The effect of air temperature and solar radiation on the occurrence of chalky rice grains in rice cultivars “Koshihikari” and “Akitakomachi”

Takahiro TAKIMOTO, Yuji MASUTOMI, Makoto TAMURA, Youji NITTA and Kenichi TANAKA

Institute for Global Change Adaptation Science, Ibaraki University, 2-1-1 Bunkyo, Mito, Ibaraki 310-8512, Japan
College of Agriculture, Ibaraki University, 3-21-1, Chuo, Ami, Inashiki, Ibaraki 300-0393, Japan
College of Food and Agriculture, Fukushima University, 1, Kanayagawa, Fukushima 960-1296, Japan
Agriculture Research Institute, Ibaraki Agriculture Center, 3402, Kamikunii, Mito, Ibaraki 311-4203, Japan

Abstract

Global warming has already affected agricultural production worldwide. In Japan, the occurrence of chalky rice grains (CRGs), which are low quality grains whose occurrence is exacerbated by high air temperature, has become a major issue. There is concern that this will become more frequent with increasing global warming; therefore, it is necessary to develop a model that can accurately estimate the impact of global warming on the occurrence of CRGs. In this study, such a model was developed for Japan’s main cultivars, “Koshihikari” and “Akitakomachi”. This model is a non-linear model and was used to investigate the differences in the occurrence of these cultivars to temperature and radiation; the occurrence of CRGs was explained as a function of air temperature and solar radiation in this model. The results showed that the occurrence of CRGs could be reproduced more accurately when both air temperature and solar radiation were considered compared to when only air temperature was considered; the latter is the case with existing models. The air temperature at which CRGs begin to appear is lower for “Koshihikari” than “Akitakomachi”, when the air temperature and solar radiation were considered compared to when only air temperature was considered; the latter is the case with existing models. The air temperature at which CRGs begin to appear is lower for “Koshihikari” than “Akitakomachi”, when the average solar radiation is small (less than 16.4 MJ m$^{-2}$ d$^{-1}$). The proposed model will hopefully be applied to impact assessments of global warming and the quantification of varietal characteristics with respect to the occurrence of CRGs.

Key words: Global warming, Rice quality, Statistical model

1. Introduction

Global warming affects food production globally (IPCC, 2014). Rice is one of the most important crops and is a staple food, especially in Asian countries; air temperature during its growing season has an impact not only on its yield but also on its quality (Peng et al., 2004; Lanning et al., 2011). In Japan, a quality degradation of rice grains has occurred in the past few decades (Terashima et al., 2001; Morita, 2008). Chalky rice grains (CRGs) are one of the important factors for determining rice grain quality, and the likelihood of their occurrence is increased by the presence of high air temperatures (Morita, 2008). Therefore, there is concern that CRG occurrence will increase with increase in global warming.

CRGs contain an opaque part within the endosperm. This phenomenon is caused by the presence of fine pores between the starch granules and amyloplasts (Tashiro and Ebata, 1975). CRGs constitute a problem at each stage, from harvest to consumption. In Japan, the ratio of CRGs in a given number of grains is one criterion for determining the rice grade, per Japan’s Agricultural Products Inspection Act. Therefore, the occurrence of CRGs directly affects the income of rice farmers. Because the accumulated density of starch is smaller than that of the perfect grain in CRGs, CRGs tend to damage during rice milling (Wang et al., 2007; Morita, 2008). In addition, CRGs are not preferred in the market because they are less sticky than ordinary grains (Yamakawa et al., 2007) and their taste is considered inferior (Cheng et al., 2005; Wakamatsu et al., 2007; Morita, 2008). Notably, interest in CRGs is not restricted to Japan; CRGs have garnered attention in other countries in Asia and Europe as well (e.g., Chen et al., 2013; Cappelli et al., 2014).

Previous studies have investigated the quantitative relationship between air temperature and the occurrence of CRGs. Masutomi et al. (2015) developed a nonlinear function model to evaluate the occurrence of CRGs in cultivar “Sai-no-kagayaki”. In addition, Morita (2005) formulated a second-order function to estimate the occurrence of CRGs in cultivar “Koshihikari”. These studies enabled the evaluation of increases or decreases in the occurrence of CRGs with air temperature changes and provided two additional suggestions regarding the occurrence of CRGs, as follows. First, there is a temperature at which CRG occurrence begins. Masutomi et al. (2015) showed that this temperature is from 25.05 to 27.28 °C, depending on the type of CRGs; Morita (2005) estimated it to be from 23 to 24 °C. In addition, Wakamatsu et al. (2007) reported that the occurrence of basal-white and white-back CRGs increases above 27 °C in cultivars “Hinohikari” and “Hanasatsuma.” Second, the occurrence of CRGs increases with increasing temperature. The occurrence of CRGs increases at a rate of 10% from 28 to 29 °C in “Koshihikari” (Morita et al., 2016), whereas it increases by 23.4% in “Sai-no-kagayaki” within the same air temperature range (Masutomi et al., 2015). These two indices may be useful for quantitatively discussing the occurrence of CRGs.

