



Breeding targets for heat-tolerant rice varieties in Japan in a warming climate

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Abstract

The breeding of heat-tolerant (HT) varieties is considered an effective adaptation measure to reduce the impacts of global warming on crops. However, little is known about how much heat tolerance needs to be attained in the breeding of HT varieties and by when the HT varieties should be introduced in a warming climate. Here, we assessed the effect of the introduction of HT rice varieties on the incidence of low-quality rice grains (chalky rice grain, CRG, as a result of high temperatures), and formulated a breeding target for rice in Japan, where high incidence of CRG is already a concern. Varieties with a 3 °C higher temperature tolerance should be bred and introduced until the 2040s under representative concentration pathways (RCPs) 2.6 and 8.5, in the pessimistic scenario, considering the uncertainties in climate models and an impact assessment model, which were large. In the median case, varieties with a 1 and 2 °C higher temperature tolerance are needed until the 2040s under RCPs 2.6 and 8.5, respectively. The findings revealed necessary efforts in breeding research and programs under conditions of global warming.

Keywords Breeding target · Global warming · Heat tolerant · Chalky rice grain · Japan · Grain quality

1 Introduction

Global warming not only directly reduces crop yields (Kinose et al. 2020; Masutomi et al. 2009; Porter et al. 2014; Rosenzweig et al. 2014; Zhao et al. 2016), but also indirectly reduces “marketable” yields via decreased crop quality. Rice, one of the world’s

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major cereals, has a high incidence of low quality rice grains, called chalky rice grain (CRG; Fig. 1) as a result of high temperatures during the ripening period (Krishnan et al. 2011; Masutomi et al. 2015; Morita et al. 2016; Takimoto et al. 2019; Tashiro & Wardlaw 1991; Xiong et al. 2017). CRG is fragile, which increases loss during milling, thus reducing the marketable yield (Bao 2019; Lyman et al. 2013; Zhao & Fitzgerald 2013). In addition, CRG has low eating quality (Chun et al. 2009; Kim et al. 2000). These characteristics of CRG result in a low market value. Hence, CRG also causes economic loss by decreasing farmers' income. In Japan, an increased incidence of CRG due to global warming has already been reported in many prefectures (MAFF 2019), and an increase in CRG and its economic impacts are predicted (Akune et al. 2015; Masutomi et al. 2019a, b). Given the current and future global warming scenarios, CRG is an issue of utmost importance in rice production and should be addressed worldwide.

Various countermeasures have been proposed to reduce the incidence of CRG (Morita et al. 2016). One such measure is the introduction of heat-tolerant (HT) varieties. Extensive breeding research and programs have focused on developing HT varieties (Ishimaru et al. 2016; Li et al. 2015; Zhu et al. 2005). However, in current and prospective global warming scenarios, the heat tolerance in new varieties and the timing of the introduction of the HT varieties are unclear. As breeding a new variety is generally expensive and time consuming (Bernardo 2008; Pardey et al. 2016; Lenaerts et al. 2019), it is essential to develop long-term plans in which necessary breeding targets of HT varieties are formulated to mitigate the current and future impacts of global warming.

The purpose of this study was to present a breeding target for the development of HT varieties to reduce the incidence of CRG in Japan. To this end, the effect of introducing HT varieties on the incidence of CRG was quantitatively assessed. The results allow us to determine breeding targets of HT varieties, that is, heat tolerance in new varieties that should be bred and the timing of introduction of the HT varieties. The breeding targets

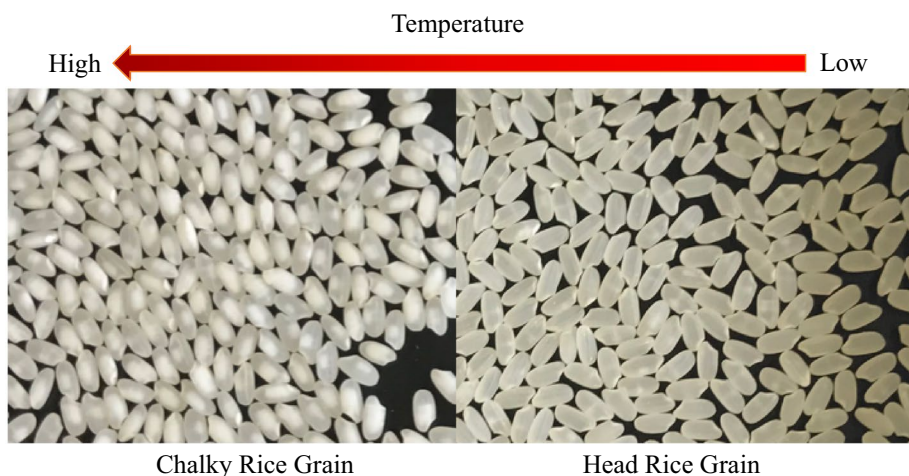


Fig. 1 Chalky (left) and head (right) rice grain. High temperatures during the ripening period result in the production of a low-quality rice grain called chalky rice grain (CRG)

based on these scientific adaptation assessments assist in the development of long-term adaptation strategies in breeding research and programs.

2 Materials and methods

2.1 Framework of assessment

The incidence of CRG was estimated using a simple statistical model (see Sect. 2.2) developed by Masutomi et al. (2015, 2019a, b). The study area covers the whole of Japan, except the Okinawa Prefecture, which has a different climate and rice cropping system from that of the other prefectures. The incidence of CRG was estimated within each 1 km grid and then averages were calculated for the whole of Japan and all prefectures (see Sect. 2.4). The estimations were conducted yearly from 2010 to 2049 and analyzed by decade (2010s: 2010–2019; 2020s: 2020–2029; 2030s: 2030–2039; 2040s: 2040–2049). NARO2017, a future climate dataset, which is bias-corrected and statistically downscaled to 1 km grids from the spatial resolutions of general circulation models (GCMs), was used for future climate scenarios in the estimations (Nishimori et al. 2019). It provides 10 climate scenarios under two representative concentration pathways (RCP2.6 and RCP8.5) and five GCMs (CSIRO-Mk3-6-0, GFDL-CM3, HadGEM2-ES, MIROC5, and MRI-CGCM3). We used all the climate scenarios for the estimations in order to consider all uncertainties in future socio-economic pathways and the climate sensitivity of GCMs. In addition, the uncertainty in the model for estimating the incidence of CRG was considered in the estimations, by using 100 sets of parameters in the model (see Sect. 2.3). Hence, 500 (= 5 GCMs × 100 parameter sets) estimates of CRG for each RCP were calculated in each 1 km grid. We then calculated the 10, 50, and 90 percentile values of the 500 estimates in each 1 km grid, and called them the optimistic (OPT), median (MED), and pessimistic (PES) cases, respectively. To assess the effect of the introduction of HT varieties, the above estimations were conducted along with the introduction of HT varieties with tolerances of 0–3 °C higher than that of the leading rice variety, Koshihikari, which accounts for one third of the rice planted in Japan. Table 1 summaries this framework of estimations and analyses in the present study.

