A THESIS FOR THE DEGREE OF MASTER OF SCIENCE

# Occurrence and modeling of un-ripened grain under high temperature and shading condition

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AUGUST, 2015

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OF SEOUL NATIONAL UNIVERSITY

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# Occurrence and modeling of un-ripened grain under high temperature and shading condition

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## Abstract

Evaluated temperature caused by global warming would affect grain filling in rice. Especially, High temperature during grain filling period reduces grain filling duration and increases potential grain growth rate. This effect could be complemented by higher assimilate supply. In other words, grain filling is determined by interaction between sink and source strength. For evaluating the climate change impact on rice yield effectively, it is important to develop a model for the estimating the filled grain ratio considering this interaction. The objects of study are to observe effects of high temperature and shading condition during ripening stage on rice yield and yield component and to develop a model of estimation filled grain ratio.

The two rice cultivars Odaebyeo (early maturing) and Hwasungbyeo (medium-maturing) were pot(1/5000a) cultured in a green house controlled to ambient temperature (AT) until heading, and pots were transferred to greenhouses controlled to the target temperatures of AT, AT+1.5, AT+3, and AT+5. A half of pots in each house was subjected to shading treatment with shade net of about 50% transmittance.

Mean and distribution of panicle heading date were not statistically different among treatments, and also significant difference was not found in panicle number and spikelet number among temperature and shading treatments. 1000-grain weight showed no significant difference among temperature treatments, while it was decreased significantly by shading treatment. Spikelet fertility tended to decrease with temperature elevation and shading treatments. Ratio of filled grain showed significant decrease with temperature elevation and shading treatment. In summary, heading date distribution, panicle number, and spikelet number were not affected by temperature and radiation condition during grain filling stage. 1000-grain weight was affected more substantially by shading condition rather than by high temperature condition. Decrease in 1000-grain weight due to shading treatment may be attributable to the quick exhaustion of pre-heading reserve carbohydrate compared to no-shading treatment. Spikelet sterility was affected by high temperature but the sensitivity was less than the occurrence of un-ripened grain. Shading condition reduced spikelet sterility, too. The decrease would be assumed to be caused by flowering time delay or hormone action. But we need more study about this phenomenon. Un-ripened grain occurrence was affected by temperature and solar radiation. An Un-ripened grain

occurred with higher in Odaebyeo than in Hwasungbyeo. The higher occurrence of unfilled grain in Odaebyeo would have been caused as pre-heading reserve carbohydrate was accumulated less due to shorter vegetative period than Hwaseongbyeo.

Base on the literature review and this result, we developed a model for predicting un-ripened grain ratio. We assumed that un-ripened grains occur when carbohydrate supply strength (source strength) is not sufficient to compensate the sink activity increase with temperature increase. Sink activity is defined as the potential grain growth rate that is derived from the potential grain growth curve. The following potential grain growth curve was formulated by incorporating the notion, that grain growth varies according to growth temperature during grain filling and grain position on a panicle which determines the priority of flowering, to the existing sigmoid potential grain model.

$$GrainWeight(dah, Gdd) = \frac{a}{1 + e^{\frac{Gdd - (c + c_1 \times dah)}{b + b_1 \times dah}}}$$

where a is maximum grain weight. b, c are coefficient that is related to grain filling duration and rate. $b_1$, and $c_1$ are coefficient to distinctly calculate grain weight of superior and inferior spikelet.

Potential growth of grains on a panicle was computed on each day after intial flowering by multiplying the probability density distribution of flowering date on a panicle by potential growth of grains differing in flowering date on a panicle. Sources are supposed to be composed of current photosynthesis after heading and pre-heading carbohydrate reserve. Pre-heading carbohydrate reserve was assumed to act as

buffer that compensate the lack of current photosynthate. Photosynthesis was calculated as a function of solar radiation, temperature and leaf senescence after heading. Grain density of rice is mainly determined by grain weight because the potential volume of grain is unchanged due to the pre-determined glume size. Therefore. The grain that has weight lower than a threshold weight is determined as un-ripened grain.

This model was calibrated with the temperature elevation and shading experiment data using Simplex method. The calibrated model predicted the treatment means of temperature elevation and shading treatments with acceptable accuracy. However, this model showed some limitations in detailed prediction of unripened grain ratio for each panicle within treatments.

Keyword : Rice, Un-ripened grain, Modelling, High temperature, Shading treatment

Student Number : 2009-23250

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# Introduction

Rice(*Oryza Sativa* L.) is one of the important grain crops in the world and cultivated widely over the world. A half of the world population lives on rice and also rice is staple crop and plays important role in the food culture and food security in Korea. Climate change accompanied by global warming is expected to exert serious impact on rice production and food security. According to the IPCC Fifth Assessment Report(2013), the global surface temperature warmed by 0.85 (0.65 to 1.06) °C from 1880 to 2012, and global mean surface temperature is projected to increase by 0.3 to 4.8°C by 2081-2100 relative to 1986-2005. Even faster warming is expected in Korea, mean surface temperature being projected to increase by 1 to 5.8 °C for 2081-2100 relative to 1986-2005.

Warming effects on crop production vary depending on region, crop, cultivar, cultivation season, etc. However, in general, crop production was projected to be negatively affected by temperature rise due to global warming. Rice yield was reported to decline by 0.6 t $ha^{-1}°C^{-1}$ with temperature increase in the daily temperature range of 22 - 32 °C (Sheehy et al, 2006). In Korea, temperature increase of 2 °C was predicted to decrease the rice production by 4.5% (Korea climate change assessment report, 2010).

For assessing the warming impact rice yield effectively, the responses of yield components under high temperature should be examined and quantified in relation to temperature condition. Effective tillers and spikelet number are mainly determined before heading stage. Fertility and filled grain ratio are mainly determined during the reproductive stage from flowering to maturity. High temperature at this reproductive stage exerts greater effects on rice yield than at the vegetative stage. High temperature during the post-flowering period causes spikelet sterility and abortion of fertilized grain, resulting the low ripened grain ratio. Grain filling is regulated not only by sink activity but also by source strength. In general, high temperature within a certain range promotes sink activity that is related to biochemical conversion of imported sucrose into storage carbohydrate as well as source strength that is related to photosynthesis and reserved carbohydrate. Whereas, temperature increase decreases grain growth duration and results in the increase of unfilled grain. As the occurrence of unripened grain is complicatedly interrelated between sink and source, it is not easy to estimate unripened grain ratio.

