in the future as the projected high temperature especially during grain filling period will reduce grain filling duration and grain weight (Yun, 1990; Lee *et al*., 1991; Chung *et al*., 2006). However, such results are based on models that have limited representation of impacts on extreme events and CO_2 fertilization effect. To derive short-term and long-term adaptation strategies for rice production, it would be helpful to assess the impact of climate change on rice yield by its yield component.

Although climate change due to global warming would also substantially affect rice production in Korea, the major cause of yield reduction could differ from that in other countries. Thus, it would be advantageous to obtain basic information for assessing the impact of global warming on rice production in Korea. The objectives were to examine the effect of elevated air temperature on rice yield in terms of yield components under elevated temperature conditions.

II. Materials and Methods

2.1. Experimental set-up

For the different temperature treatments during rice growing season pot experiments were conducted in temperature-controlled plastic houses located at the Experimental Farm of Seoul National University (37°16'N and 126°59'E), Suwon, Korea in 2008 and 2009. The plastic houses were controlled to three temperature regimes in 2008; ambient (T1), ambient+1.5°C (T2) and ambient+3.0°C (T3) in 2008, and four temperature regimes in 2009; ambient (T1), ambient+1.5°C (T2), ambient+3.0°C (T3), and ambient+5.0°C (T4). In the year 2008, a japonica rice variety "Hwaseongbyeo" was transplanted with three 25 days old seedlings per a 1/5000a Wagner pot on 8th June and grown at two nitrogen fertilizer levels of 120 kg N/ha (0.5 g/pot) and 180 kg N/ha (0.75 g/pot). In the year 2009 two rice cultivars "Hwaseongbyeo" (*Japonica*) and "Dasanbyeo" (*Tongil*-type) were transplanted with three 25 days old seedlings per a 1/5000a Wagner pot on 9th June and grown at a nitrogen fertilizer levels of 120 kg N/ha (0.5 g/pot). Nitrogen fertilizers was applied in three splits; 50%, 20%, and 30% as basal, tillering, and panicle N fertilizer. Phosphorus fertilizer of 120 kg P_2O_5/ha (0.5 g/pot) was applied 100% as basal fertilizer before transplanting and potassium fertilizer of 120 kg K_2O/ha (0.5 g/pot) were applied 70% as basal and 30% at around panicle initiation stage.

2.2. Measurement of rice yield and statistical analysis

Grain yield and yield components were measured with 20 pots sampled at harvest. Final yield of rough rice was adjusted to 14% of water content.

Data were analyzed with statistical program SAS version 9.1 (SAS Inc. USA). Statistical significance of temperature treatments to nitrogen levels and rice varieties were analyzed by two ways nested ANOVA and Duncan's multiple range test.

III. Results

3.1. Temperature regimes

Daily series of air temperature inside the experimental plastic houses in the years 2008 and 2009 are shown in Fig. 1. The recorded temperatures were a little different from the targeted set temperature for each treatment. In the year 2008, mean temperatures recorded during rice growing season were 23.7°C in ambient temperature (T1), and higher by 1.7 (T2) and 3.0°C (T3) than T1. In the year 2009 mean temperatures recorded during rice growing season was 24.0°C in ambient temperature (T1), and higher by 1.7 (T2), 2.9 (T3) and 4.6°C (T4) as compared to T1.

3.2. Responses of yield and yield components to temperature treatments

As presented in Table 1, grain yield and yield components except spikelets per panicle were not significantly different among temperature elevation treatments and showed no interactions between temperature treatments and N fertilizer levels in the 2008 experiment. Spikelet number per panicle tended to increase with temperature rise in N fertilizer level of 120 kg N ha^{-1}, whereas it was not significantly different among temperature treatments in N fertilizer level of 180 kg N ha^{-1}. In 2009 experiment, panicle and spikelet number were