Table 1 Framework of assessment: estimation and analysis

Item	Estimation	Analysis
Area	Japan*	Japan*
Spatial Resolution	1 km	Whole Japan and each prefecture*
Year	2010–2049	2010s, 2020s, 2030s, 2040s
RCP	RCP2.6, RCP8.5	RCP2.6, RCP8.5
GCM	CSIRO-Mk3-6-0, GFDL-CM3, HadGEM2-ES, MIROC5, MRI-CGCM3	OPT, MED, PES
CRG Model	100 parameter set	
Heat Tolerant (HT)	0, 0.5, 1.0, 1.5, 2.0, 2.5, 3.0	0, 0.5, 1.0, 1.5, 2.0, 2.5, 3.0

*Except Okinawa Prefecture

2.2 Model for estimating chalky rice grain

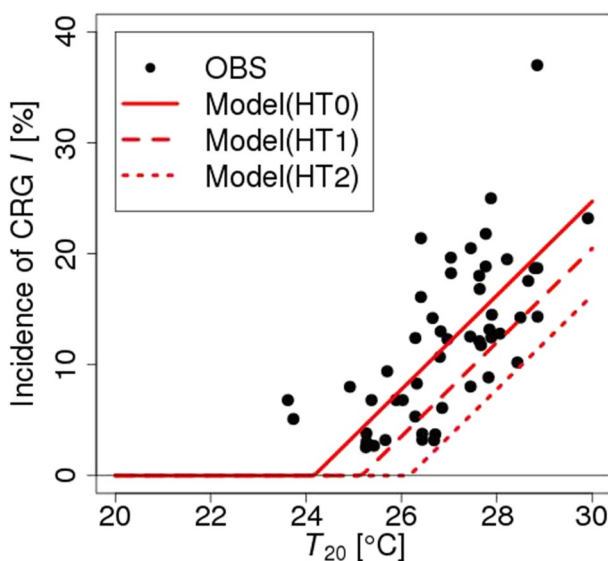
The incidence of CRG was estimated using the following equation based on Masutomi et al. (2015; 2019a, b):

$$I = \max\{0, k_T(T_{20} - (T_{\text{crit}} + T_{\text{HT}}))\} \quad (1)$$

where I [%] is the incidence of CRG, T_{20} [°C] is the daily temperature averaged over 20 days after the flowering date, T_{crit} [°C] is a parameter for the threshold of T_{20} at which CRG begins to appear, k_T [%/°C] is a parameter for the sensitivity to temperature, and T_{HT} [°C] is a parameter for HT varieties. The accuracy of the model for the estimation of the incidence of CRG in Japan was intensively validated in Masutomi et al. (2019a, b) for cases without HT varieties ($T_{\text{HT}} = 0$). They reported that the correlation between observations and model estimations was 0.661 and significant ($p < 0.001$).

T_{HT} was newly adopted in the present study in order to assess the effect of the introduction of HT varieties. In the model, $I = 0$, if $T_{20} \leq T_{\text{crit}} + T_{\text{HT}}$; otherwise, $I > 0$. In the case of $T_{20} > T_{\text{crit}} + T_{\text{HT}}$, I linearly increases with T_{20} according to k_T . Figure 2 shows observations (plots) and the models (red lines) with the optimal values for the model parameters in the case of $T_{\text{HT}} = 0, 1$, and 2 (hereinafter, $T_{\text{HT}} = X$ is represented as HTX; the method of model parameterization is described in Sect. 2.3). For example, in the case of $T_{\text{HT}} = 1$ (HT1), T_{crit} substantively increases by 1 degree, and the incidence of CRG becomes lower than that in the case of $T_{\text{HT}} = 0$ (HT0). This is equivalent to the effect of the introduction of a variety with 1 °C higher temperature tolerance. Thus, setting a value of T_{HT} allows us to assess the incidence of CRG when HT varieties are introduced. In the present study, the effect of the introduction was assessed for seven types of HT varieties ($T_{\text{HT}} = 0, 0.5, 1, 1.5, 2, 2.5$, and 3). It should be noted that Takimoto et al. (2019) reported that T_{crit} is actually different among varieties. Although they also reported that another model parameter, k_T , is different among

Fig. 2 Relationship between T_{20} [°C] and the incidence of CRG I [%]. Red lines represent models for three cases (HT0, HT1, and HT2). Black points are observations (Masutomi et al. 2019a, b)



varieties, the changes in k_T are not considered in this study due to the complexity of the analysis.

2.3 Model parameterization and the uncertainty

T_{crit} and k_T are parameters statistically estimated using observations of I and T_{20} . In order to consider the uncertainty of the model, 100 sets of the two parameters were estimated using the bootstrap resampling method (Efron 1979). For the observations of I , we used the same data used by Masutomi et al. (2019a, b). It included 53 samples for Koshihikari from four sites across Japan. For T_{20} , the Mesh Agro-Meteorology Data was used (Ohno et al. 2016). The procedure of parameter estimations is as follows (Masutomi et al. 2012; 2015).

Step1: By using the observations, an optimal parameter set, T_{crit}^* and k_T^* , that minimizes the error between the observations and estimations for I was estimated. In the present study, the downhill simplex method was used for the minimization (Nelder and Mead 1965). The incidence of CRG estimated by T_{20} for sample i , $T_{20,i}$, and the optimal parameter set, T_{crit}^* and k_T^* , was expressed as $I_{\text{est},i}^*$ and is given by the following equation:

$$I_{\text{est},i}^* = \max \{0, k_T^* (T_{20,i} - (T_{\text{crit}}^* + T_{\text{HT}}))\} \quad (2)$$

Step2: Residual values for sample i from the observations, $I_{\text{obs},i}$, to the estimations, $I_{\text{est},i}^*$, was expressed as R_i and calculated as follows:

$$R_i = I_{\text{est},i}^* - I_{\text{obs},i} \quad (3)$$

Step3: By adding randomly sampled R_i to the observed $I_{\text{obs},i}$, pseudo-observations for I , $\widehat{I}_{\text{obs},i}$, were obtained as follows:

$$\widehat{I}_{\text{obs},i} = I_{\text{obs},i} + \text{RS}(R_i) \quad (4)$$

where $\text{RS}(R_i)$ indicates random sampling from a set of R_i . Random sampling was repeated 53 times to produce 53 samples of $\widehat{I}_{\text{obs},i}$.

Step 4: Using the 53 samples of $\widehat{I}_{\text{obs},i}$, a parameter set that minimizes the error between the pseudo-observations and estimations for I was estimated.

Step 5: Steps 3 and 4 were repeated 99 times to produce 99 sets of the parameters. At last, 100 sets of the parameters were produced by adding the optimal parameter set to the 99 sets of the parameters. Fig. 9 shows the frequency of the values for each parameter and Fig. 10 shows the plots of the 100 parameter sets.

2.4 Input data and data processing procedure

Figure 3 shows the input data and the data processing procedure. In step 1, the incidence of CRG was annually estimated in each 1 km grid from 2010 to 2049 using the model explained in Sect. 2.2. For the gridded estimations, T_{20} is needed for each 1 km grid. The gridded T_{20} was calculated from the gridded data for daily temperatures and