Most previous experimental studies have focused on only the occurrence of CRGs among cultivars (e.g., Wakamatsu et al., 2007; Takata et al., 2010). The information we can obtain from
these studies is the qualitative differences among cultivars. In other words, these studies cannot answer how the heat tolerance of cultivar "A" compares to that of cultivar "B" quantitively. A model developed to estimate CRG occurrence may provide the ability to make such comparisons and enable the assessment of quantitative differences among varieties. In addition, such models could enable the selection of more suitable varieties for planting in the future under increased global warming conditions.

However, the occurrence of CRGs is also affected by solar radiation, as confirmed experimentally (Saito, 1987; Kondo et al., 2006; Kondo, 2010); previous models have not rarely evaluated this. Saito (1987) investigated rice quality under changing solar radiation conditions by applying shading treatment to cultivar “Sasanishiki.” They reported that white-core and white-belly CRGs particularly were affected by the shading treatment. Kondo et al. (2006) also showed that the occurrence of milky-white and white-core grains was higher under low sunshine conditions in cultivar “Koshihikari.” Based on these studies, one can see that it is necessary to consider not only the effect of air temperature but also that of solar radiation while modelling the occurrence of CRGs.

Okada et al. (2011) developed a model to estimate rice quality, which considers both air temperature and solar radiation. This model enables evaluation of the impact of global warming by addressing changes in both temperature and solar radiation. However, the rice quality that they focused on was the percentage of first-grade rice in each prefecture. The factors determining the rice grade include not only CRGs, but also cracked grains and grains damaged by insects or diseases. The mechanisms of formation for these grains seem to differ. Therefore, it may be desirable to model imperfect rice types individually.

Yoshida et al. (2016) developed a process model that considers the nitrogen dynamics upon the application of various fertilizers to the cultivar “Koshihikari.” Their results showed that the simulated carbohydrate content and plant nitrogen content available per single spikelet are correlated with the occurrence of CRGs. By using this model, it was possible to evaluate the reduction of CRGs by nitrogen fertilization. However, this process model uses daily maximum and minimum temperatures and solar radiation as those meteorological conditions that affect rice growth. Namely, air temperature indirectly affects the occurrence of CRGs. As they noted, exposure to high air temperature is the factor most influencing the occurrence of CRGs. Therefore, a model to predict the occurrence of CRGs by explicitly considering air temperature is still necessary. This makes it possible to simply assess the impact of changes in meteorological conditions due to climate change on the occurrence of CRGs. Furthermore, the coupling with crop models allows us to evaluate both crop growth and CRGs.

The objective of this study was to develop a model to estimate the occurrence of CRGs, accounting for the effects of both air temperature and solar radiation, and to quantify the varietal difference in the occurrence of CRGs using the developed model.

2. Model and data

2.1 Model

We developed a model based on Eq. (1) in Masutomi et al. (2015). In their model, no CRGs occur at temperatures below the critical air temperature ($T_{cr}$, i.e., the air temperature at which CRGs first appear), but CRG formation is observed at temperatures above $T_{cr}$, and the occurrence of CRGs increases linearly:

$$ I(\bar{T}) = \begin{cases} 0 & (\bar{T} < T_{cr}) \\ k(\bar{T} - T_{cr}) & (\bar{T} \geq T_{cr}) \end{cases} $$

(1)

Here, $I(\%)$ is the occurrence of CRGs, $\bar{T}(°C)$ is the average daily mean air temperature over a given period, and $k$ ($°C^{-1}$) is the sensitivity of the occurrence to $\bar{T}$ above $T_{cr}$.

We incorporate the effect of solar radiation on the occurrence of CRGs into the model. Kondo et al. (2006) and Kondo (2010) indicated that, given identical air temperatures, a lower sunshine duration or lower solar radiation tends to give rise to milky-white and white-core grains, types of CRG. Saito (1987) also experimentally showed that the occurrence of white-core and white-belly grains changes depending on the intensity of solar radiation. Based on these studies, we incorporate the effect of solar radiation on the occurrence of CRGs by expressing critical temperature as a linear function of solar radiation:

$$ I(\bar{T}, \bar{S}) = \begin{cases} 0 & (\bar{T} < a\bar{S} + b) \\ k(\bar{T} - a\bar{S} - b) & (\bar{T} \geq a\bar{S} + b) \end{cases} $$

(2)

where $a$ (°C MJ m$^{-2}$ d$^{-1}$) is the sensitivity of solar radiation to critical temperature, and $b$ (°C) is the critical air temperature when solar radiation is equal to zero. $\bar{S}$ (MJ m$^{-2}$ d$^{-1}$) is the average daily accumulation of solar radiation over a given period. Accordingly, substituting $T_{cr} = a\bar{S} + b$ into Eq. (1) gives us Eq. (2).