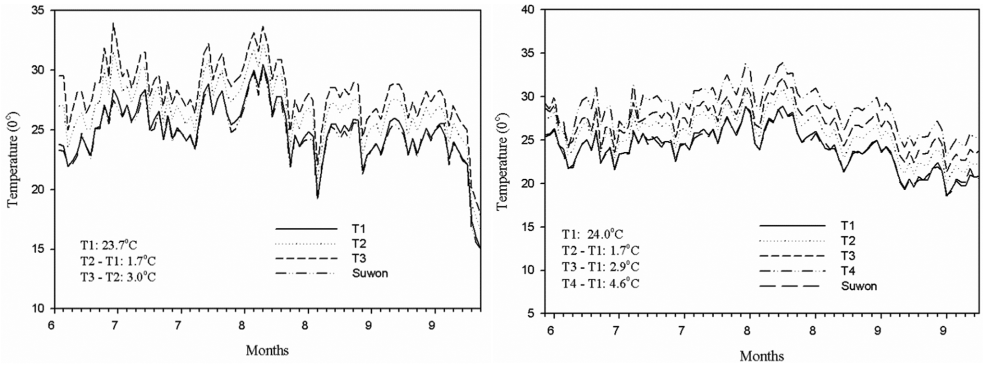

Fig. 1. Daily marches of air temperature inside the experimental plastic house in 2008 and 2009 that were set at ambient temperature (T1), ambient+1.5°C (T2), ambient+3.0°C (T3), and ambient+5.0 (T4).

Table 1. Yield components and grain yield of a rice cultivar "Hwaseongbyeo" under different air temperature regimes at two nitrogen fertilizer levels in 2008

Treatment		Panicle No. (no./pot)	Spikelets (no./panicle)	Spikelets (no/pot)	Ripened Grain (%)	1000 grain Weight (g)	Yield (g/pot)	Harvest Index (%)
N fertilizer (Kg N/ha)	Air temperature							
120	Ambient	9.25	63.33	586.75	96.54	22.95	12.89	37.79
	Ambient+1.5	10.00	57.28	573.25	95.65	22.54	12.36	39.24
	Ambient+3.0	9.00	68.22	608.67	96.67	22.90	13.47	42.64
	Mean	9.42	62.94	589.56	96.28	22.80	12.91	39.89
180	Ambient	10.50	63.08	661.50	95.67	22.99	14.55	42.05
	Ambient+1.5	11.75	67.38	793.50	95.05	22.78	17.21	42.31
	Ambient+3.0	11.00	75.88	831.00	94.66	23.82	18.72	43.45
	Mean	11.08	68.78	762.00	95.13	23.20	16.83	42.60
Pooled	Ambient	9.88	63.21^{b}	624.13	96.10	22.97	13.72	39.92^{b}
	Ambient+1.5	10.88	62.33^{b}	683.38	95.35	22.66	14.79	40.77^{b}
	Ambient+3.0	10.00	72.05^{a}	719.83	95.66	23.36	16.10	43.05^{a}
	LSD	NS	5.19	NS	NS	NS	NS	2.03
Temp.(T)	-	1.39^{NS}	9.76**	2.07^{NS}	1.23^{NS}	0.75^{NS}	2.50^{NS}	5.66*
Nitrogen(N)	-	9.11**	9.11**	19.38**	6.85**	0.60^{NS}	20.56**	11.96**
T × N	-	0.16^{NS}	2.97**	1.70^{NS}	0.99^{NS}	0.31^{NS}	1.88^{NS}	1.67^{NS}

NS, *, **, not significant, significant at the 0.05, 0.01 probability levels, respectively

not significantly different among temperature treatments, while ripened grain ratio, 1000-grain weight, grain yield, and harvest index were significantly different among temperature treatments and showed significantly different varietal responses to temperature treatments. Ripened grain ratio was significantly reduced at the temperature elevation treatment of 5°C (T4) above ambient temperature in Hwaseongbyeo but tended to decrease significantly from the temperature elevation treatments of 1.5°C (T2) in Dasanbyeo. Similar to the ripened grain ratio, 1000-grain weight tended to decrease significantly from the temperature elevation treatment of 3°C (T3) and 1.5°C (T2) above ambient temperature in Hwaseongbyeo and Dasanbyeo, respectively. Owing to the reduction of ripened grain ratio and 100-grain weight, grain yield tended to decrease significantly from the temperature elevation treatment of 5°C (T4) and 3°C (T3) above ambient temperature in Hwaseongbyeo and Dasanbyeo, respectively.