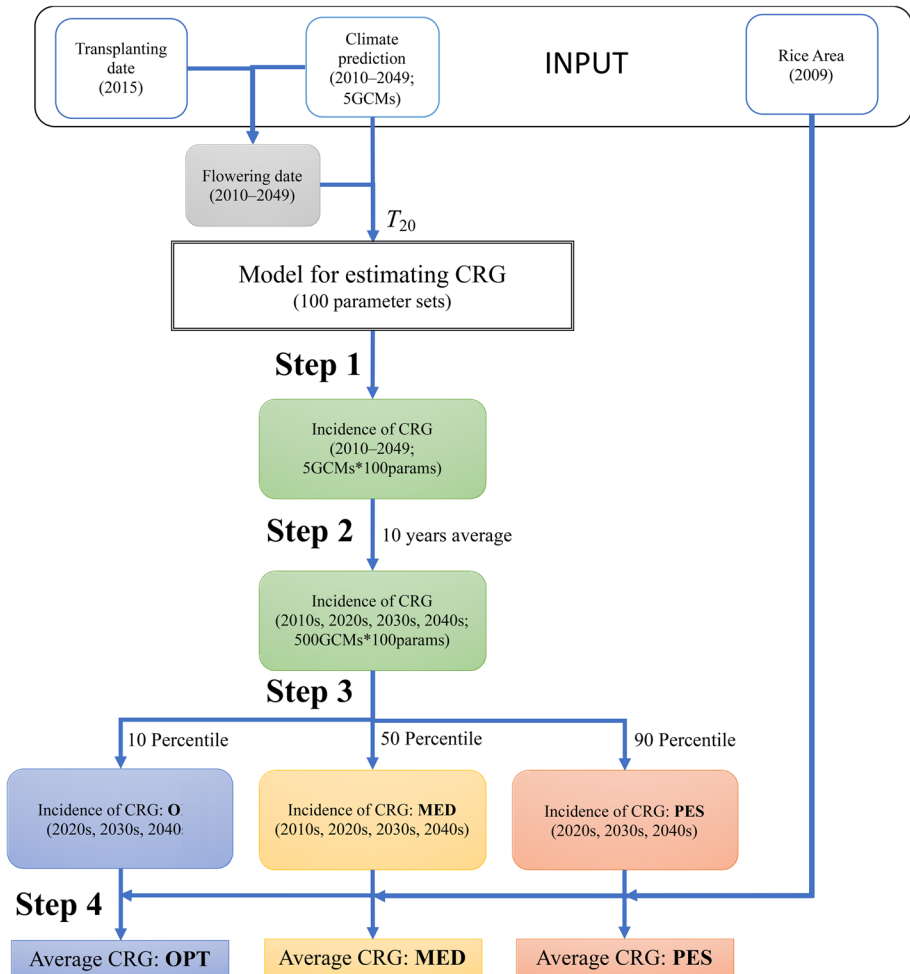


Fig. 3 Input data and data processing procedure. Average incidence of CRG in the three cases OPT, MED, and PES (taking into consideration the uncertainties) was estimated using future climate scenarios from five GCMs and a model for estimating CRG with 100 parameter sets

flowering dates. For the gridded daily temperatures, NARO2017 was used. The gridded flowering dates were estimated using the method proposed by Fukui et al. (2015). Their method requires gridded data of transplanting dates, daily temperatures, and day length. The transplanting gridded dates for each agricultural region are reported by the Ministry of Agriculture, Forestry, and Fishery. We interpolated the values in 2015 into a 1-km grid and used them for the estimation of the flowering dates. NARO2017

was used for the gridded daily temperatures for the estimation of flowering dates. Gridded day length was calculated from latitudes in each 1 km grid. At the end of step 1, we had 500 (=5 GCMs \times 100 parameters) estimations for the incidence of CRG for each year from 2010 to 2049. In step 2, the 500 annual estimations were averaged by decade. At the end of this step, we still had 500 estimations for each decade. In

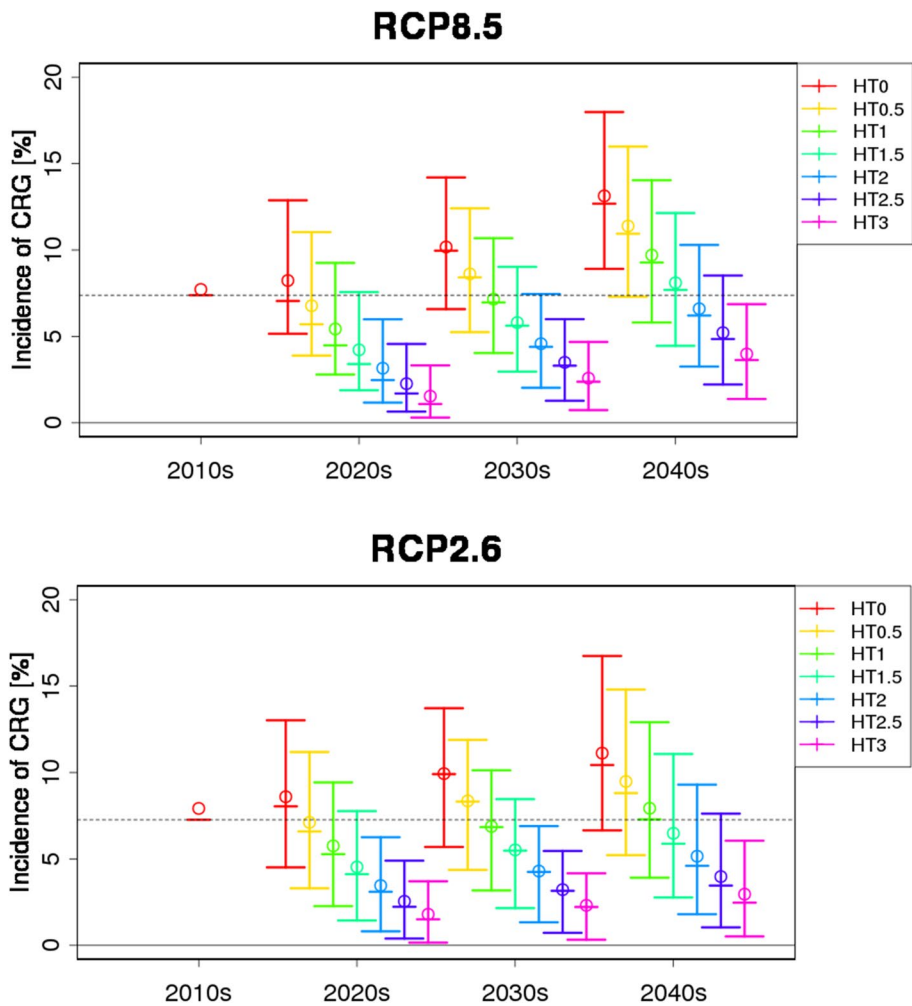


Fig. 4 Average incidence [%] of CRG for the whole of Japan under representative concentration pathway (RCP) 2.6 (top) and 8.5 (bottom). The uppermost, middle, and bottommost horizontal lines in the 2020s, 2030s, and 2040s indicate the PES, MED, and OPT cases, respectively. The line in the 2010s indicates the MED cases. The circles are mean values

step 3, we calculated 10, 50, and 90 percentile values from the 500 estimates in each 1 km grid and represented them as OPT, MED, and PES cases, respectively. It should be noted that the OPT and PES cases were not calculated in the 2010s. In step 4, the averages for the incidence of CRG over the whole of Japan and in each prefecture were calculated, by using 1 km gridded data of rice areas in 2009 obtained from the Mesh Agro-Meteorology Data (Ohno et al. 2016). The above estimations from steps 1 to 4 were conducted for two RCPs and seven HT cases.

3 Results

3.1 Incidence of CRG without HT varieties (HT0)

Figure 4 and Table 3 show the average incidence of CRG for the whole of Japan from the 2010s to 2040s when seven HT varieties are introduced. In this section, we discuss the incidence of CRG in case of HT0 (i.e., no HT varieties). In the MED case, the incidence of CRG increased from 7.3 to 10.4% under RCP2.6 and from 7.4 to 12.7% under RCP8.5. The incidence of CRG in the 2040s in the MED case under RCP8.5 was 2.3% higher than that under RCP2.6, whereas the differences between RCPs were small until the 2030s.

The incidence of CRG from the 2020s to 2040s in the PES case was considerably higher than that in the MED case. The incidence of CRG in the PES case increased from 7.3 to 16.7% under RCP2.6 and from 7.4 to 18% under RCP8.5. The differences between the PES and MED cases ranged from 3.8 to 6.3%. As in the MED case, the incidence of CRG in the 2040s in the PES case under RCP8.5 was 1.3% higher than that under RCP2.6.