According to previous studies, the averaging period for influencing the occurrence of CRGs varies among cultivars. Meteorological variables to explain the occurrence of CRGs also differ among cultivars (Morita, 2005). Morita (2005) showed that basal-white grains of cultivar “Koshihikari” were affected the most by the average daily mean air temperature for 20 days after the heading period. However, the occurrence of CRGs in cultivar “Akitakomachi” was strongly affected by the average daily maximum air temperature for 10 to 30 days or 10 to 20 days after the heading period (Matsumoto et al., 2008). Hence, it is assumed that the meteorological variables and period that can influence the occurrence of CRGs vary among cultivars and types of CRGs. Morita (2005) also described that there is still no consensus on whether daytime, nighttime, maximum, and minimum air temperature affects the occurrence of CRGs.

In this study, we used the daily mean value of air temperature because it resulted in more robust field experimental data than the daily minimum and maximum air temperature. This may be caused by the definitions of daily maximum and minimum air temperatures for meteorological observations. As described in section 2.2, we used meteorological data sets based on the Automated Meteorological Data Acquisition System (AMeDAS) observations provided by the Japan Meteorological Agency. Since 2008, the minimum and maximum air temperatures have been defined as the minimum and maximum values observed every 10 seconds, respectively, in the AMeDAS system. The daily mean air temperature was considered more appropriate as an index for the occurrence of CRGs than an instantaneous
temperature, such as the daily maximum or minimum air temperature in this study. We sought the optimum period around the heading period for averaging the daily mean air temperature and accumulated solar radiation. At the same time, we determined the optimum parameters \( a, b, k, \) and \( T_0 \) to fit the observed occurrence of CRGs. The downhill simplex method was employed to estimate these parameters (Masutomi et al., 2015).

In this method, first the average air temperature and solar radiation were obtained. The start of the averaging period was set as from 6 days prior to 10 days after the heading, including heading period. The end of the averaging period was set as between 15 days and 44 days from the start of the averaging period. Air temperature and solar radiation were averaged from each starting period to each ending period. Therefore, the total number of data sets of average air temperature and solar radiation was 510. Then, the parameters were determined by the following procedure for each of these datasets:

Step A1. The initial value was set to a random real number between \(-100\) and 100 for all parameters.

Step A2. Model estimation was conducted using the parameters and meteorological data and error was evaluated.

Step A3. Based on the error information, the downhill simplex method was used to set the new parameters (Nelder and Mead, 1965).

Step A4. Steps A2–A3 were repeated and the convergence criterion was determined.

Step A5. Steps A1–A4 were repeated 2,000 times until the convergence criterion was satisfied.

Step A6. The parameter with the smallest residual sum of squares was chosen as the optimum parameter.

Step A7. Steps A1–A6 were performed for all 510 averaging periods.

Finally, the averaging period with that with the smallest error was considered optimal and selected. In this way, the model parameters and the averaging period for air temperature and solar radiation were determined.

The bootstrap method was applied to evaluate the uncertainties of model parameters obtained from Eq. (2). The method was performed for the optimum parameters and averaging periods in Eq. (2) in the case of both cultivars, by the following procedure:

Step B1. The residual vector was generated by subtracting the estimation vector in the optimum model from the observation vector.

Step B2. 16 data points, the number of observed data points, were sampled with replacement from the residual vector and added to the estimation vector using the optimum model. This procedure was repeated 1,000 times to generate 1,000 additional vectors.

Step B3. Steps A1–A6 were performed on these data to determine the parameters.

Finally, 1,000 parameter sets were obtained. We also used the leave-one-out method for evaluating the predictability of the model for the occurrence of CRGs. Details of these methods were described in Masutomi et al. (2015).

In addition to the above model, the following model was considered, but not adopted, in this study, because it showed lower accuracy. The model was a logistic regression expressing CRGs as a function of air temperature and solar radiation. Assuming that the occurrence of CRGs follows the binomial distribution, \( mS + nT + l \) which is a linear predictor, its occurrence was estimated by the maximum likelihood method. Here, \( m, n, \) and \( l \) indicate model parameters. As a result, the accuracy of the model by the leave-one-out method was 3.59% and 3.52% despite the root-mean-square error (RMSE) with respect to “Koshihikari” and “Akitakomachi” respectively. These results were less accurate than Eq. (2), as described in Section 3.1.

### 2.2 Data

The field experiment was done at the Ibaraki Agricultural Institute at Ibaraki Prefecture, Japan (35.89°N, 140.21°E) from 2008 to 2015. The soils of the field are categorized as coarse-textured haplic gray lowland soils. The rice cultivars used in this experiment are “Koshihikari” and “Akitakomachi.” The former is the most popular cultivar in Japan and the latter is mainly cultivated in northern Japan. Both cultivars are major crops in the Ibaraki Prefecture, where the experimental field is located; these cultivars occupy approximately 90% of the total cropping area in the prefecture (Beikoku-kikou, 2018).