The aims of this experiment are to examine the occurrence of unripened grains under evaluated temperature and shading condition and construct a component model for predicting the un-ripened grain ratio in rice.

# Literature Review

Grain filling is the process of grain yield formation through accumulating dry matter into the fertilized spikelet. Accumulation of carbohydrate and protein in the fertilized spikelet is affected by temperature, solar radiation, and nutrition status of plant.(Lee et al. 2009).

1. Effect of high temperature on grain filling

Grain filling is the process that sucrose imported in grain is converted to storage starch. Photosynthesis, respiration, translocation and so on that are related to grain filling are biochemical processes of which activities are affected by temperature. Therefore grain filling rate and duration are affected by temperature (Kobata & Uemuki, 2004). Optimal temperature on grain filling is reported to be in the range of 21 to 25°C, varying with cultivars (Lee et al. 2009). Single grain weight does not change up to 26.7°C during grain filling period and every temperature increase of 1°C above this temperature decreases grain weight by 4.4 % up to 35.7 °C (Tashiro & Wardlaw, 1989).

In general, high temperature at ripening stage reduce grain weight, degrade grain quality (Barnabás et al., 2008), and decrease amylase content in grain decrease (Yamakawa et al., 2007). High temperature during grain-filling reduces grain-filling duration and increase grain growth rate but the increase of growth rate don't completely compensate the shortened grain filling duration. However, Kobata & Uemuki (2004) reported that as the source strength is as strong as increased sink activity caused by high temperature, grain weight was not reduced. Therefore, high temperature don't affect potential grain weight. In the other hand, increasing respiration in grain due to high temperature also increases unripened grain occurrence (Wassmann et al., 2009).

3. Sink activity

The grain growth is linearly related to the increase in endosperm cell number and the activity of sucrose synthesis, and ADP-glucose pyrophosphorylase (AGPase) (Liang et al., 2001). As there is no large difference in each weight of endosperm cell, endosprem cell number is the main factor of sink capacity (Fu et al., 2011). Hormones affects endosperm cell division (Zhang et al., 2009). Sucrose synthesis is a main enzyme of which activity is regarded as biochemical index of sink activity (Fu et al., 2011).  Non-structural carbohydrate content is related to sink strength (Fu et al., 2011) Cytokinin and IAA are related to grain filling through endosperm cell division (Zhang et al. 2009) GAs is no significant related to cell division. ABA plays positive role of grain filling. Both ACC and ethylene play negative role of cell division (Yang, J. et al 2006 , Zhang et al. 2009). Both AGPase and Q-enzyme (starch branching enzyme) play key roles in starch synthesis (Nakamura, Y., & Yuki, K., 1992).

Superior spikelet is early anthesis spikelets. Superior spikelets are filled fast and become big and heavy grain, whereas  inferior spikelets are filled late and produce poor grain (Yang, J. & Zhang, J., 2010 , Iwasaki et al. 1992). Chalky kernels occur due to the increase of inferior spikelet under high temperature (Tsukaguchi, T. & Iida, Y., 2008). Superior spikelet at early grain filling stage and under the restricted carbohydrate supply condition have a priority for carbohydrate supply (Okawa et al., 2003).

4. Source strength

The contribution of photosynthesis during grain filling is estimated at 60 - 100% of carbohydrate in grain depending on cultivar and environmental condition and the remaining comes from the pre-heading carbohydrate reserve (Yoshida, 1981). Shortage of photosynthesis at early grain filling stage is compensated by the reserved carbohydrate before heading, playing the role of carbohydrate supply buffer for grain growth (Kobata et al, 2000). Abundant radiation condition enhances assimilation for grain growth (Kobata & Uemuki, 2004) and the increased availability of assimilate makes grain dry matter increase (Sato, & Inaba, 1976.).

# Materials and Methods

This experiments were conducted in temperature-controlled green houses at the experimental farm of Seoul National University, Suwon, Korea in 2014.

## 1. Experimental set-up

### 1.1 cultivar and cultivation

Odaebyeo (early maturing cultivar) and Hwasungbyeo (medium maturing culticar) were sown on May 1$^{st}$ and transplanted in a 1/5000a Wagner pot on May 16$^{th}$ in 2014. Fertilizer was applied at the rate of N-P-K fertilizer of 180-90-11.4kg/ha.

### 1.2 Temperature & shading treatment

At the initial heading stage, twelve pots for each cultivar were transferred to the four plastic houses that were automatically controlled to ambient temperature (AT), AT+1.5℃, AT+3.0℃ and AT+5.0℃. Air temperature and solar radiation for each plastic house were monitored with data logger equipped with platinum resistor thermoprobe and pyranometer, respectively, throughout the growing season (Figure 1.)

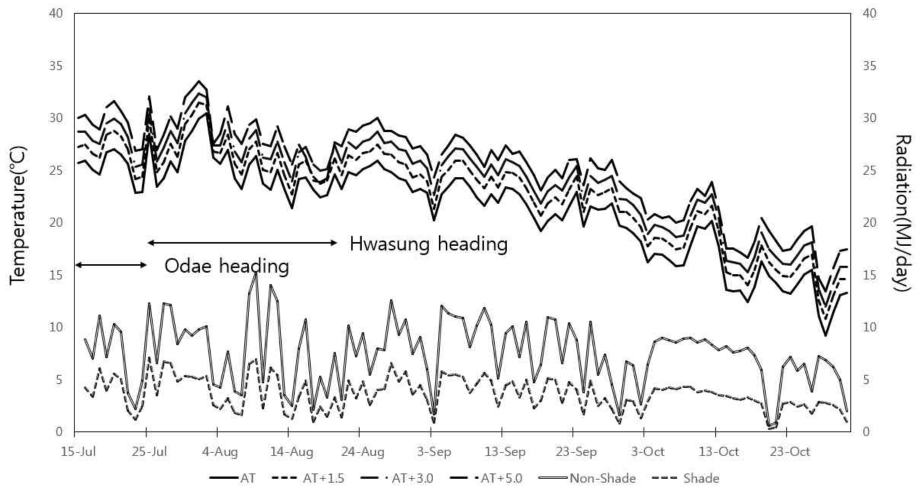



Figure 1. Daily air temperature and radiation inside green house during grain filling period

2. Measurement

Heading date of each panicle was labeled and recorded, After harvest, the number of spikelet for each panicle were counted, grain weight and moisture content were measured for the ripened grains of each panicle. Spikelet sterility was evaluated manually by pressing spikelet between thumb and index fingers. Among the fertilized spikelets. sunk and floated grains in salt water with 1.06 specific gravity were classified as ripened and unripened grains, respectively. filled grain ratio

2-1. Definition

Spikelet fertility(sterility) is the ratio of fertilized(unfertilized) grain in total grain.