On the contrary, the incidence of CRG from the 2020s to 2040s in the OPT case was considerably lower than that in the MED case. The incidence of CRG in the OPT

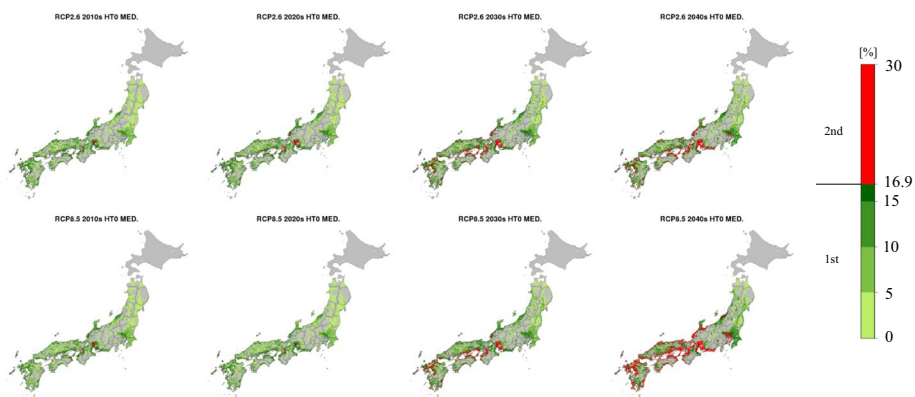


Fig. 5 Incidence [%] of CRG in the MED case with HT0 under representative concentration pathway (RCP) 2.6 (top) and RCP8.5 (bottom). The grids with no paddy rice field and/or in which rice cannot grow are in grey; 16.9% of the incidence of CRG is the threshold between the first and second grades (Masutomi et al. 2019a, b)

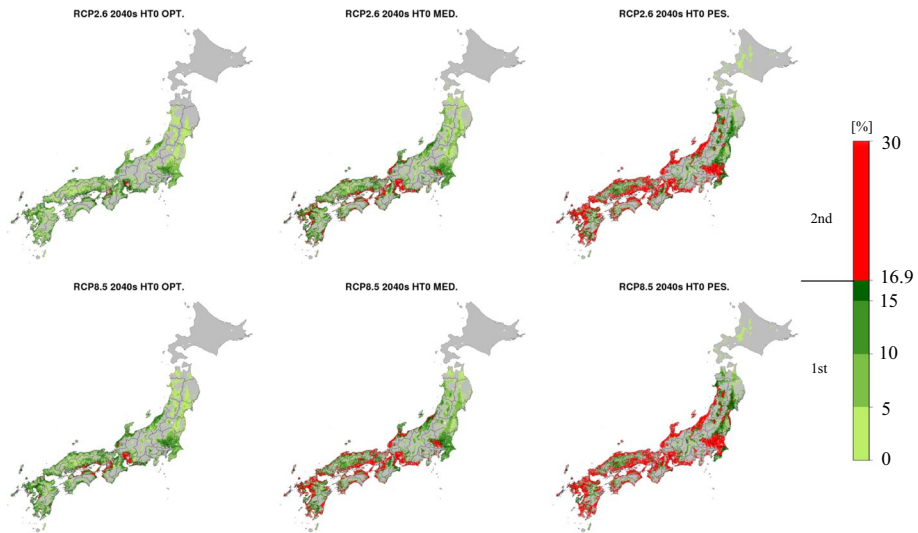


Fig. 6 Incidence [%] of CRG in the OPT (left), MED (center), and PES (right) cases with HT0 in the 2040s under representative concentration pathway (RCP) 2.6 (top) and RCP8.5 (bottom). The grids with no paddy rice field and/or in which rice cannot grow are in grey; 16.9% of the incidence of CRG is the threshold between the first and second grades (Masutomi et al. 2019a, b)

case was lower from the 2020s to 2040s under RCP2.6 compared to that in the 2010s in the MED case, but it increased from the 2020s to 2040s. Under RCP8.5, the incidence of CRG in the OPT case was lower in the 2020s and 2030s but higher in the 2040s than that in the 2010s in the MED case. The differences between the OPT and MED cases were between 1.9 and 4.2%. As in the other cases, the incidence of CRG in the 2040s in the OPT case under RCP8.5 was 2.2% higher than that under RCP2.6.

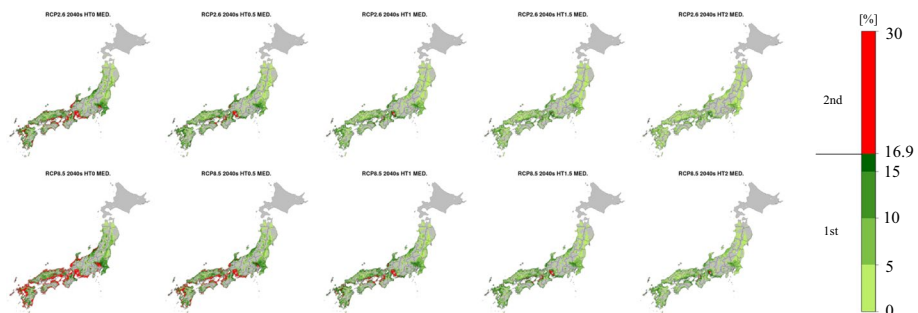


Fig. 7 Incidence [%] of CRG in the 2040s in the MED case with HT0 to HT2 under representative concentration pathway (RCP) 2.6 (top) and RCP8.5 (bottom)

The results with no HT varieties showed that the incidence of CRG increased in the MED and PES cases, and even in the OPT case, it increased in the 2040s under RCP8.5.

Figure 5 shows the spatial distribution of the incidence of CRG in the MED case with HT0. In the future, the area of high incidence of CRG will expand in the western coastal area and appear in the eastern coastal areas, where it was limited in the 2010s. The area of high incidence of CRG in the 2040s under RCP8.5 will be larger than that under RCP2.6, but there will be no large difference until the 2030s between RCPs. These results are consistent with those of Masutomi et al. (2019a, b).

Figure 6 shows the spatial distribution of the incidence of CRG in the OPT, MED, and PES cases with HT0 in the 2040s. There were large differences in the spatial distribution of the incidence of CRG among the three cases. In the PES case, a high incidence of CRG was seen in many areas even under RCP2.6, but in small areas in the OPT cases under RCP2.6.

3.2 Effect of the introduction of HT varieties

Figure 4 and Table 3 clearly show that the introduction of HT varieties could decrease the incidence of CRG. For example, if an HT variety with 1 °C higher temperature tolerance (HT1) is introduced in the 2040s in the MED case, the incidence of CRG will decrease from 10.4 to 7.3% under RCP2.6 and from 12.7 to 9.3% under RCP8.5. However, it is also shown that the effect per 1 °C of higher temperature tolerance gradually decreased as more HT varieties were introduced. For example, in the MED case under RCP2.6, the difference in the incidence of CRG with HT1 and HT2 was 2.7% (7.3–4.6%), but that with HT2 and HT3 was 2.1% (4.6–2.5%).

Figure 7 shows the spatial distribution of the incidence of CRG in the 2040s in the MED case when the HT varieties are introduced. It can be seen that the area of high incidence of CRG will shrink upon introducing the HT varieties. If a HT variety with 2 °C higher temperature tolerance is introduced in the 2040s under RCP2.6, none of the areas would have

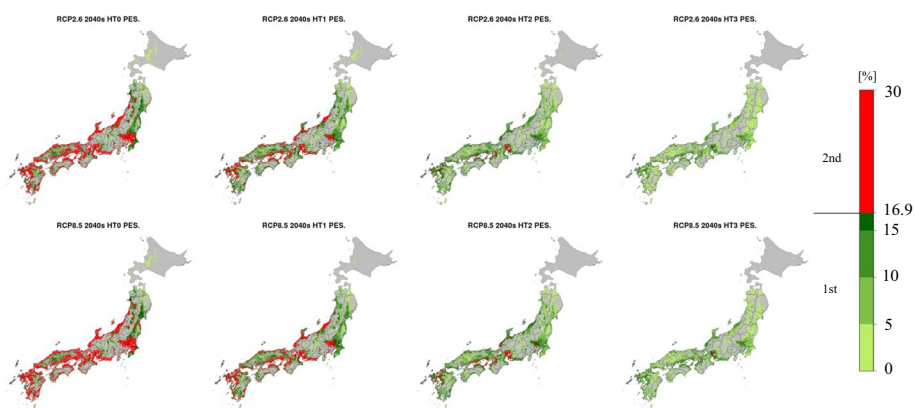


Fig. 8 Incidence [%] of CRG in the 2040s in the PES case with HT0 to HT3 under representative concentration pathway (RCP) 2.6 (top) and RCP8.5 (bottom)

a high incidence of CRG. However, an area corresponding to a high incidence of CRG still remained under RCP8.5 but was small.