Both cultivars were transplanted twice a year with a difference of about 10 days. Basal nitrogen fertilizer containing 1% each of nitrogen, phosphorus, and potassium was added to “Koshihikari” and “Akitakomachi” at 0.7 kg N a\(^{-1}\) and 0.6 kg N a\(^{-1}\), respectively. Topdressing nitrogen fertilizer containing 17% each of nitrogen, and potassium was added 15 and 30 days prior to heading with 0.3 kg N a\(^{-1}\) for “Koshihikari” and “Akitakomachi”, respectively. Young rice seedlings were transplanted at 22.2 hills per square meter, with five seedlings per hill. Table 1 shows the transplanting date, heading period, and maturity date. Irrigated water was managed by the following procedure. The flooding condition was maintained from transplanting to the middle of tillering stage. After the number of stems reached about 350 m\(^2\), midseason drainage was carried out for 1 to 2 weeks depending on the weather condition. Pre-harvest drainage started 30 and 25 days after heading in the “Koshihikari” and “Akitakomachi”, respectively. The rice was sampled from 2 areas with 2.16 m\(^2\), which including 48 stumps in each area, in the fields. About 1,000 grains passed through 1.85 mm sieve were visually classified by a technical expert into each type of CRG, including white-core, milky-white, white-back, basal-white, and white-belly. In this study, the model was developed using the sum of occurrence events for each type of CRG, because the number of sample data was too small to develop a model for each type of CRG.

We used the daily mean air temperature and daily accumulated solar radiation from the MeteoCrop DB (Kuwagata et al., 2011), which is an agro-meteorological database based on AMeDAS observations. The AMeDAS station was installed near the experimental field at a distance of less than 200 m and used to observe air temperature, precipitation, sunshine duration, and wind speed. The MeteoCrop DB provided the solar radiation converted from observed sunshine duration and air temperature at the AMeDAS station. Because of the consistent quality and quantity of data, both the daily mean air temperature and daily accumulated solar radiation obtained from MeteoCrop DB were used in this study.
3. Results and discussion

3.1 Model improvement by considering the sensitivity of solar radiation to critical temperature

The variations in the occurrence of CRGs across eight years are shown in Fig. 1 and Table 1. The minimum and maximum occurrences of CRGs in "Koshihikari" was 3.0% with later transplanting in 2009 and 19.3% with later transplanting in 2013. In "Akitakomachi," the values were 1.9% with earlier transplanting in 2013 and 16.8% with earlier transplanting in 2010. On average, the occurrences of CRGs for "Koshihikari" and "Akitakomachi" were 9.7% and 7.0%, respectively.

Table 2 shows the results of parameters and statistics calculated with Eq. (1) and Eq. (2). The RMSE in Eq. (1), used to determine the optimum model for "Koshihikari" and "Akitakomachi", were 3.53% and 2.50%, respectively. Moreover, the RMSE in the leave-one-out method for "Koshihikari" was 4.31% in Eq. (1) and 3.11% in Eq. (2) (Fig. 2, Fig. 3, and Table 2). The RMSE in Eq. (2) for both "Koshihikari" and "Akitakomachi" were 2.55% and 1.77%, respectively, and the optimum averaging periods in Eq. (2) for "Koshihikari" and "Akitakomachi" were 34 days and 37 days from day 5 prior to the heading period, respectively. This optimum averaging period corresponds to the ripening period.

The RMSE was improved by incorporating both solar radiation and air temperature in the model. Comparing Eq. (1) and (2), it was found that not only the RMSE but also the sensitivity parameter $k$ for the air temperature changed on incorporating both factors. The $k$ increased by 2-3 times for both cultivars. These two results suggest that models that do not consider solar radiation may underestimate the sensitivity to air temperature. In an impact assessment of global warming, it was found that difference in $k$ greatly affects the prediction of CRG occurrence. Thus, consideration of solar radiation can contribute to a more accurate estimation of impact assessment. In addition, the Akaike’s Information Criteria (AIC) of Eq. (1) and Eq. (2) were compared to investigate the complexity and accuracy of

Table 1. Rice phenology and the occurrence of chalky rice grains in this experiment. The former and latter values separated by slash indicate earlier and later transplanting in the year, respectively.