Filled(unfilled) grain ratio is the ratio of filled(unfilled) grain in fertilized grain.

Ripened grain ratio is the ratio of filled (unfilled) grain in total grain.

3. Statistical analysis

The frequency of heading date of panicles was fitted to the following normal distribution function;

$$f(day) = PN \times \frac{1}{\sqrt{2\pi\sigma}} e^{-\frac{(day - day_m)^2}{2\sigma^2}} \quad [1]$$

where f(day) is the frequency of heading, PN is the total panicle number, $day_m$ is peak date of heading, σ is standard deviation of heading date distribution.

Analysis of variance (ANOVA) was used to test the significance among temperature elevation treatments and shading treatments.

Pearson correlation analysis was used to identify the association among/between ripened grain ratio, fertility, total grain number, fertilized grain number, solar radiation and temperatures.

## 4. Model description

During grain filling stage, sucrose is transported from source (e.g. leaf and stem) to sink (grain). Grain weight increase per day is determined by interaction between the daily sink activity and the source strength. We assumed that grain growth that is lower than the potential grain growth induced un-ripened grains. We made algorithm to estimate the ratio of filled grain through calculating sink activity and source strength. The algorithm was described as in flow chart (Figure 2).

First step of model is to calculate the daily sink activity. In this model, sink activity was defined as potential grain growth rate. Daily potential grain growth rate was assumed to be affected by temperature and spikelet position. Equation [2] is a grain growth equation modified from a equation that describe grain weight increase through the growing degree day accumulation after flowering (Lee et al., 2009) to reflect the effect of spikelet position on grain growth.

$$GrainWeight(dah, Gdd) = \frac{a}{1 + e^{\frac{Gdd(day) - (c + c_1 \times dah)}{b + b_1 \times dah}}} \qquad [2]$$

Where a is maximum grain weight. b, c are coefficient that is related to grain filling duration and rate. $b_1$, and $c_1$ are coefficient to distinctly calculate grain weight of superior and inferior spikelet. Gdd is growing degree day that is calculated by the following equation [3]:

$$Gdd(day) = \sum_{i=1}^{day} (T_{day} - BT) \qquad [3]$$

where $T_{day}$ is mean air temperature. BT is base temperature. In this model, we set BT = 0.

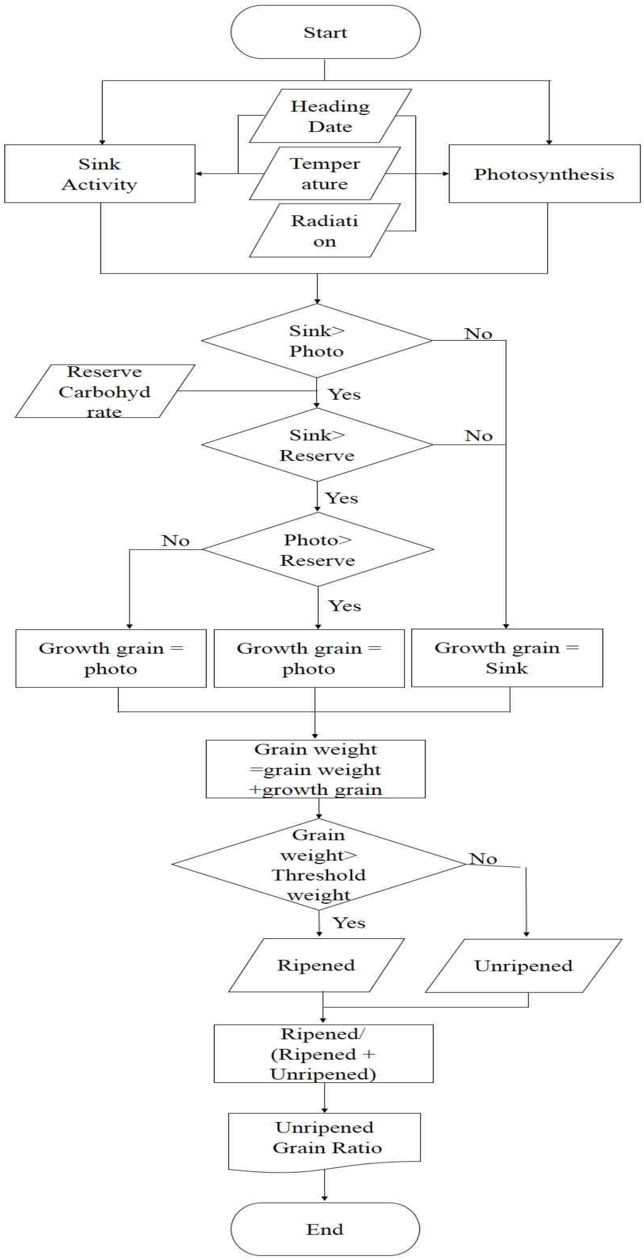



Figure 2. Flow chat of the model for estimating unripened grain ratio

sink is sink activity at a day. photo is amount of daily photosynthesis. reserve is state of reserved carbohydrate at a day. Growth grain is increase in grain weight. Threshold weight set 0.018g.