3.3. Responses of yield components to mean air temperature during grain filling period

The responses of yield components and harvest index to air temperature were fitted to quadratic equations as in Fig. 2. In the mean temperature range of 23-28°C during ripening period, the temperature responses of 1000-grain weight and ripened grain ratio were quite different between two cultivars “Hwaseongbyeo” and “Dasanbyeo”. Dasanbyeo showed very sharp decrease of 1000-grain weight and ripened grain ration with temperature rise above 23°C. Whereas, Hwaseongbyeo showed very gentle decrease in 1000-grain weight with temperature rise and little changes in ripened grain ration within the temperature range of 23-27°C, dropping sharply above this temperature range. On the contrary to 1000-grain weight and ripened grain ration, harvest index was higher and varied less according to temperature in Dasanbyeo than in Hwaseongbyeo. Hwaseongbyeo showed large decrease of harvest index above 27°C.

IV. Discussion

High temperature stress would be one of the important abiotic stresses to rice production in the future climate that is characterized by the increase in both frequency and intensity of high temperature along with its large variability. Results from a series of experiment under anticipated-temperature rise indicated that rice yield would be affected by 1000-grain weight and ripened grain ratio under high temperature during grain filling periods. Such findings would guide development of varieties for climate change adaptation by introducing traits on grain weight and grain filling ratio tolerant to high temperature conditions in Korea.

Grain yield and its components were affected by temperature elevation treatments differentially according to the tested cultivars but not according to nitrogen levels (Table 1). Among yield components, the number of panicle and spikelets per pot were not significantly different among temperature treatments in both cultivars tested. The panicle number is determined by the difference between the differentiated and the degenerated

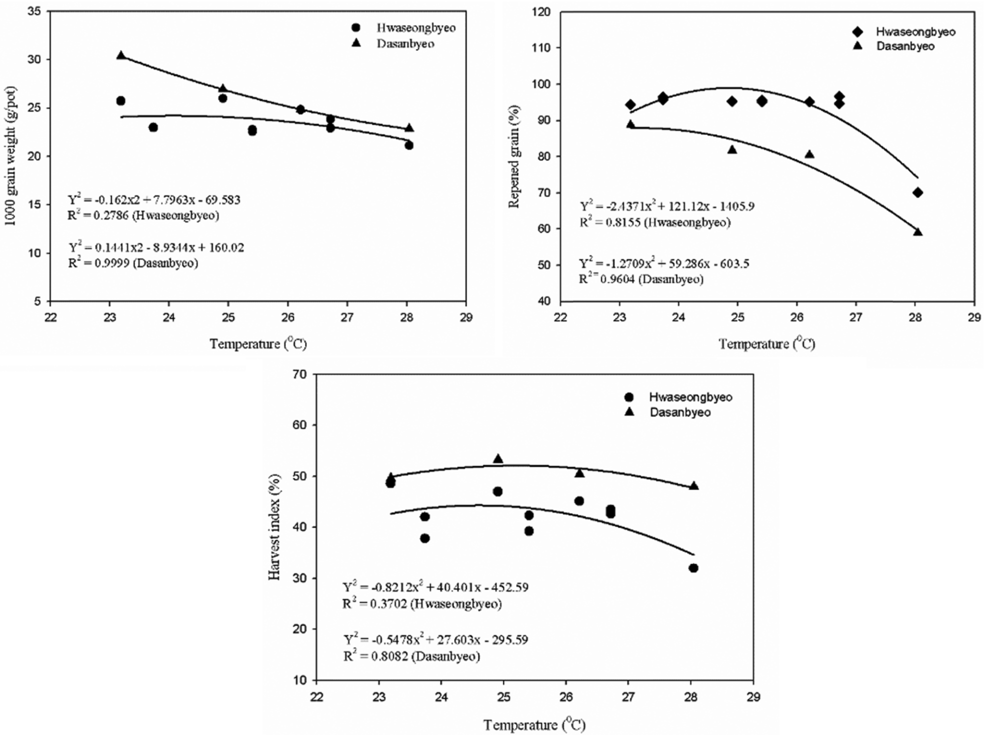

Fig. 2. Responses of 1000-grain weight, ripened grain ratio, and harvest index to mean air temperature during grain filling period of 40 days.