Figure 8 shows the spatial distribution of the incidence of CRG in the 2040s in the PES case when the HT varieties are introduced. The area of high incidence of CRG in the 2040s in the PES case will be larger under both RCPs than that in the 2010s in the MED case, even if an HT variety with 2 °C higher temperature tolerance is introduced. Therefore, varieties that are more than 2 °C more tolerant will be required in the 2040s in the PES case.

4 Discussion

4.1 The effect of HT varieties on the incidence of CRG

We simulated the effect of HT varieties to discuss breeding targets to reduce of the incidence of CRG. The results show that, for example, an HT variety with 1 °C higher temperature tolerance (HT1) will decrease the incidence of CRG from 10.4% to 7.3% under RCP2.6 and from 12.7 to 9.3% under RCP8.5. The most important feature of the present study is that we showed quantitative effects of HT varieties, while it is obvious that the introduction of HT varieties decreases the incidence of CRG. There have been only two studies where the incidence of CRG in Japan is quantitatively assessed (Ishigooka et al. 2021; Masutomi et al. 2019a, b), but there are no studies on the quantitative assessment of the effect of HT varieties. The quantitative assessment of the effect of HT varieties allows us to formulate quantitative breeding targets that indicate when and how higher HT varieties should be bred and introduced. Breeding targets will be discussed in the following Sect. 4.2.

Several physiological and molecular mechanisms of heat tolerance for HT varieties have been reported. Morita and Nakano (2011) showed that an HT rice variety stored large nonstructural carbohydrate in the stem, which contributes to a high ripening rate under high temperatures. Tanaka et al. (2009) observed that high temperatures caused cessation of development of the nucellar epidermis, which is a pathway for sucrose in grains, at 14 days after flowering in a heat-sensitive variety but had little influence on the nucellar epidermis in HT varieties. Tanamachi et al. (2016) reported that the expression of a starch synthesis-related gene could be maintained under high temperatures for HT varieties and the expression of a starch-degradation-related gene was not increased by high temperature in an HT variety. In the model used in the present study, the difference in heat tolerance among rice varieties can be expressed as that of the values of the model parameters (T_{crit} and k_T). Actually, Takimoto et al. (2019) showed that these values are different among rice varieties. The ability to represent the difference in heat tolerance between varieties with a

Table 2 Breeding targets of heat-tolerant (HT) varieties: HT that needs to increase [°C]

	RCP2.6				RCP8.5		
	2020s	2030s	2040s		2020s	2030s	2040s
PES	2	2	3	PES	2	2.5	3
MED	0.5	1	1	MED	0	1	2
OPT	0	0	0	OPT	0	0	0.5

small number of parameters is a key feature of the model used in the study. It is noted that only the value of T_{crit} was changed in this study for simplicity.

4.2 Breeding target

The introduction of HT varieties is one of the effective measures for adaptation to global warming in the agricultural sector. However, we have not understood when and how higher HT varieties should be bred and introduced. As breeding a new variety generally requires considerable expense and time (Bernardo 2008; Pardey et al. 2016; Lenaerts et al. 2019), it is important to develop long-term plans in which necessary breeding targets are provided in consideration of the current and future global warming trends. The purpose of this study was to clarify breeding targets through simulations, and this is the most important feature of the present study.

Breeding targets can be discussed based on the results in Sect. 3. For this purpose, it is necessary to first determine an acceptable incidence of CRG. In the discussion here, it is set to the incidence of CRG in the MED case in the 2010s (RCP2.6: 7.3%; RCP8.5: 7.4%), but it is actually determined by stakeholders, including producers and policy makers. Once it is determined, we can calculate the breeding targets of HT varieties, that is, heat tolerance of HT varieties that should be bred and the timing of their introduction in order to keep the incidence of CRG below the acceptable level. This calculation is equivalent to selecting HT varieties below the dotted line in Fig. 4. Table 2 shows the breeding targets of HT varieties selected in this manner. In the MED case, HT varieties with 2 °C higher heat tolerance should be bred and introduced until the 2040s under RCP8.5, whereas HT varieties with 1 °C higher heat tolerance will be sufficient under RCP2.6. Thus, in the MED case, more HT varieties are needed in the 2040s under RCP8.5 than that under RCP2.6. In policy-making, it is often necessary to assume the worst-case scenario (PES). In the PES case, HT varieties with 3 °C higher heat tolerance should be bred and introduced until the 2040s under RCP2.6, as well as under RCP8.5.

While the whole of Japan is discussed here, the same assessments and discussions can be applied for each prefecture in Japan. Tables 4 and 5 shows the effect of the introduction of HT varieties in prefectures in which Koshihikari is the leading rice variety.

In the above, the current incidence of CRG was set as the acceptable incidence, but other values can be set as well. For example, the threshold value of the incidence of CRG that reduces the grade from first to second can be set as the acceptable incidence. Masutomi et al. (2019a, b) assumed this threshold to be 16.9% based on historical values. Using this as a baseline, for example, Ibaraki in the PES case shows that HT varieties with higher HT of 0.5 °C for RCP2.6 and 1 °C for RCP8.5 are required in the 2040s, according to Tables 3, 4, and 5. It is important to note that these are based on the 10-year average incidence of CRG. If the 10-year average incidence of CRG is 16.9%, the incidence would have exceeded 16.9% in 5 years of the decade and the grade would have declined. Therefore, in order to avoid exceeding 16.9% every year, the acceptable incidence should be set to be less than 16.9%. The acceptable incidence can be set based on the impact of CRG on food security. However, there have been no studies on the extent to which food security is threatened by the incidence of CRG. Further research progress is expected.

The present study provides a science-based approach for the development of breeding targets. We believe that these breeding targets will provide breeders and related researchers with clear visions for the direction and intensity of future breeding strategies. Studies on

the development of breeding targets to reduce the impacts of climate change on crops are limited (Challinor et al. 2016; Ramirez-Villegas et al. 2018; Tanaka et al. 2015). It is hoped that the present approach will be applied to other countries, regions, and crops in the future.

4.3 Long-term strategy combined with other countermeasures

Although only breeding targets of HT varieties were considered here, various management options and technologies have been proposed to reduce the incidence of CRG (Morita et al. 2016). Each of these measures has different costs, effects, and lead times to achieve the desired effect. Therefore, it is important to understand the characteristics of each management and technology, and then develop a long-term adaptation strategy that combines them over the future global warming scenario. For example, the utilization of varieties with different ripening timing or a shift in transplanting date could unsynchronize the ripening period and the high temperature period (Ishigooka et al. 2017). It has also been reported that the incidence of CRG can be reduced by optimizing the application of agricultural materials such as fertilizers (Tanaka et al. 2010), plant growth regulators (Fahad et al. 2016a, b), and water management (Chiba et al. 2017; Hayashi et al. 2011). These are adaptive management strategies and technologies that can be implemented without much loss of cost and time. Therefore, it is hoped that such adaptation measures are immediately implemented to adapt to the impacts that have already appeared, while simultaneously breeding new HT varieties, which is time-consuming and costly but should be promoted as a long-term strategy.

4.4 Future challenges

In this study, we assessed the effect of the introduction of HT varieties and discussed breeding targets. However, the feasibility of the breeding targets is currently unknown and beyond the scope of the present study. Several HT varieties have been developed so far, and extensive breeding research and programs to develop HT varieties have been conducted (Ishimaru et al. 2016). Research and breeding programs will improve breeding capacity and optimize the logistics of breeding, e.g., increase in the speed of selection cycles, so that the feasibility of their eventual implementation will increase. However, the most important problem in linking the breeding research and programs with the present study results is that a quantitative method for measuring heat tolerance in rice varieties has not been established. Hence, heat tolerance in existing HT varieties is not quantitatively known. Therefore, the establishment of a quantitative method is a critical first step.