| Year | Cultivar | Transplanting (DOY) | Heading (DOY) | Maturity (DOY) | White-core (%) | Milky-white (%) | White-back (%) | Basal-white (%) | White-belly (%) | Total (%) |
|------|----------|---------------------|--------------|---------------|----------------|----------------|---------------|----------------|---------------|----------|
| 2008 | "Koshihikari" | 119 / 128 | 209 / 214 | 248 / 253 | 3.0 / 2.6 | 7.9 / 6.6 | 3.2 / 1.2 | 0.8 / 1.1 | 0.2 / 0.3 | 15.1 / 11.6 |
| 2009 | "Koshihikari" | 118 / 127 | 206 / 209 | 245 / 247 | 1.2 / 0.6 | 10.1 / 2.2 | 1.0 / 0.0 | 0.1 / 0.1 | 11.5 / 3.0 |
| 2010 | "Koshihikari" | 118 / 127 | 206 / 208 | 241 / 245 | 1.5 / 1.0 | 5.8 / 9.3 | 1.8 / 1.3 | 1.0 / 0.8 | 0.0 / 0.8 | 10.1 / 13.2 |
| 2011 | "Koshihikari" | 118 / 126 | 211 / 213 | 248 / 250 | 3.5 / 4.0 | 2.8 / 1.8 | 3.0 / 0.5 | 1.5 / 0.5 | 0.3 / 1.3 | 11.0 / 8.0 |
| 2012 | "Koshihikari" | 117 / 128 | 209 / 213 | 244 / 248 | 0.7 / 0.5 | 2.2 / 2.5 | 0.4 / 0.2 | 0.3 / 0.4 | 1.4 / 1.0 | 5.0 / 4.6 |
| 2013 | "Koshihikari" | 116 / 127 | 204 / 210 | 240 / 247 | 0.6 / 1.3 | 5.1 / 8.9 | 0.1 / 0.8 | 2.0 / 7.5 | 0.5 / 0.7 | 8.3 / 19.3 |
| 2014 | "Koshihikari" | 118 / 127 | 205 / 209 | 243 / 249 | 0.8 / 1.3 | 3.2 / 4.0 | 0.7 / 0.5 | 1.0 / 1.6 | 0.4 / 0.3 | 6.0 / 7.7 |
| 2015 | "Koshihikari" | 117 / 127 | 202 / 207 | 240 / 246 | 0.6 / 0.4 | 6.9 / 6.0 | 0.5 / 0.8 | 3.1 / 1.8 | 0.7 / 0.2 | 11.8 / 9.2 |
| 2008 | "Akitakomachi" | 119 / 128 | 200 / 205 | 237 / 243 | 0.4 / 0.8 | 7.3 / 3.0 | 1.4 / 4.7 | 0.5 / 0.6 | 1.1 / 0.8 | 10.6 / 9.9 |
| 2009 | "Akitakomachi" | 118 / 127 | 197 / 201 | 236 / 240 | 0.4 / 0.4 | 2.5 / 2.1 | 0.3 / 0.3 | 0.1 / 0.1 | 0.2 / 0.2 | 3.5 / 2.9 |
| 2010 | "Akitakomachi" | 118 / 127 | 197 / 202 | 233 / 237 | 1.5 / 0.0 | 8.3 / 4.8 | 2.5 / 6.3 | 1.0 / 0.3 | 3.5 / 0.5 | 16.8 / 11.9 |
| 2011 | "Akitakomachi" | 118 / 126 | 200 / 202 | 239 / 241 | 1.5 / 1.8 | 2.0 / 2.8 | 3.5 / 3.8 | 0.0 / 0.5 | 0.3 / 0.0 | 7.3 / 8.8 |
| 2012 | "Akitakomachi" | 117 / 128 | 199 / 203 | 232 / 237 | 1.0 / 0.3 | 1.5 / 1.4 | 0.9 / 1.3 | 0.5 / 0.4 | 1.1 / 0.7 | 5.0 / 4.1 |
| 2013 | "Akitakomachi" | 116 / 127 | 193 / 196 | 230 / 233 | 0.3 / 0.3 | 0.8 / 2.4 | 0.3 / 0.4 | 0.4 / 0.7 | 0.2 / 0.3 | 1.9 / 4.1 |
| 2014 | "Akitakomachi" | 118 / 127 | 194 / 199 | 232 / 236 | 0.6 / 0.4 | 0.6 / 0.3 | 1.5 / 0.9 | 0.6 / 0.8 | 0.5 / 0.3 | 3.8 / 2.6 |
| 2015 | "Akitakomachi" | 117 / 127 | 194 / 199 | 231 / 237 | 0.5 / 0.4 | 7.0 / 5.5 | 1.0 / 0.9 | 1.2 / 1.3 | 0.5 / 0.9 | 10.2 / 8.9 |

Fig. 1. Yearly variation in the occurrence of chalky rice grains of cultivars (a) "Koshihikari" and (b) "Akitakomachi". Superscripts $e$ and $l$ indicate earlier and later transplanting in the year, respectively. Patterns indicate types of chalky rice grains.
the models (Akaike, 1998). For “Koshihikari,” the AIC values of Eq. (1) and Eq. (2), when using the optimal parameters, were 93.7 and 83.42, respectively; for “Akitakomachi,” they were 82.79 and 71.77, respectively (Table 2). Based on these results, it can be inferred that the occurrence of CRGs can be more accurately determined by considering both solar radiation and air temperature, in the case of both varieties (Fig. 4).

3.2 Characteristic differences in CRG occurrence between “Koshihikari” and “Akitakomachi”

The 95% confidential intervals of the parameters $k$, $a$, and $b$ in Eq. (2), as calculated by the bootstrap method, were 3.51–9.62% per °C, 0.36–0.59 °C (MJ m$^{-2}$ d$^{-1}$)$^{-1}$, and 13.08–18.14 °C, respectively, for “Koshihikari” and were 6.52–11.02% per °C, 0.23–0.35 °C (MJ m$^{-2}$ d$^{-1}$)$^{-1}$ and 18.81–20.99 °C, respectively, for “Akitakomachi” (Fig. 5).