Table 2. Yield components and grain yield of two rice cultivars under different air temperature regimes in 2009

Treatment		Panicle No. (no./pot)	Spikelets (no./panicle)	Spikelets (no/pot)	Ripened grain (%)	1000 grain weight (g)	Yield (g/pot)	Harvest index (%)
Rice varieties	Air temperature							
Hwaseong byeo	Ambient	12.60	60.71	759.10	94.31^{a}	25.71^{a}	18.41^{a}	48.51^{a}
	Ambient+1.5	12.00	61.88	739.00	95.35^{a}	25.96^{a}	18.30^{a}	46.98^{ab}
	Ambient+3.0	12.70	56.81	719.40	95.15^{a}	24.80^{b}	16.93^{a}	45.09^{b}
	Ambient+5.0	12.40	59.76	739.30	70.04^{b}	21.11^{c}	10.78^{b}	31.94^{c}
	Mean	12.43	59.79	739.20	88.71	24.40	16.10	43.13
Dasan byeo	Ambient	11.50	83.41	954.30	88.76^{a}	30.34^{a}	25.89^{a}	49.60^{a}
	Ambient+1.5	11.60	89.06	1024.50	81.69^{b}	26.95^{b}	22.63^{a}	53.24^{ab}
	Ambient+3.0	10.50	85.69	894.10	80.34^{b}	24.82^{c}	17.95^{b}	50.44^{ab}
	Ambient+5.0	11.50	81.39	917.90	58.90^{c}	22.83^{d}	12.59^{c}	47.98^{b}
	Mean	11.28	84.89	947.70	77.42	26.24	19.76	50.31
Pooled	Ambient	12.05	72.06	856.70	91.53^{a}	28.03^{a}	22.15^{a}	49.05^{a}
	Ambient+1.5	11.80	75.47	881.75	88.52^{ba}	26.46^{b}	20.46^{a}	50.11^{a}
	Ambient+3.0	11.60	71.25	806.75	87.74^{b}	24.81^{c}	17.44^{b}	47.77^{a}
	Ambient+5.0	11.95	70.58	828.60	64.47^{c}	21.97^{d}	11.68^{c}	39.96^{b}
	LSD	NS	NS	NS	3.07	0.97	2.08	3.94
Temp.(T)	-	0.30^{NS}	0.95^{NS}	1.46^{NS}	135.53**	82.66**	43.63**	35.10**
Varieties(V)	-	10.19**	126.35**	59.26**	110.60**	41.78**	27.62**	85.33**
T × V	-	1.11^{NS}	0.61^{NS}	0.920^{NS}	3.68*	12.15**	4.37**	16.53**

NS, *, **, not significant, significant at the 0.05, 0.01 probability levels, respectively

tiller number. As the higher temperatures at active tillering stage increased tiller numbers (Yoshida, 1973) but high temperature after the active tillering stage increased the degeneration of tillers (Yamamoto *et al.*, 1985), the temperature elevation treatments to which rice plants were exposed throughout the rice growing season would have not changed the panicle number significantly as compared to the ambient temperature. On the contrary to panicle and spikelet number, 1000-grain weight and ripened grain ratio were decreased significantly under the treatments raising the air temperature to the level of 3.0°C and 5.0°C above the ambient air temperature in Dasanbyeo and Hwaseongbyeo, respectively (Table 1 and Table 2), even though these two cultivars showed similar heading dates and thus experienced similar temperature during ripening period. As shown in Fig. 2, grain weight and ripened grain ratio decreased sharply with temperature rise above 23°C in Dasanbyeo, while very little changes in the temperature range of 23-27°C in Hwaseongbyeo. These indicate that Hwaseongbyeo is less sensitive to high temperature stress during grain filling period. Optimum temperature for grain filling in japonica rice was reported to be in the range of 21-22°C in the average temperature during 40 days after heading (Murata, 1964; Kim, 1983). At the supra-optimal temperature, grain weight generally decreases due to the reduction of grain filling period that results from the accelerated panicle senescence rather than the earlier shortage of assimilate due to leaf senescence (Kim *et al.*, 2011). And also genotypic differences in the sensitivity of grain filling to high temperature have been reported (Yoshida and Hara, 1977) similarly to the results of the present study. Un-ripened grains include un-fertilized grains due to spikelet sterility and partially filled grains that were aborted at early stage of grain development after fertilization. Spikelet sterility occurs at high temperatures during microsporogenesis and anthesis of rice (Satake and Yoshida, 1978; Tashiro and Wardlaw, 1991; Kim *et al.*, 1996a; Kim *et al.*, 1996b; Matsui *et al.*, 1997). And the varietal differences in the tolerance to high temperature-induced sterility during flowering have been well documented (Osada *et al.*, 1973; Satake and Yoshida, 1978; Yoshida *et al.*, 1981; Jagadish *et al.,* 2007; Matsui *et al.*, 2001). Early abortion of developing grains occurs by high temperature during early stage of grain filling because caryopsis loses its function under high temperature (Sato and Inaba, 1976). It is not clear whether less sensitiveness of grain ripening ratio to high temperature in Hwaseongbyeo could be attributed to the less sensitiveness of spikelet sterility and/or early abortion of grain development to high temperature.