Nguyen et al. (2014) reported that the distribution of flowering date follows normal distribution curve. The probability density of flowering date in a panicle is estimated by the following equation[4] to consider the ratio of superior and inferior spikelets.

$$Fd(Hday) = \frac{1}{\sqrt{2\pi\sigma}} e^{-\frac{(day-m)^2}{2\sigma^2}} \quad [4]$$

where Fd(Hday) is the relative frequency of flowering, Hday is the heading date, m is peak date of flowering, σ is standard deviation of heading date distribution. In this model, we set m = 5 , σ = 2.

We need to consider the effect of spikelet number per a panicle on filled grain ratio. but this experiment show that there are no significant relation between filled grain ratio and spikelets number. therefore this model didn't reflect the effect of spikelet number on grain filling.

Second step is to calculate photosynthesis. We assumed that solar radiation and leaf nitrogen content is linearly related to photosynthesis. The relation was formulated by the follow equation[5]:

$$P(day) = c \times Radiation \times N_{day} \times TRF(T_{day}) \quad [5]$$

where c is coefficient, radiation is the daily total solar radiation (MJ/day). $N_{day}$ is nitrogen content at the day. TRF(Tday) is the temperature response function of photosynthesis.

Solar radiation is observed valuel. $N_{day}$ is estimated by the following equation [7] :

$$N_{day} = \frac{N_{\min} + (N_{\min} + N_{\max})}{1 + \frac{day}{th}} \qquad [6]$$

where $N_{min}$ is minimum nitrogen content, $N_{max}$ is maximum nitrogen content, th is constant. We set $N_{max}$ = 2.2473, $N_{min}$ = 1.0775 and th =28.9653 according to the reporty of Kim (2010).

The response of photosynthesis to temperature was described by ba eta function[7].

$$TRF(T_{day}) = e^k \times \left(\frac{T_{day} - T_{base}}{T_{opt} - T_{base}}\right)^a \times \left(\frac{T_{crit} - T_{day}}{T_{crit} - T_{opt}}\right)^b \qquad [7]$$

where Tbase ,Topt ,and Tcrit is minimum, optimum, and maximum temperature for photosynthesis. a, b, and k are constant. In this model, Tbase ,Topt, and Tcrit are 10, 25, and 40℃, respectively. a, b, and k are 1, 1, and 0, respectively.

The third step is to consider about pre-heading reserve carbohydrate. We assumed the pre-heading reserve carbohydrate is constant because temperature and shading treatment were conducted after heading. We set the pre-heading reserve carbohydrate to decrease with time for representing the consumption of reserve.

The fourth step is to compare among potential grain weight growth rate, photosynthesis rate, and reserved carbohydrate. If potential grain weight growth rate is not the biggest value among them. Actual grain weight growth rate is set to he the sasme as potential grain weight growth rate. and If potential grain weight rate is the biggest value among them, actual grain weight growth rate is set to the bigger value between photosynthesis and reserve carbohydrate. Final grain weight is calculated through daily sum of actual grain weight growth rate.

Finally, We assumed that the volume of grain is constant because the endosperm cell is surrounded by the glumes of which size is predetermined before heading. Therefore, grain density is mainly determined by grain weight. The grain that is lighter than the threshold weight was considered as unripened grain. The threshold weight set as 0.018g per grain.

The parameters of model was calibrated by simplex method using the temperature elevation and shading treatment experiment data

# Results

## 1. Yield and yield components

As presented in Table 1. heading started at 14$^{th}$ July and ended at 28$^{th}$ July in In Odeabyeo, lasting 13 days. In Hwasungbyeo, heading started at 26$^{th}$ July and ended at 19$^{th}$ August, lasting 25 days. The frequency of heading date in each cultivar were fitted to normal distribution equation [1]. The distributions of heading date were not statistically different among treatments (Figure 3., Table 2.). Because temperature and shading treatment started after heading, the treatments didn't affect heading distribution.

Table 1. Average dates of first heading, 50% heading ,and end of heading. As there were no significant differences among treatments, data were presented average over temperature and shading treatments

| Cultivar | Odaebyeo | Hwasungbyeo |
|---|---|---|
| First heading date | 14-Jul | 26-Jul |
| 50% heading date | 19-Jul | 8-Aug |
| End of heading date | 28-Jul | 19-Aug |

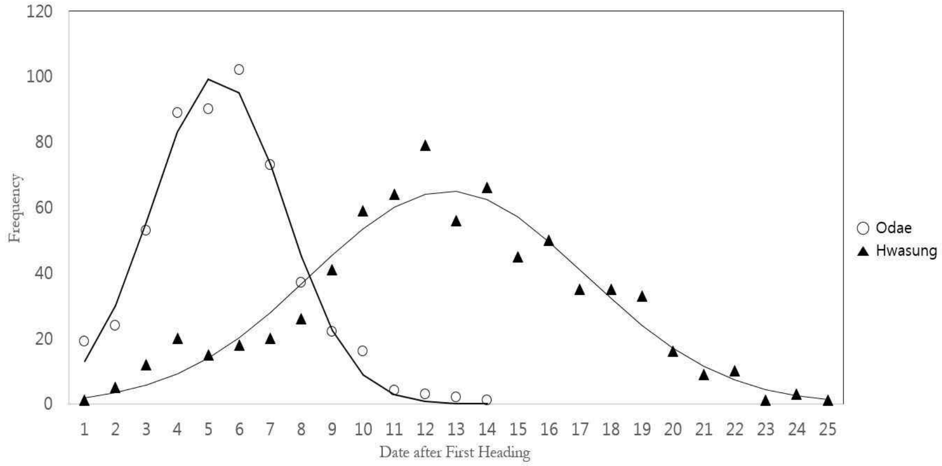



Figure 3. The frequency distribution of heading date in two cultivars Odaebyeo and Hwasungbyeo