Figure 6 shows the difference in $T_{cr}$ between “Koshihikari” and “Akitakomachi.” The $T_{cr}$ for “Koshihikari” was found to be smaller than that for “Akitakomachi,” despite considering parameter uncertainty when $S$ is less than 16.4 MJ m$^{-2}$ d$^{-1}$. However, such low radiation cases are rare because the mean and standard deviations of $S$ in the experimental period were 18.88

### Table 2. Model parameters and statistics in Eq. (1) and Eq. (2) for each cultivar.

|           | “Koshihikari” | “Akitakomachi” |
|-----------|---------------|----------------|
| Eq. (1)   |               |                |
| Optimum $k$ (% °C$^{-1}$) | 2.04 | 3.42 |
| Optimum $T_{cr}$ (°C) | 22.06 | 24.22 |
| Optimum averaging period | 15 days from 5 days after heading | 29 days from 1 day prior to heading |
| RMSE in optimum model (%) | 3.53 | 2.50 |
| AIC in optimum model | 93.7 | 82.79 |
| RMSE in leave-one-out method (%) | 4.31 | 2.82 |
| Eq. (2)   |               |                |
| Optimum $k$ (% °C$^{-1}$) | 6.59 | 8.76 |
| Optimum $a$ (°C (MJ m$^{-2}$ d$^{-1}$)$^{-1}$) | 0.45 | 0.29 |
| Optimum $b$ (°C) | 16.41 | 19.89 |
| Optimum averaging period | 34 days from 5 days prior to heading | 37 days from 5 days prior to heading |
| RMSE in optimum model (%) | 2.55 | 1.77 |
| AIC in optimum model | 83.42 | 71.77 |
| RMSE in leave-one-out method (%) | 3.11 | 2.33 |

![Fig. 2](image2.png)

**Fig. 2.** Comparisons between the observed and predicted occurrences of chalky rice grains of cultivars (a) “Koshihikari” and (b) “Akitakomachi” in Eq. (1). Predicted values were estimated by the leave-one-out method.

![Fig. 3](image3.png)

**Fig. 3.** Comparisons between the observed and predicted occurrences of chalky rice grains of cultivars (a) “Koshihikari” and (b) “Akitakomachi” in Eq. (2). Predicted values were estimated by the leave-one-out method.
and 2.01 MJ m$^{-2}$ d$^{-1}$, respectively. The difference in $T_a$ between cultivars is not clear when $S$ is larger than 16.4 MJ m$^{-2}$ d$^{-1}$ because the uncertainty of $T_a$ is overlapped. It may be possible to clarify this difference if we have data on extreme years in the future.

Fig. 4. Occurrence of chalky rice grains of cultivars (a) “Koshihikari” and (b) “Akitakomachi” in relation to air temperature ($\bar{T}$) and solar radiation ($\bar{S}$). Lines indicate optimum models obtained by Eq. (2) when $S$ equals 15, 19, and 23 MJ m$^{-2}$ d$^{-1}$.

Fig. 5. Optima and uncertainties for three parameters for cultivars “Koshihikari” (K) and “Akitakomachi” (A) in Eq. (2); sensitivity $k$ (% °C$^{-1}$) and solar radiation dependency for critical temperatures $a$ (°C (MJ m$^{-2}$ d$^{-1}$)$^{-1}$) and $b$ (°C). The upper and lower whiskers indicate the 97.5th and 2.5th percentiles, respectively. The top and bottom boundaries of the box are the 75th and 25th percentiles, respectively. The bold line in the box is the median. These statistics were obtained using the bootstrap method. The open circle indicates the optimum parameter value.

Fig. 6. Relationship between solar radiation ($\bar{S}$) and critical temperature ($T_a$) in Eq. (2) for both cultivars. Filled area indicates the 95th percentile of $T_a$ with the bootstrap method. Deep colored lines indicate $T_a$ with optimum parameters.
The sensitivities, $k$ values, of “Koshihikari” and “Akitakomachi” were found to be 8.76 and 6.59% per °C, respectively (Table 2). When we consider the parameter uncertainty using the bootstrap method, $k$ overlaps within the 95% confidence interval. However, differences in uncertainty are possible owing to the presence of differences in the range of parameters (Fig. 5).

As mentioned in Section 2.1, CRG sensitivity to meteorological elements varies by type. For example, milky-white grains are highly sensitive to solar radiation (Morita et al., 2016). According to the experimental results, the ratios of milky-white grains to the total CRGs were, on average, 46.5% and 54.9% for “Akitakomachi” and “Koshihikari”, respectively. Therefore, it is considered that the parameter $a$ indicating the sensitivity to solar radiation was larger in “Koshihikari” because of the high percentage of milky-white grains. Further, white-back and basal-white grains, which are highly sensitive to temperature, accounted for 24.7% and 34.5% of the total CRGs for “Koshihikari” and “Akitakomachi,” respectively (Morita et al., 2016). Therefore, the parameter $k$ for the temperature sensitivity is considered to have been larger in “Akitakomachi.”