Owing to the reduction of 1000–grain weight and ripened grain ratio, grain yield was significantly reduced from the temperature treatments of 3.0°C and 5.0°C above the ambient air temperature in Dasanbyeo and Hwaseongbyeo, respectively. The greater sensitivity of grain yield response to temperature rising in Dasanbyeo than in Hwaseongbyeo was attributable to the sharp decrease of 1000-grain weight and ripened grain ratio with the temperature rise above 23°C during ripening period (Fig. 2).

In conclusion, the ongoing global warming is expected to decrease the grain yield not only by decreasing the grain weight due to the grain filling period reduction but also decreasing the ripened grain ratio that results from spikelet sterility and early abortion of rice kernel development in the future. However, the yield reduction would be mitigated by adopting and/or improving the less sensitive varieties to high temperature.

적 요

기후변화로 야기되는 미래의 고온 환경은 벼의 생산성을 저하시킬 것으로 예측되고 있다. 본 연구에서는 기후변화에 따른 국내 벼 생산성의 신뢰성 있는 영향평가 기초자료를 확보하기 위해 고온 환경에서의 벼의 수량과 수량 구성 요소의 반응을 조사하고 분석하였다. 실험은 1/5000a 와그너 포트를 이용하여 2008년과 2009년에 걸쳐 서울대학교 부속실험농장(37°16'N, 128°59'E)의 온도조절 플라스틱 하우스에서 실시되었다. 2008년에는 자포니카계의 화성벼를 공시품종으로 이용하였으며, 시비수준을 120kg N ha^{-1}와 180kg N ha^{-1}로 하였다. 온도처리는 대기온도, 대기온도 대비 +1.5°C, +3.0°C의 세 수준으로 하였다. 2009년에는 화성벼와 통일계의 다산벼를 공시품종으로 하여 120kg N ha^{-1} 수준으로 시비하였다. 온도처리는 대기온도, 대기온도 대비 +1.5°C, +3.0°C 및 +5.0°C 수준으로 처리하였다. 수량 및 수량구성요소의 온도처리에 따른 영향은 품종별로 상이한 반응을 보였다. 이삭수와 이삭당 영화수는 두 품종 모두 온도처리의 영향을 받지 않았으나, 천립중과 등숙률에 대해 화성벼는 5.0℃, 다산벼는 1.5°C 이상의 온도처리에서 유의하게 감소하였다. 포트당 수량은 화성벼의 경우 5.0°C, 다산벼는 3.0°C 및 5.0°C 온도처리에서 유의한 감소를 나타냈다. 등숙기간 동안의 평균기온에 대한 천립중과 등숙률 반응 또한 품종별로 다르게 나타났다. 다산벼의 경우 23°C 이상의 평균 온도에 대해 등숙률과 천립중이 급격히 감소한데 반해, 화성벼는 23°C부터 27°C 범위에 대해 등숙률과 천립중의 변화가 크지 않았다. 기후변화에 의한 지속적인 기온상승이 예상되는 가운데 온도상승에 따른 등숙률과 천립중의 감소는 미래 기후 환경에서의 벼의 수량 감소를 야기하는 주요 원인으로 예측된다. 다만, 상승된 기온에 대한 벼의 반응은 품종별로 상이하기 때문에 고온에 둔감한 품종의 도입 또는 그러한 특성을 지닌 품종의 육종을 통해 기후변화에 따른 수량 감소의 위험을 낮출 수 있을 것이다.

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