Table 2. Estimated parameters of normal distribution of heading date distribution in two cultivars

| Treatment | Average | Standard deviation | R-square | Average | Standard deviation | R-square |
|---|---|---|---|---|---|---|
| | Odaebyeo | | | Hwasungbyeo | | |
| AT | 5.39 | 2.182 | 0.9092 | 15.43 | 5.188 | 0.6453 |
| AT(SD) | 5.358 | 2.145 | 0.7992 | 12.82 | 3.739 | 0.7202 |
| AT+1.5 | 4.638 | 2.179 | 0.9309 | 12.26 | 3.569 | 0.6191 |
| AT+1.5(SD) | 5.364 | 2.11 | 0.8927 | 13.45 | 4.088 | 0.6862 |
| AT+3.0 | 4.528 | 2.116 | 0.9109 | 12.39 | 3.86 | 0.7916 |
| AT+3.0(SD) | 6.029 | 1.936 | 0.8329 | 12.08 | 4.212 | 0.7675 |
| AT+5.0 | 5.501 | 1.732 | 0.8888 | 13.32 | 5.012 | 0.6714 |
| AT+5.0(SD) | 5.19 | 2.332 | 0.7769 | 10.8 | 4.012 | 0.6675 |
| Total | 5.308 | 2.13 | 0.9781 | 12.75 | 4.422 | 0.9216 |

The panicle number in Odaebyeo and Hwasungbyeo was ranged from 10 to 13 and from 13 to 18, respectively. However, there were no significant differences in panicle number among temperature treatments(Table 3.). Shading treatment reduced panicle number only in Hwasungbyeo, Spikelet number per panicle varied in range of 60 to 70, revealing no significant differences between cultivars, temperature treatments, and shading treatments(Table 3.).

As shown in Table 4, 1000-grains weight was not affected significantly by temperature elevation treatments while 1000-grains weight decreased significantly by shading treatment. Spikelet fertility showed no significant differences among elevated temperature treatments but decreased significantly by shading tratment in Odaebyeo. Whereas, spikelet fertility tended to decrease significantly with temperature elevation above ambient and by shading treatment in Hwasungbyeo. spikelet fertility decreasing more sharply with temperature elevation under shading treatment. Ripened grain ratio was significantly decreased with elevated temperatures and by shading treatment in both cultivars, showing no interactive effects between temperat and shading treatments. Unripened grain ratio showed significant decrease with elevated temperature and by shading in both cultivars. As in Table 4 and figure 3, the unripened grain ratio with temperature elevation showed more sharp increase under shading condition, revealing interactions between temperature and shading treatments. Unripened grain ratio of each panicle was plotted against the average temperature during 30 days after heading of each panicle as Box-plot (Figure 4). Un-ripened grain tended to increase with temperature increase above 28°C under no-shading condition, while un-ripened grain tended to increase with temperature increase above about 24.5°C under shading condition decrease(Figure 4.).

Table 3. Panicle number and spikelet number and filling period as affect by different temperature and radiation regime from initial heading stage in two cultivars

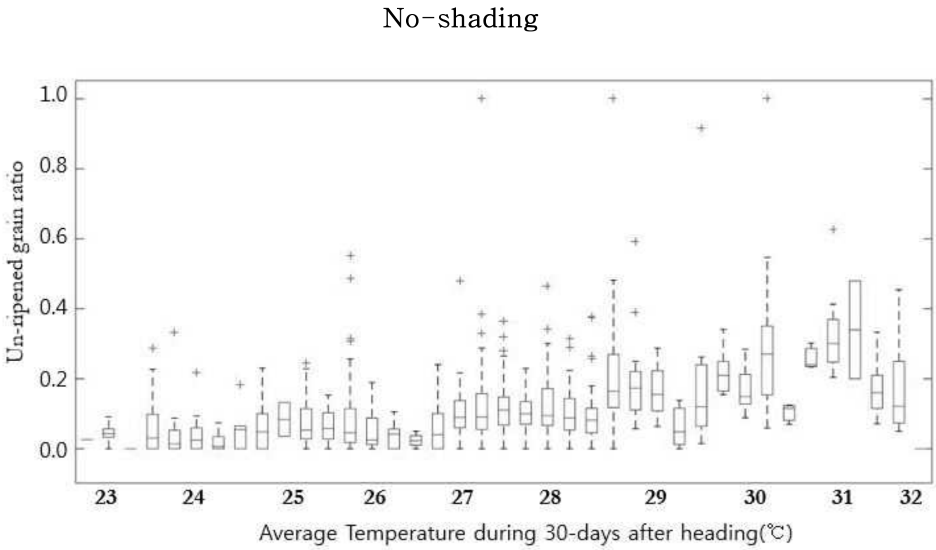
| Cultivar | Temp. treatment | Panicles/pot | | Spikelets/panicle | |
|---|---|---|---|---|---|
| | | No-shade | shade | No-shade | shade |
| **Odae** | AT | 12.7 | 11.2 | 60.7 | - |
| | AT+1.5 | 9.8 | 11.7 | 66.4 | 61.9 |
| | AT+3.0 | 12.3 | 10.8 | 69.6 | 64.0 |
| | AT+5.0 | 11.2 | 11.5 | 63.7 | 65.7 |
| F-value | Temp | 2.661. | 1.678ns | 2.182ns | 0.414ns |
| | Shade | 0.055ns | | 0.336ns | |
| | Temp x Shade | 1.306ns | | 1.091ns | |
| **Hwa-Sung** | AT | 18.0 | 16.3 | 65.7 | 59.1 |
| | AT+1.5 | 15.5 | 15.3 | 64.6 | 61.5 |
| | AT+3.0 | 14.7 | 13.0 | 67.7 | 62.2 |
| | AT+5.0 | 15.7 | 13.8 | 63.9 | 65.5 |
| F-value | temp | 0.1ns | 1.789ns | 0.489ns | 1.11ns |
| | Shade | 60.18*** | | 3.949. | |
| | Temp x Shade | 0.248ns | | 1.107ns | |

NS, . ,*, **, ***, not significant, significant at the 0.1, 0.05, 0.01, 0.001 significant levels, respectively