We can also compare $T_{cr}$ with the corresponding values in previous studies. According to the experimental results of this study, the observed range of $\overline{S}$ in “Koshihikari” was 15.4–22.3 MJ m$^{-2}$ d$^{-1}$. This corresponds to 23.4–26.4 °C in $T_{cr}$. On the other hand, Morita (2005) reported that $T_{cr}$ in “Koshihikari” was 23–24 °C, but the range of solar radiation was not specified. Although the details of solar radiation in Morita (2005) must be analyzed, there seems to be no major discrepancy between the results of both studies. Masutomi et al. (2015) reported the $T_{cr}$ to be 25.05 °C in “Sai-no-kagayakai” for milky-white and white-core grains, which are the most easily formed. Although direct comparisons cannot be made because the varieties are different, 25.05 °C corresponds to 19.2 MJ m$^{-2}$ d$^{-1}$ for “Koshihikari” and 17.8 MJ m$^{-2}$ d$^{-1}$ for “Akitakomachi,” and both solar radiation levels are almost the average conditions. Therefore, there seems to be no contradiction between $T_{cr}$ in “Sai-no-kagayakai” and that in this study.

Our results suggest that CRGs can occur more easily in “Koshihikari” than “Akitakomachi” when $\overline{S}$ is less than 16.4 MJ m$^{-2}$ d$^{-1}$ and that the sensitivity $k$ may have been larger in “Akitakomachi” than “Koshihikari.” However, thus far, the difference between cultivars is not clear when $\overline{S}$ is larger than 16.4 MJ m$^{-2}$ d$^{-1}$. According to the report by the Ministry of Agriculture, Forestry and Fisheries, the tolerance of “Koshihikari” and “Akitakomachi” to high temperatures is ranked as intermediate (MAFF, 2018). However, the results of this study suggested that there is a difference in $T_{cr}$ at $\overline{S}$ less than 16.4 MJ m$^{-2}$ d$^{-1}$. Therefore, the results of this study show that the response is different from the viewpoint of the sensitivity to meteorological conditions even in cultivars ranked to the same heat tolerance. The meteorological dependence of the difference between the occurrences of CRGs in “Koshihikari” and “Akitakomachi” is shown in Fig. 7. This figure shows that “Koshihikari” tends to have more occurrence of CRGs than “Akitakomachi” in lower $\overline{S}$ case, and vice versa.

4. Conclusions

We aimed to develop a new model that accurately estimates the occurrence of CRGs and to quantify the varietal differences with respect to the occurrence of CRGs. We found that our newly proposed model, which considers not only the effect of air temperature but also that of solar radiation, had better predictability of the occurrence of CRGs than existing models, in which only air temperature was considered. Using our model, we revealed that CRGs began to occur at lower air temperatures in the case of “Koshihikari” than in the case of “Akitakomachi”, when the average solar radiation was small (less than 16.4 MJ m$^{-2}$ d$^{-1}$). It is expected that the proposed model will be applied to...
impact assessments of global warming and the quantification of varietal characteristics with respect to the occurrence of CRGs.

Acknowledgements

A part of this work was supported by the Social Implementation Program on Climate Change Adaptation Technology (SI-CAT), MEXT, Japan.

References

Akaikke H, 1998: Information Theory and an Extension of the Maximum Likelihood Principle. In Selected Papers of Hirotugu Akaikke. Springer, New York, pp. 199–213. Beikoku-kikou, 2018: in Japanese; http://www.komenet.jp/pdf/H29sakutuke.pdf; accessed 23 April, 2019.

Cappelli G, Bregaglio S, Romani M, Feccia S, Confalonieri R, 2014: A software component implementing a library of models for the simulation of pre-harvest rice grain quality. Computers and Electronics in Agriculture 104, 18–24. doi: 10.1016/j.compag.2014.03.002

Chen C, Huang J, Zhu L, Shah F, Nie L, Cui K, Peng S, 2013: Varietal difference in the response of rice chalkiness to temperature during ripening phase across different sowing dates. Field Crops Research 151, 85–91. doi: 10.1016/j.fcr.2013.07.016

Cheng FM, Zhong LJ, Wang F, Zhang GP, 2005: Differences in cooking and eating properties between chalky and translucent parts in rice grains. Food Chemistry 90, 39–46. doi: 10.1016/j.foodchem.2004.03.018

IPCC, 2014: Summary for policymakers. In: Climate Change 2014: Impacts, Adaptation, and Vulnerability. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1–32.

Kondo M, 2010: Effects of high-temperature stress on growth and grain filling in rice. Gamma Field Symposia 47, 67–74.

Kondo M, Morita S, Nakamoto C, Koyama Y, Ueno N, Hosoi J, Ishida Y, Yamakawa T, Nakayama Y, Yoshioka Y, Ohashi Y, Iwai M, Ohdaira Y, Nakatsu S, Katsuba Z, Hajima M, Mori Y, Kimura H, Salata M, 2006: Effects of air temperature during ripening and grain protein contents on chalkiness in rice. Abstracts of Meeting of the CSSJ 222, 14. doi: 10.14829/jcsproc.222.0.14.0 (in Japanese).

