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Critical air temperature and sensitivity of the incidence of chalky rice kernels for the rice cultivar "Sai-no-kagayaki"

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ABSTRACT

A high incidence of chalky rice kernels (CRKs), caused mainly by a high air temperature during the grain-filling period, has become a significant problem for rice production in Japan. Adding to the problem, global warming will increase the incidence of CRKs into the future. The objective of this study is to quantify two parameters that represent basic characteristics of the incidence of CRKs: T_{cr}, the critical air temperature at which CRKs begin to occur; and S_t, the sensitivity of the incidence to air temperature changes above T_{cr}. We quantify these two parameters for three groups of CRKs, into which all five types of CRKs can be divided: white-back and white-belly (BAB); white-based (BSD); and milky-white and white-core (MAC). To quantify the parameters, we first propose a simple statistical model that includes T_{cr} and S_t. Then, using field experimental data, we statistically quantify them according to the three groups of CRKs. The rice cultivar used in this study is "Sai-no-kagayaki." The results showed that T_{cr}s for BAB, BSD, and MAC were 27.28 °C, 25.13 °C, and 25.05 °C, respectively. The corresponding values of S_ts were 10.51%/°C, 10.28%/°C, and 2.61%/°C. From these results, BSD and MAC occur at an air temperature about 2 °C lower than BAB does, and BAB and BSD have sensitivity to air temperature changes about four-fold that of MAC. Thus, BSD has both a lower critical air temperature and a higher sensitivity to air temperature changes. These characteristics can explain the observed high incidence of BSD in the past and at present. Estimations of the incidences of CRKs using the proposed model with the quantified parameters show that the incidence in BSD is likely to continue to be higher than in the other types even in the early stages of a warmer future under global warming.

1. Introduction

Recently, chalky rice kernels (CRKs), caused mainly by a high air temperature during the grain-filling period, have been increasingly seen across a broad area of Japan (MAFF, 2006). CRKs are not preferred by consumers and processors because of low eating quality (Kim et al., 2000; Wakamatsu et al., 2007; Chun et al., 2009) and production loss during the milling process due to their fragility (Webb, 1991). Hence, a high incidence of CRKs decreases the grade and price of rice grains, thereby reducing the income of rice producers. The recent high incidence of CRKs has become problematic in rice production in Japan and urgent agricultural countermeasures are needed.

One reason for the recent high incidence of CRKs is thought to be global warming (Morita, 2008). In fact, average annual air temperature has increased by 1.15 °C over the past 100 years in Japan (MRI, 2013a) and a trend for increasing air temperatures during the grain-filling period has been seen for several regions in Japan (MAFF, 2006). The Meteorological Research Institute in Japan (MRI, 2013b) has projected that air temperatures in summer, which is the grain-filling period for rice in Japan, will increase by 2.74 °C before the end of this century (2076–2095) relative to the air temperature at the end of the last century (1980–1999). There is no doubt that the incidence of CRKs will increase into the future and become more problematic unless agricultural countermeasures are implemented to reduce the incidence of CRKs.

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The critical air temperature at which CRKs begin to occur (T_{cr}) and the sensitivity of the incidence to air temperature changes above T_{cr} (S_t) are the most important values for characterizing the incidence of CRKs. By ascertaining these values for all types of CRKs (white-back, white-based, white-belly, milky-white, and white-core) we can quantify the differences in the characteristics of CRK incidences for all types. This information would be useful for understanding the difference in tolerance to high air temperatures for each type. By using these values, we can also project the incidence of CRKs, which would be helpful for taking prompt action and supporting producers, as well as allowing stakeholders to discuss and develop effective agricultural countermeasures.

A few studies have estimated T_{cr}, but we know of no studies on S_t. Tashiro and Wardlaw (1991) used a phytotron to give rough values of T_{cr} for milky-white kernels, and Morita (2005) and Wakamatsu et al. (2007, 2008) used data from field experiments to roughly estimate T_{cr}. We therefore know only rough values for T_{cr} thus far. Several modeling studies on the incidence of CRKs have been conducted (Nagahata et al., 2006; Nakagawa et al., 2008; Oya and Yoshida, 2008; Wakiyama et al., 2010), but they did not propose any values for T_{cr} and S_t. Accurate values for T_{cr} and S_t and methods to quantify T_{cr} and S_t are therefore lacking.