In the present study, only T_{crit} was changed to consider the effect of HT varieties. However, it is known that k_T , another model parameter, is different among varieties (Takimoto et al. 2019). Therefore, it is necessary to consider changes in k_T when the effect of HT varieties is assessed. This is one of the important future challenges. Regarding this point, it is very difficult to create high temperature conditions in the field. Hence, model development has to be based on statistical methods using long-term data under natural conditions. If there is a technology that eliminates this limitation, it will be a major breakthrough in model development. In addition, the model considers only temperature as an explanatory variable, but it is well known that the incidence of CRG depends on other environmental variables including radiation, CO₂, and wind (Ishigooka et al. 2021; Takimoto et al. 2019; Usui et al. 2016; Wada et al. 2014). Including these variables is also an important challenge in the assessment of the effect of HT variables.

Appendix

Table 3 Average incidence [%] of chalk rice grain (CRG) for the whole of Japan from the 2010s to 2040s under representative concentration pathway (RCP) 2.6 (top) and RCP8.5 (bottom) when seven heat-tolerant (HT) varieties are introduced from HT0 to HT3.

HT	2010s	2020s	2030s	2040s
0.0	7.3	8 (4.5, 13)	9.9 (5.7, 13.7)	10.4 (6.7, 16.7)
0.5	-	6.6 (3.3, 11.2)	8.3 (4.4, 11.9)	8.8 (5.2, 14.8)
1.0	-	5.3 (2.3, 9.4)	6.8 (3.2, 10.1)	7.3 (3.9, 12.9)
1.5	-	4.1 (1.4, 7.8)	5.5 (2.2, 8.5)	5.9 (2.8, 11.1)
2.0	-	3.1 (0.8, 6.3)	4.2 (1.3, 6.9)	4.6 (1.8, 9.3)
2.5	-	2.2 (0.4, 4.9)	3.2 (0.7, 5.5)	3.5 (1, 7.6)
3.0	-	1.5 (0.2, 3.7)	2.2 (0.3, 4.2)	2.5 (0.5, 6.1)
HT	2010s	2020s	2030s	2040s
0.0	7.4	7.1 (5.2, 12.9)	10 (6.6, 14.2)	12.7 (8.9, 18)
0.5	-	5.7 (3.9, 11)	8.4 (5.2, 12.4)	10.9 (7.3, 16)
1.0	-	4.5 (2.8, 9.3)	7 (4, 10.7)	9.3 (5.8, 14)
1.5	-	3.4 (1.9, 7.6)	5.6 (3, 9)	7.7 (4.5, 12.1)
2.0	-	2.5 (1.2, 6)	4.4 (2, 7.5)	6.2 (3.3, 10.3)
2.5	-	1.7 (0.6, 4.6)	3.3 (1.3, 6)	4.8 (2.2, 8.5)
3.0	-	1.1 (0.3, 3.3)	2.4 (0.7, 4.7)	3.6 (1.4, 6.9)

The values on the left of the parentheses represent the median (MED) case and the values in the parenthesis represent the optimistic (OPT) and pessimistic (PES) cases

Table 4 Average incidence [%] of chalk rice grain (CRG) by prefecture from the 2010s to 2040s under representative concentration pathway (RCP) 2.6 when seven heat-tolerant (HT) varieties are introduced from HT0 to HT3