Kuwagata T, Yoshimoto M, Ishigooka Y, Hassewa T, Utsumi M, Nishimori M, Masaki Y, Saito O, 2011: MeteoCrop DB: an agro-meteorological database coupled with crop models for studying climate change impacts on rice in Japan. Journal of Agricultural Meteorology 67, 297–306. doi: 10.2480/agrmnet.67.4.9

Lanning SB, Siebenmorgen TJ, Counce PA, Ambarddekar AA, Mauromoustakos A, 2011: Extreme nighttime air temperatures in 2010 impact rice chalkiness and milling quality. Field Crops Research 124, 132–136. doi: 10.1016/j.fcr.2011.06.012

Masutomi Y, Arakawa M, Minoda T, Yonekura T, Shimada T, 2015: Critical air temperature and sensitivity of the incidence of chalky rice kernels for the rice cultivar “Sai-no-kagayaki.” Agricultural and Forest Meteorology 203, 11–16. doi: 10.1016/j.agrformet.2014.11.016

Matsumoto K, Senoo T, Miyatake N, Nakajima A, Okubo K, Sugimoto S, 2008: Effects of temperature during the ripening period, method of fertilizer application on occurrence of chalky grains in rice cultivar “Akitakomachi.” Bulletin of the Agricultural Experimental Station, Okayama Prefectural General Agriculture Center 26, 1–6 (in Japanese).

Ministry of Agriculture, Forestry and Fisheries (MAFF), 2018: Rice. (in Japanese; http://www.nihshu2.maff.go.jp/info/sinsakijun/kijun/1440.pdf; accessed 26 February 2019).

Morita S, 2005: The occurrences of immature grain with white portions and deep ditch, and grain weight decrease in rice under high temperature during ripening. Journal of Agricultural Science 60, 442–446 (in Japanese).

Morita S, 2008: Prospect for developing measures to prevent high-temperature damage to rice grain ripening. Japanese Journal of Crop Science 77, 1–12. doi: 10.1626/jcs.77.1. (in Japanese with English abstract).

Morita S, Wada H, Matsue Y, 2016: Countermeasures for heat damage in rice grain quality under climate change. Plant Production Science 19, 1–11. doi: 10.1080/1343943X.2015.1128114

Nelder JA, Mead R, 1965: A simplex method for function minimization. The Computer Journal 7, 308–313. doi: http://dx.doi.org/10.1093/comjnl/7.4.308

Okada M, Iizumi T, Hayashi Y, Yokozawa M, 2011: Modeling the multiple effects of temperature and radiation on rice quality. Environmental Research Letters 6, 034031. doi: 10.1088/1748-9326/6/3/034031

Peng S, Huang J, Sheehy JE, Laza RC, Visperas RM, Zhong X, Centeno GS, Khush GS, Cassman KG, 2004: Rice yields decline with higher night temperature from global warming. Proceedings of the National Academy of Science 101, 9971–9975. doi: 10.1073/pnas.0403720101

Saito M, 1987: Influence of shading levels in the ripening period on the yield of rice plant and the quality of brown rice. Tohoku Journal of Crop Science 30, 48–49. doi: 10.1626/jcs.76.71. (in Japanese).

Takata S, Sakata M, Kameshima M, Yamamoto Y, Miyazaki A, 2010: Varietal difference in the relation between the occurrence of white immature kernels caused by a high temperature during the ripening period and the amount of basal nitrogen application in rice. Japanese Journal of Crop Science 79, 150–157. (in Japanese with English abstract).

Tashiro T, Ebata M, 1975: Studies on white-belly rice kernel: IV. Opaque rice endosperm viewed with a scanning electron microscope. Japanese Journal of Crop Science 44, 205–214.

Terashima K, Saito Y, Sakai N, Watanabe T, Ogata T, Akita S, 2001: Effects of high air temperature in summer of 1999 on ripening and grain quality of rice. Japanese Journal of Crop Science 79, 449–458. (in Japanese with English abstract).

Wakamatsu K, Sasaki O, Uezono I, Tanaka A, 2007: Effects of high air temperature during the ripening period on the grain quality of rice in warm regions of Japan. Japanese Journal of Crop Science 76, 71–78. doi: 10.1626/jcs.76.71. (in Japanese with English abstract).

Wang J, Wan X, Li H, Pfeiffer WH, Crouch J, Wan J, 2007: Application of identified QTL-marker associations in rice quality improvement through a design-breeding approach. Theoretical and Applied Genetics 115, 87–100. doi: 10.1007/s00122-007-0545-x

Yamakawa H, Hirose T, Kuroda M, Yamaguchi T, 2007: Comprehensive expression profiling of rice grain filling-related genes under high temperature using DNA microarray. Plant Physiology 144, 258–277. doi: 10.1104/pp.107.098665

Yoshida H, Takehisa K, Kojima T, Ohno H, Sasaki K, Nakagawa H, 2016: Modeling the effects of N application on growth, yield and plant properties associated with the occurrence of chalky grains of rice. Plant Production Science 19, 30–42. doi: 10.1080/1343943X.2015.1128111