The objective of this study is to quantify T_{cr} and S_t for all types of CRKs. To achieve this, we first propose a simple statistical model that includes T_{cr} and S_t as model parameters. Then, we estimate the values for T_{cr} and S_t by statistical regression on the field experimental data. The rice cultivar used in this study is "Sai-no-kagayaki," which was bred in Saitama Prefecture, Japan in 2005. This cultivar was harvested from about 11,500 ha in Saitama Prefecture in 2012, making it the second largest harvested cultivar in the prefecture that year (Saitama Pref., 2013) and fourteenth largest in Japan as a whole (SRSO, 2013). This cultivar is known to have a low tolerance to high air temperatures, and a high incidence of CRKs occurred in 2010 because of extremely high air temperatures during the ripening period (Arakawa et al., 2011). Consequently, developing effective agricultural countermeasures to reduce the incidence of CRKs for the cultivar is an urgent matter.

2. Method and data

2.1. Model

To quantify the critical air temperature at which CRKs begin to occur (T_{cr}) and the sensitivity of the incidence to air temperature changes above T_{cr} (S_t), we propose the following statistical model, which includes the two parameters:

$$I = \max(Sc(T_{30} - T_{cr}),\quad 0) \tag{1}$$

here I [%] is the incidence of CRKs and T_{30} [°C] is the average air temperature during the grain-filling period related to the incidence of CRKs, which is 30 days from heading. Eq. (1) is designed under the assumption that CRKs begin to occur at T_{cr} and the sensitivity of the incidence to air temperature changes above T_{cr} is S_t. Note that some studies have used 20 days from heading for the grain-filling period in relation to the incidence of CRKs (Terashima et al., 2001; Morita, 2005; Wakamatsu et al., 2007; Wakiyama et al., 2010), but we use 30 days because a model with air temperatures averaged over 20 days after heading (T_{20}) gave poorer agreement with field experimental data than did the present model, as shown in Table 1. However, it should be noted that the grain-filling period related to the incidence of CRKs may depend on rice cultivar.

Our objective is to quantify T_{cr} and S_t for all types of CRKs: white-back, white-based, white-belly, milky-white, and white-core. Unfortunately, the discriminator device used in this study (Satake, RGQI20A) cannot discriminate between white-back and white-belly or between milky-white and white-core. Hence, we quantify T_{cr} and S_t for three groups, into which all types of CRKs are categorized: white-back and white-belly (BAB); white-based (BSD); and milky-white and white-core (MAC).

Table 1
Root mean square errors [%] for the incidence of CRKs between simulations and observations for the models that used T_{30} and T_{20}.

	T_{20}	T_{30}
BAB	3.38	1.69
BSD	6.53	6.44
MAC	2.30	1.89

2.2. Quantification of T_{cr} and S_t

2.2.1. Optimization of T_{cr} and S_t

The values of T_{cr} and S_t are quantified so that difference in the incidence of CRKs between observations in field experiments and estimations from Eq. (1) is minimized. In this study, the simplex method is used for the minimization (Nelder and Mead, 1965). To reduce the dependency on initial value as much as possible, we conduct the following procedure.

Step 1: The ranges of initial values for T_{cr} and S_t are set to be from −100 to 100.
Step 2: A set of parameters for T_{cr} and S_t is selected at random from the range of initial values defined in Step 1.
Step 3: T_{cr} and S_t are quantified by applying the simplex method to the set of initial values selected in Step 2.
Step 4: The root mean square error (RMSE) of the incidence between the observations and the estimations is quantified.
Step 5: Steps 2 to 4 are carried out 1000 times.
Step 6: The T_{cr} and S_t with the least RMSE are defined as the optimal values for T_{cr} and S_t.

The model with the optimal values for T_{cr} and S_t is referred to as the optimal model herein.

2.2.2. Uncertainty in T_{cr} and S_t

The values of parameters found by statistical methods have some uncertainty. We quantify the uncertainty in T_{cr} and S_t by using the bootstrap method (Efron, 1979) according to the following procedure.

Step 1: A vector is made from the observations of incidence of CRKs. Similarly, a corresponding vector is made from estimations using the optimal model. These vectors are called the observation and estimation vectors, respectively. Each vector has 18 elements, which is the number of samples, as will be shown in the next section.
Step 2: A residual vector is made by subtracting the observation vector from the estimation vector.
Step 3: An additional 1000 residual vectors are made by sampling at random from the residual vector made in Step 2.
Step 4: An additional 1000 observation vectors are made by adding the new 1000 residual vectors made in Step 3 to the estimation vector.
Step 5: The 1000 new observation vectors made in Step 4 are used to estimate 1000 pairs of T_{cr} and S_t.
Step 6: The 95% confidence intervals of T_{cr} and S_t are calculated from the 1000 pairs of T_{cr} and S_t obtained in Step 5. We quantify the uncertainty in T_{cr} and S_t by using these 95% confidence intervals.