Fukushima					Ibaraki					Tochigi					Gunma				
HT	2010s	2020s	2030s	2040s	HT	2010s	2020s	2030s	2040s	HT	2010s	2020s	2030s	2040s	HT	2010s	2020s	2030s	2040s
0.0	2.91 (0.5)	4.01 (0.6)	5.02 (0.7)	5.02 (0.7)	0.0	7.93 (0.7)	8.04 (0.5)	10.0 (0.5)	10.0 (0.5)	0.0	7.42 (0.5)	8.02 (0.5)	8.02 (0.5)	8.02 (0.5)	0.0	7.02 (0.4)	7.02 (0.4)	8.02 (0.4)	8.02 (0.4)
0.5	2.10 (0.7)	3.01 (0.7)	3.01 (0.7)	3.01 (0.7)	0.5	7.02 (0.7)	7.02 (0.7)	8.02 (0.5)	8.02 (0.5)	0.5	6.02 (0.7)	6.02 (0.7)	7.02 (0.5)	7.02 (0.5)	0.5	5.02 (0.4)	5.02 (0.4)	6.02 (0.4)	6.02 (0.4)
1.0	1.02 (0.2)	2.02 (0.5)	2.02 (0.4)	2.02 (0.4)	1.0	6.02 (0.7)	6.02 (0.7)	7.02 (0.5)	7.02 (0.5)	1.0	4.02 (0.2)	4.02 (0.2)	5.02 (0.5)	5.02 (0.5)	1.0	4.02 (0.2)	4.02 (0.2)	5.02 (0.4)	5.02 (0.4)
1.5	0.70 (0.2)	1.02 (0.4)	1.02 (0.4)	1.02 (0.4)	1.5	4.02 (0.2)	4.02 (0.2)	5.02 (0.5)	5.02 (0.5)	1.5	3.02 (0.2)	3.02 (0.2)	4.02 (0.5)	4.02 (0.5)	1.5	3.02 (0.2)	3.02 (0.2)	4.02 (0.4)	4.02 (0.4)
2.0	0.02 (0.1)	0.02 (0.1)	0.02 (0.1)	0.02 (0.1)	2.0	2.02 (0.2)	2.02 (0.2)	3.02 (0.5)	3.02 (0.5)	2.0	1.02 (0.2)	1.02 (0.2)	2.02 (0.5)	2.02 (0.5)	2.0	1.02 (0.2)	1.02 (0.2)	2.02 (0.4)	2.02 (0.4)
2.5	0.02 (0.1)	0.02 (0.1)	0.02 (0.1)	0.02 (0.1)	2.5	1.02 (0.2)	1.02 (0.2)	2.02 (0.5)	2.02 (0.5)	2.5	0.02 (0.1)	0.02 (0.1)	1.02 (0.5)	1.02 (0.5)	2.5	0.02 (0.1)	0.02 (0.1)	1.02 (0.4)	1.02 (0.4)
3.0	0.02 (0.1)	0.02 (0.1)	0.02 (0.1)	0.02 (0.1)	3.0	0.02 (0.1)	0.02 (0.1)	1.02 (0.5)	1.02 (0.5)	3.0	0.02 (0.1)	0.02 (0.1)	0.02 (0.5)	0.02 (0.5)	3.0	0.02 (0.1)	0.02 (0.1)	0.02 (0.4)	0.02 (0.4)
Saitama					Chiba					Niigata					Toyama				
0.0	12.01 (0.1)	14.02 (0.1)	15.02 (0.2)	15.02 (0.2)	0.0	7.02 (0.1)	8.02 (0.2)	10.0 (0.4)	10.0 (0.4)	0.0	10.0 (0.1)	10.0 (0.1)	10.0 (0.1)	10.0 (0.1)	0.0	12.02 (0.1)	14.02 (0.1)	15.02 (0.2)	15.02 (0.2)
0.5	10.02 (0.1)	12.02 (0.1)	13.02 (0.2)	13.02 (0.2)	0.5	6.02 (0.1)	7.02 (0.2)	8.02 (0.4)	8.02 (0.4)	0.5	9.02 (0.1)	9.02 (0.1)	9.02 (0.1)	9.02 (0.1)	0.5	10.02 (0.1)	12.02 (0.1)	13.02 (0.2)	13.02 (0.2)
1.0	8.02 (0.1)	10.02 (0.1)	11.02 (0.2)	11.02 (0.2)	1.0	5.02 (0.1)	6.02 (0.2)	7.02 (0.4)	7.02 (0.4)	1.0	7.02 (0.1)	7.02 (0.1)	7.02 (0.1)	7.02 (0.1)	1.0	8.02 (0.1)	10.02 (0.1)	11.02 (0.2)	11.02 (0.2)
1.5	6.02 (0.1)	8.02 (0.1)	9.02 (0.2)	9.02 (0.2)	1.5	4.02 (0.1)	5.02 (0.2)	6.02 (0.4)	6.02 (0.4)	1.5	6.02 (0.1)	6.02 (0.1)	6.02 (0.1)	6.02 (0.1)	1.5	7.02 (0.1)	8.02 (0.1)	9.02 (0.2)	9.02 (0.2)
2.0	4.02 (0.1)	6.02 (0.1)	7.02 (0.2)	7.02 (0.2)	2.0	3.02 (0.1)	4.02 (0.2)	5.02 (0.4)	5.02 (0.4)	2.0	4.02 (0.1)	4.02 (0.1)	4.02 (0.1)	4.02 (0.1)	2.0	5.02 (0.1)	6.02 (0.1)	7.02 (0.2)	7.02 (0.2)
2.5	3.02 (0.1)	4.02 (0.1)	5.02 (0.2)	5.02 (0.2)	2.5	2.02 (0.1)	3.02 (0.2)	4.02 (0.4)	4.02 (0.4)	2.5	3.02 (0.1)	3.02 (0.1)	3.02 (0.1)	3.02 (0.1)	2.5	4.02 (0.1)	5.02 (0.1)	6.02 (0.2)	6.02 (0.2)
3.0	2.02 (0.1)	3.02 (0.1)	4.02 (0.2)	4.02 (0.2)	3.0	1.02 (0.1)	2.02 (0.2)	3.02 (0.4)	3.02 (0.4)	3.0	2.02 (0.1)	2.02 (0.1)	2.02 (0.1)	2.02 (0.1)	3.0	3.02 (0.1)	4.02 (0.1)	5.02 (0.2)	5.02 (0.2)
Ishikawa					Fukui					Yamanashi					Nagano				
0.0	10.02 (0.1)	12.02 (0.1)	13.02 (0.2)	13.02 (0.2)	0.0	10.02 (0.1)	12.02 (0.1)	13.02 (0.2)	13.02 (0.2)	0.0	8.02 (0.1)	9.02 (0.1)	10.02 (0.2)	10.02 (0.2)	0.0	10.02 (0.1)	12.02 (0.1)	13.02 (0.2)	13.02 (0.2)
0.5	8.02 (0.1)	10.02 (0.1)	11.02 (0.2)	11.02 (0.2)	0.5	8.02 (0.1)	10.02 (0.1)	11.02 (0.2)	11.02 (0.2)	0.5	7.02 (0.1)	8.02 (0.1)	9.02 (0.2)	9.02 (0.2)	0.5	8.02 (0.1)	10.02 (0.1)	11.02 (0.2)	11.02 (0.2)
1.0	6.02 (0.1)	8.02 (0.1)	9.02 (0.2)	9.02 (0.2)	1.0	6.02 (0.1)	8.02 (0.1)	9.02 (0.2)	9.02 (0.2)	1.0	6.02 (0.1)	7.02 (0.1)	8.02 (0.2)	8.02 (0.2)	1.0	7.02 (0.1)	8.02 (0.1)	9.02 (0.2)	9.02 (0.2)
1.5	4.02 (0.1)	6.02 (0.1)	7.02 (0.2)	7.02 (0.2)	1.5	4.02 (0.1)	6.02 (0.1)	7.02 (0.2)	7.02 (0.2)	1.5	5.02 (0.1)	6.02 (0.1)	7.02 (0.2)	7.02 (0.2)	1.5	6.02 (0.1)	7.02 (0.1)	8.02 (0.2)	8.02 (0.2)
2.0	3.02 (0.1)	4.02 (0.1)	5.02 (0.2)	5.02 (0.2)	2.0	3.02 (0.1)	4.02 (0.1)	5.02 (0.2)	5.02 (0.2)	2.0	4.02 (0.1)	5.02 (0.1)	6.02 (0.2)	6.02 (0.2)	2.0	5.02 (0.1)	6.02 (0.1)	7.02 (0.2)	7.02 (0.2)
2.5	2.02 (0.1)	3.02 (0.1)	4.02 (0.2)	4.02 (0.2)	2.5	2.02 (0.1)	3.02 (0.1)	4.02 (0.2)	4.02 (0.2)	2.5	3.02 (0.1)	4.02 (0.1)	5.02 (0.2)	5.02 (0.2)	2.5	4.02 (0.1)	5.02 (0.1)	6.02 (0.2)	6.02 (0.2)
3.0	1.02 (0.1)	2.02 (0.1)	3.02 (0.2)	3.02 (0.2)	3.0	1.02 (0.1)	2.02 (0.1)	3.02 (0.2)	3.02 (0.2)	3.0	2.02 (0.1)	3.02 (0.1)	4.02 (0.2)	4.02 (0.2)	3.0	3.02 (0.1)	4.02 (0.1)	5.02 (0.2)	5.02 (0.2)
Gifu					Shizuoka					Aichi					Mie				
0.0	10.02 (0.1)	12.02 (0.1)	13.02 (0.2)	13.02 (0.2)	0.0	10.02 (0.1)	12.02 (0.1)	13.02 (0.2)	13.02 (0.2)	0.0	10.02 (0.1)	12.02 (0.1)	13.02 (0.2)	13.02 (0.2)	0.0	10.02 (0.1)	12.02 (0.1)	13.02 (0.2)	13.02 (0.2)
0.5	8.02 (0.1)	10.02 (0.1)	11.02 (0.2)	11.02 (0.2)	0.5	8.02 (0.1)	10.02 (0.1)	11.02 (0.2)	11.02 (0.2)	0.5	8.02 (0.1)	10.02 (0.1)	11.02 (0.2)	11.02 (0.2)	0.5	8.02 (0.1)	10.02 (0.1)	11.02 (0.2)	11.02 (0.2)