Table 4. Ripened grain ratio, spikelet fertility, unripened grain ratio, 1000-grains weight, yield as affected by different temperature and radiation regimes from initial heading stage in two rice cultivars

| Cultivar | Temp. treat. | Ripened grain ratio(%) | | Spikelets fertility(%) | | unripened grain ratio (%) | | 1000-Grain weight (g) | | Yield(g/pot) |
|---|---|---|---|---|---|---|---|---|---|---|
| | | No-shade | shade | No-shade | shade | No-shade | shade | No-shade | shade | No-shade |
| **Odaebyeo** | AT | 86.4a | - | 96.2 | - | 11.2a | - | 24.7 | - | 14.1a |
| | AT+1.5 | 87.2a | 44.2 | 95.7 | 91.5 | 8,9a | 52.2 | 25.5 | 23.3 | 14.6a |
| | AT+3.0 | 70.0b | 43.3 | 94.4 | 90.9 | 26.1b | 52.3 | 23.7 | 24.1 | 15.4a |
| | AT+5.0 | 71.7b | 39.7 | 95.2 | 87.2 | 24.6b | 54 | 24.3 | 22.6 | 9.8b |
| F-value | Temp | 11.38*** | 0.811ns | 0.66ns | 1.626ns | 13.97*** | 0.033ns | 1.712ns | 2.385ns | 3.368* |
| | Shade | 112.6*** | | 26.27*** | | 103.5*** | | 7.635** | | 76.5*** |
| | Temp x Shade | 0.122ns | | 0.2334ns | | 2.506. | | 0.0509. | | 2.266ns |
| **Hwa-Sungbyeo** | AT | 91.7a | 86.0a | 96.4a | 94.2a | 5.0a | 8,7a | 22.2 | 21.7 | 24.9a |
| | AT+1.5 | 91.0a | 76.2b | 95.3ab | 93.2ab | 4.6a | 18.4b | 23.0 | 21.9 | 21.6b |
| | AT+3.0 | 82.9b | 68.9bc | 94.6b | 89.7bc | 12.4b | 23.4c | 23.1 | 21.7 | 20.1b |
| | AT+5.0 | 83.0b | 63.2c | 94.5b | 87.3c | 12.2b | 27.7d | 22.5 | 21.9 | 20.6b |
| F-value | temp | 9.158*** | 11.06*** | 3.239* | 4.922* | 10.22*** | 11.11*** | 2.32ns | 0.485ns | 2.948. |
| | Shade | 28.66*** | | 19.47*** | | 26.88*** | | 26.07*** | | 60.18*** |
| | Temp x Shade | 0.0405ns | | 2.600. | | 3.411* | | 1.366ns | | 0.547ns |

NS, . ,*, **, ***, not significant, significant at the 0.1, 0.05, 0.01, 0.001 significant levels, respectively



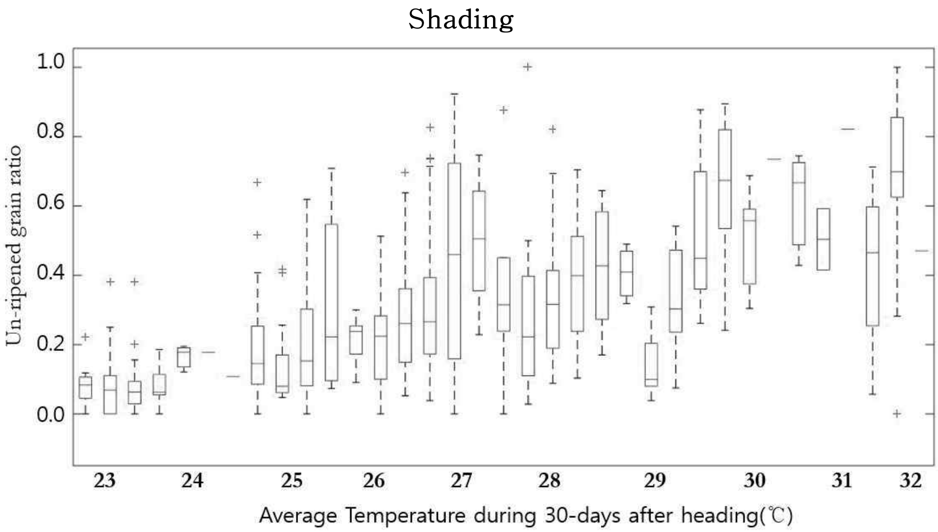




Figure 4. The box plots about ratio of un-ripened grain ratio as affected by average temperature during 30-day after each panicle heading in two cultivar

As in table 5, unripened grain ratio showed highly significant positive correlation with solar radiation while significant negative correlation with air temperature during 30days after heading of each panicle. No correlation were found between the number of fertilized grain and unripened grain ratio, indicating that sink capacity is not the restriction factor in grain filling at least in this experiment as the number of fertilized grain is correspondent to sink capacity at grain filling stage. However, a significant positive correlation were found between unripened grain ratio and fertility, which was caused by the fact that temperature and solar radiation exerted similar effects on them.

Table 5. Correlation of unripened grain ration with fertility, fertilized grain number, solar radiation, and temperature

| Cultivar | Fertility(%) | Fertilized spikelets/ panicle | Radiation | Temperature |
|---|---|---|---|---|
| Odaebyeo | 0.45*** | 0.05ns | 0.70*** | -0.28*** |
| Hwasungbyeo | 0.53*** | -0.04ns | 0.40*** | -0.33*** |

Radiation and temperature are average values during 30 days after heading of each panicle NS, *, **, ***, not significant, significant at the 0.05, 0.01, 0.001 significanxe levels, respectively

2. Model calibration

The model was programmed in a programming, JAVA to simulate the occurrence of the unripened grain ratio using the measured daily air temperature and solar radiation, and heading date. The model was calibrated by Simplex method using the present experiment data. The parameters estimated are shown in in Table 6. The bigger the parameter $b_1$ , the lower the peak sink demand in inferior spikelet. The bigger the parameter $c_1$ , the longer the filling duration in inferior spikelet.

Table 6. Model parameters estimated using Simplex method.

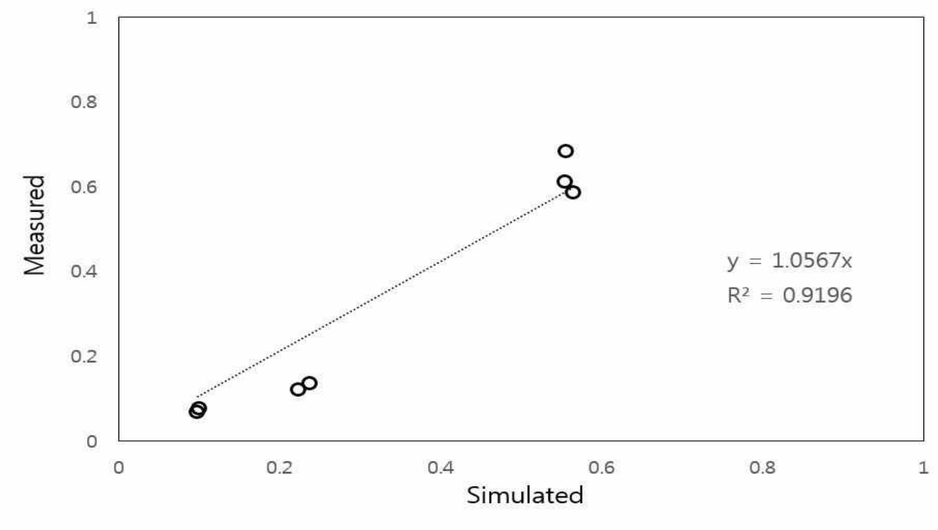
| | a | b | $b_1$ | c | $c_1$ | R |
|---|---|---|---|---|---|---|
| Odaebyeo | 25 | 80 | 8.4 | 200 | 100 | 2.3 |
| Hwasungbyeo | | | 9.8 | | 85 | 2.4 |

a, b, $b_1$, c, and $c_1$ are parameters of equation[2]

R is the initial pre-heading reserve carbohydrate.

As presented in Figure 5, this model simulated the unripened grain occurrence as affected by temperature and solar radiation treatment with acceptable accuracy.

Odaebyeo




Hwasungbyeo

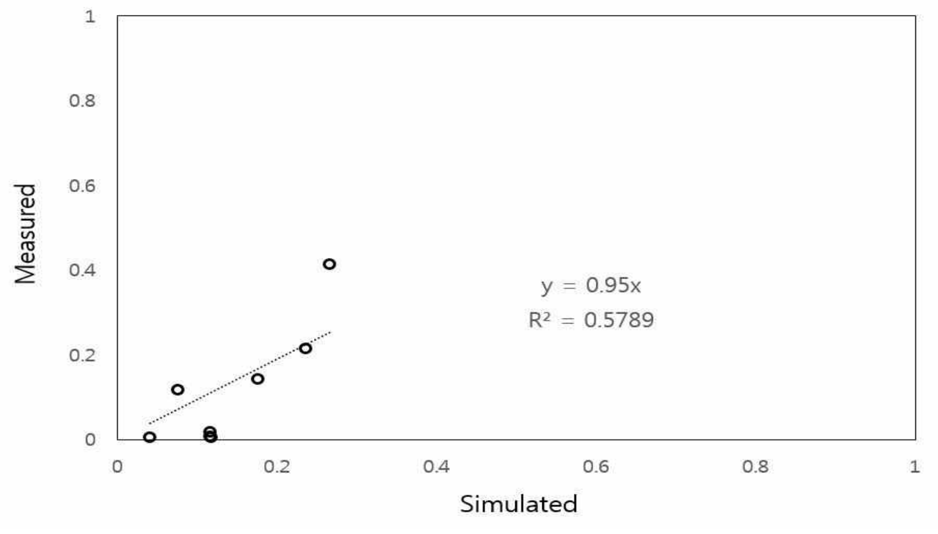



Figure 5. Relationship between the simulated and measured unfilled grain ratio in Odaebyeo and Hwasungbyeo

# Discussion

Rice yield decreased under evaluated temperature and low radiation condition during grain filling period. This yield decreases were mainly attributed to not only the increase of un-fertilized spikelet and unripened grain and but als the decrease of 1000-grain weight. High temperature during grain filling exerted negative effect on yield by increasing spikelet sterility and unripened grain. Whereas shading exerted negative effect on yield by increasing unripened grain as well as reducing 1000-grain weight (Table 3, Table 4).

Panicle number, and spikelet number were not affected by temperature and radiation treatments after heading (Table 3) as panicle development and spikelet differentiation occur before heading (Yoshida, 1981).

Shading reduced 1000-grain weight. while elevated temperature did not reduced 1000-grains weight significantly (Table 4), on the contrary to the previous report (Tashiro & Wardlaw, 1989). The previous study would have measured weight of the grain on a whole panicle. But this experiment measured grain weight using fully ripened grains on a panicle. Inferior grain in this experiment was likely to be excluded by gravity selection because inferior spikelets are smaller and lighter than superior spikelets (Takayuki, & Seizo , 1963). Therefore we could infer that high temperature mainly affects weight of grains from inferior spikelets. In contrast, shading reduced 1000-grains weight, implying that both superior and inferior spikelet were affected by solar radiation.

Sterility was affected by high temperature but the sensitivity was less than unripened grain ratio. Temperature at flowering time is a main factor of determining fertility (Jagadishet al, 2007). Spikelet fertility under shading decreased, too. However, no clear reason cannot be found for low radiation-induced spikelet sterility, requiring further study on this phenomenon.

Unripened grain ratio showed significant decrease with elevated temperature and by shading in both cultivars. As in Table 4 and figure 3, the unripened grain ratio with temperature elevation showed more sharp increase under shading condition, revealing interactions between temperature and shading treatments. Unripened grain tended to increase with temperature increase above 28°C under no-shading condition, while unripened grain tended to increase with temperature increase above about 24.5°C under shading condition decrease(Figure 4.). These temperatures are higher han the reported optimal temperature for grain filling that ranges from 21 to 25°C (Lee et al. 2009).

The model simulates the occurrence of unfilled grain using air temperature and solar radiation as driving variables. As shown in Figure 5, the calibrated model predicted the treatment means of temperature elevation and shading treatments with acceptable accuracy. However, this model showed some limitations in detailed prediction of unripened grain ratio for each panicle within treatments. Except solar radiation and temperature, some factors such as total spikelet number or fertilized spikelet number, plant nutrient state, leaf area and so on can exert influences on unripened grain occurrence. We need further consideration on these factors for improving this model.

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고온과 차광조건에서 미성숙립 발생과 미성숙립 예측 모델 구축

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초 록

기후변화로 인한 대기온도 상승은 벼의 등숙과정에 영향을 주어 최종적으로는 벼의 수량에도 영향을 미칠 것으로 예상된다. 특히, 등숙기간 동안 고온은 알곡 잠재 생장률을 증가시키고 그것에 대한 공급부의 능력의 보상이 이루어지지 않아 결과적으로 최종수량에 심대한 영향을 주게 될 것이다. 이러한 등숙과정에 대한 온도 및 일사의 영향을 수식으로 표현을 하게 되면 미래기후 조건에 대한 수량 반응을 더욱 잘 이해 할 수 있을 것이다. 이 연구의 목적은 고온과 차광조건에서 벼의 수량과 수량구성요소, 특히 미성숙미률의 반응을 관찰하고 그 관찰을 토대로 미성숙미률을 예측하는 모델을 구축하는 것이다.

본 실험은 2014년 서울대학교 부속농장 온도조절 하우스에서 오대벼(조생종)와 화성벼(중생종)를 이용하여 수행을 하였다. 외기온(ambient temperature, AT)온실에서 출수 전까지 1/5000a 와그너 포트에 1주 3본으로 이식하여 재배를 하였다. 그리고 출수 후에 외기온(AT) 온실, 그리고 목표 온도를 외기온 보다 각각 1.5, 3,

5ºC 높게 조절되는 온실들로 이동을 하여서 재배를 하였으며 온실당 개체의 절반은 약 50% 차광이 되는 차광막을 이용하여 차광처리를 하였다. 수확 전에는 이삭 별로 출수일과 개체당 이삭수, 이삭이 노화되는 시기를 조사하였으며 수확 후에 이삭당 영화수, 불임률, 미성숙미율, 천립중을 조사 하였다. 미성숙미는 수정된 영화중 비중이 1.06 이하인 알곡으로 정의를 하였다.

출수일 분포는 온도처리간 및 온도처리와 일사처리 간에 통계적인 유의한 차이가 없었다. 개체당 이삭수와 이삭당 영화수도 온도처리간 및 온도ㅇ와 차광 처리간에 차이가 없었다. 천립중은 온도처리간에 통계적으로 유의한 처리의 차이는 없었으나 차광처리에서는 유의하게 감소하였다.

불임률의 경우에는 고온처리에서 증가하는 경향을 보였으나  화성벼에서만 통계적으로 유의하게 증가하였다. 한편 차광처리에서도 유의한 불임률의 증가가 관찰되었다. 미성숙미율의 경우는 고온조건과 차광조건에서 두 품종 모두 통계적으로 유의하게 증가하는 경향을 보였다.

천립중의 경우 온도 조건보다는 일사조건에 민감하게 반응을 하였으며,. 차광조건은 출수전 저장탄수화물을 일찍 소진하게 만들었기 때문에 천립중의 감소가 일어난 것으로 판단된다. 불임률은 온도에 영향을 받기는 하나 그 민감도가 정지미율에 비하여 둔감 하였고 일사 조건에도 영향을 받는다는 사실을 발견 하였다. 일사조건에 반응한 이유로 개화시간의 지연이나 호르몬의 작용 등을 예상을 할 수 있으나 더 자세한 메커니즘은 추후 연구가 필요하다. 미성숙미율의 경우 온도와 일사 모두에서 반응이 나타났으며 불임률보다 더욱 민감하게 반응을 하였다. 그리고 조생종인 오대의 경우 중생종인 화성보다 평균적으로 높은 미성숙미률을 보였으며,

차광조건에서는 50%가 넘는 미성숙미률이 관찰 되었는데 이는 영양생장기간이 짧아 출수전 저장산물의 축적이 부족하기 때문인 것으로 보인다. 화성의 경우 차광조건이 차광하지 않은 조건에 비하여 온도 반응이 더욱 민감하게 나타났다. 즉 일사가 등숙에 주요한 요인이며 또한 일사의 제한은 등숙에 대한 온도의 반응을 더욱 민감하게 만드는 것을 알 수 있다.

위의 관찰의 결과와 문헌의 조사를 통하여서 미성숙미 발생을 예측할 수 있는 모델을 구성하였다. 즉, 온도의 증가에 따른 알곡 잠재 생장률의 증가를 공급부(source)의 능력이 충분히 보상을 하지 못할 때 미성숙미가 발생하는 것으로 가정을 하였다. 수용부(sink)의 활력은 알곡의 잠재 생장곡선을 통해 표현되는데 기존 문헌의 알곡 잠재생장곡선 식에 알곡의 생장이 온도와 영화의 위치에 따라 반응을 달리한다는 사실을 추가하여 아래와 같이 표현하였다.

$$GrainWeight(dah, Gdd) = \frac{a}{1 + e^{\frac{Gdd - (c + c_1 \times dah)}{b + b_1 \times dah}}}$$

(a : 알곡의 최대 무게 b, c 알곡의 생장기간과 생장속도에 관련된 계수 $b_1$, $c_1$ 는 강세영화와 약세영화를 구분하여 계산하기 위한 계수)

이렇게 표현된 알곡 잠재 생장을 영화 개화분포의 식과 곱하여 이삭 내 개화일별 알곡들의 생장을 계산 하였다. 공급부의 역할을 하는 것은 일일 광합성과 저장산물이라고 생각 할 수 있는데 저장

산물의 경우는 일정한 공급량을 유지시키는 완충 작용의 역할을 하게 설계 하였으며 온도, 일사, 잎의 노화 등이 영향을 미치는 일일 광합성은 일정 이상에서 공급부의 세기를 결정을 하는 요인으로 설계 하였다. 껍질로 둘러싸여 있는 알곡의 특성으로 부피의 변화가 크지 않다고 가정하면 무게의 변화가 비중을 주로 결정한다고 생각하여 등숙 후 일정 이상의 무게가 되지 못한 이삭을 미성숙미로 판별하였다.

위의 온도처리 및 차광처리 실험 결과를 이용하여 모델의 파라미터를 simplex 방법을 이용하여 추정 하여 구동을 하였을 때 실험 처리 평균간 차이를 잘 모사 하였지만 처리 내 이삭별 관찰 값의 변이를 세세하게 모사하는 데는 다소 한계가 있었다.