1.0	6.02 (0.1)	8.02 (0.1)	9.02 (0.2)	9.02 (0.2)	1.0	6.02 (0.1)	8.02 (0.1)	9.02 (0.2)	9.02 (0.2)	1.0	6.02 (0.1)	7.02 (0.1)	8.02 (0.2)	8.02 (0.2)	1.0	6.02 (0.1)	8.02 (0.1)	9.02 (0.2)	9.02 (0.2)
1.5	4.02 (0.1)	6.02 (0.1)	7.02 (0.2)	7.02 (0.2)	1.5	4.02 (0.1)	6.02 (0.1)	7.02 (0.2)	7.02 (0.2)	1.5	4.02 (0.1)	6.02 (0.1)	7.02 (0.2)	7.02 (0.2)	1.5	4.02 (0.1)	6.02 (0.1)	7.02 (0.2)	7.02 (0.2)
2.0	3.02 (0.1)	4.02 (0.1)	5.02 (0.2)	5.02 (0.2)	2.0	3.02 (0.1)	4.02 (0.1)	5.02 (0.2)	5.02 (0.2)	2.0	3.02 (0.1)	4.02 (0.1)	5.02 (0.2)	5.02 (0.2)	2.0	3.02 (0.1)	4.02 (0.1)	5.02 (0.2)	5.02 (0.2)
2.5	2.02 (0.1)	3.02 (0.1)	4.02 (0.2)	4.02 (0.2)	2.5	2.02 (0.1)	3.02 (0.1)	4.02 (0.2)	4.02 (0.2)	2.5	2.02 (0.1)	3.02 (0.1)	4.02 (0.2)	4.02 (0.2)	2.5	2.02 (0.1)	3.02 (0.1)	4.02 (0.2)	4.02 (0.2)
3.0	1.02 (0.1)	2.02 (0.1)	3.02 (0.2)	3.02 (0.2)	3.0	1.02 (0.1)	2.02 (0.1)	3.02 (0.2)	3.02 (0.2)	3.0	1.02 (0.1)	2.02 (0.1)	3.02 (0.2)	3.02 (0.2)	3.0	1.02 (0.1)	2.02 (0.1)	3.02 (0.2)	3.02 (0.2)
Shiga					Kyoto					Hyogo					Tottori				
0.0	10.02 (0.1)	12.02 (0.1)	13.02 (0.2)	13.02 (0.2)	0.0	10.02 (0.1)	12.02 (0.1)	13.02 (0.2)	13.02 (0.2)	0.0	10.02 (0.1)	12.02 (0.1)	13.02 (0.2)	13.02 (0.2)	0.0	10.02 (0.1)	12.02 (0.1)	13.02 (0.2)	13.02 (0.2)
0.5	8.02 (0.1)	10.02 (0.1)	11.02 (0.2)	11.02 (0.2)	0.5	8.02 (0.1)	10.02 (0.1)	11.02 (0.2)	11.02 (0.2)	0.5	8.02 (0.1)	10.02 (0.1)	11.02 (0.2)	11.02 (0.2)	0.5	8.02 (0.1)	10.02 (0.1)	11.02 (0.2)	11.02 (0.2)
1.0	6.02 (0.1)	8.02 (0.1)	9.02 (0.2)	9.02 (0.2)	1.0	6.02 (0.1)	8.02 (0.1)	9.02 (0.2)	9.02 (0.2)	1.0	6.02 (0.1)	7.02 (0.1)	8.02 (0.2)	8.02 (0.2)	1.0	6.02 (0.1)	8.02 (0.1)	9.02 (0.2)	9.02 (0.2)
1.5	4.02 (0.1)	6.02 (0.1)	7.02 (0.2)	7.02 (0.2)	1.5	4.02 (0.1)	6.02 (0.1)	7.02 (0.2)	7.02 (0.2)	1.5	4.02 (0.1)	6.02 (0.1)	7.02 (0.2)	7.02 (0.2)	1.5	4.02 (0.1)	6.02 (0.1)	7.02 (0.2)	7.02 (0.2)
2.0	3.02 (0.1)	4.02 (0.1)	5.02 (0.2)	5.02 (0.2)	2.0	3.02 (0.1)	4.02 (0.1)	5.02 (0.2)	5.02 (0.2)	2.0	3.02 (0.1)	4.02 (0.1)	5.02 (0.2)	5.02 (0.2)	2.0	3.02 (0.1)	4.02 (0.1)	5.02 (0.2)	5.02 (0.2)
2.5	2.02 (0.1)	3.02 (0.1)	4.02 (0.2)	4.02 (0.2)	2.5	2.02 (0.1)	3.02 (0.1)	4.02 (0.2)	4.02 (0.2)	2.5	2.02 (0.1)	3.02 (0.1)	4.02 (0.2)	4.02 (0.2)	2.5	2.02 (0.1)	3.02 (0.1)	4.02 (0.2)	4.02 (0.2)
3.0	1.02 (0.1)	2.02 (0.1)	3.02 (0.2)	3.02 (0.2)	3.0	1.02 (0.1)	2.02 (0.1)	3.02 (0.2)	3.02 (0.2)	3.0	1.02 (0.1)	2.02 (0.1)	3.02 (0.2)	3.02 (0.2)	3.0	1.02 (0.1)	2.02 (0.1)	3.02 (0.2)	3.02 (0.2)
Shimane					Hiroshima					Yamaguchi					Tokushima				
0.0	10.02 (0.1)	12.02 (0.1)	13.02 (0.2)	13.02 (0.2)	0.0	10.02 (0.1)	12.02 (0.1)	13.02 (0.2)	13.02 (0.2)	0.0	10.02 (0.1)	12.02 (0.1)	13.02 (0.2)	13.02 (0.2)	0.0	10.02 (0.1)	12.02 (0.1)	13.02 (0.2)	13.02 (0.2)
0.5	8.02 (0.1)	10.02 (0.1)	11.02 (0.2)	11.02 (0.2)	0.5	8.02 (0.1)	10.02 (0.1)	11.02 (0.2)	11.02 (0.2)	0.5	8.02 (0.1)	10.02 (0.1)	11.02 (0.2)	11.02 (0.2)	0.5	8.02 (0.1)	10.02 (0.1)	11.02 (0.2)	11.02 (0.2)
1.0	6.02 (0.1)	8.02 (0.1)	9.02 (0.2)	9.02 (0.2)	1.0	6.02 (0.1)	8.02 (0.1)	9.02 (0.2)	9.02 (0.2)	1.0	6.02 (0.1)	8.02 (0.1)	9.02 (0.2)	9.02 (0.2)	1.0	6.02 (0.1)	8.02 (0.1)	9.02 (0.2)	9.02 (0.2)
1.5	4.02 (0.1)	6.02 (0.1)	7.02 (0.2)	7.02 (0.2)	1.5	4.02 (0.1)	6.02 (0.1)	7.02 (0.2)	7.02 (0.2)	1.5	4.02 (0.1)	6.02 (0.1)	7.02 (0.2)	7.02 (0.2)	1.5	4.02 (0.1)	6.02 (0.1)	7.02 (0.2)	7.02 (0.2)
2.0	3.02 (0.1)	4.02 (0.1)	5.02 (0.2)	5.02 (0.2)	2.0	3.02 (0.1)	4.02 (0.1)	5.02 (0.2)	5.02 (0.2)	2.0	3.02 (0.1)	4.02 (0.1)	5.02 (0.2)	5.02 (0.2)	2.0	3.02 (0.1)	4.02 (0.1)	5.02 (0.2)	5.02 (0.2)
2.5	2.02 (0.1)	3.02 (0.1)	4.02 (0.2)	4.02 (0.2)	2.5	2.02 (0.1)	3.02 (0.1)	4.02 (0.2)	4.02 (0.2)	2.5	2.02 (0.1)	3.02 (0.1)	4.02 (0.2)	4.02 (0.2)	2.5	2.02 (0.1)	3.02 (0.1)	4.02 (0.2)	4.02 (0.2)
3.0	1.02 (0.1)	2.02 (0.1)	3.02 (0.2)	3.02 (0.2)	3.0	1.02 (0.1)	2.02 (0.1)	3.02 (0.2)	3.02 (0.2)	3.0	1.02 (0.1)	2.02 (0.1)	3.02 (0.2)	3.02 (0.2)	3.0	1.02 (0.1)	2.02 (0.1)	3.02 (0.2)	3.02 (0.2)
Kagawa					Ehime					Kouchi					Nagasaki				
0.0	10.02 (0.1)	12.02 (0.1)	13.02 (0.2)	13.02 (0.2)	0.0	10.02 (0.1)	12.02 (0.1)	13.02 (0.2)	13.02 (0.2)	0.0	10.02 (0.1)	12.02 (0.1)	13.02 (0.2)	13.02 (0.2)	0.0	10.02 (0.1)	12.02 (0.1)	13.02 (0.2)	13.02 (0.2)
0.5	8.02 (0.1)	10.02 (0.1)	11.02 (0.2)	11.02 (0.2)	0.5	8.02 (0.1)	10.02 (0.1)	11.02 (0.2)	11.02 (0.2)	0.5	8.02 (0.1)	10.02 (0.1)	11.02 (0.2)	11.02 (0.2)	0.5	8.02 (0.1)	10.02 (0.1)	11.02 (0.2)	11.02 (0.2)
1.0	6.02 (0.1)	8.02 (0.1)	9.02 (0.2)	9.02 (0.2)	1.0	6.02 (0.1)	8.02 (0.1)	9.02 (0.2)	9.02 (0.2)	1.0	6.02 (0.1)	7.02 (0.1)	8.02 (0.2)	8.02 (0.2)	1.0	6.02 (0.1)	8.02 (0.1)	9.02 (0.2)	9.02 (0.2)
1.5	4.02 (0.1)	6.02 (0.1)	7.02 (0.2)	7.02 (0.2)	1.5	4.02 (0.1)	6.02 (0.1)	7.02 (0.2)	7.02 (0.2)	1.5	4.02 (0.1)	6.02 (0.1)	7.02 (0.2)	7.02 (0.2)	1.5	4.02 (0.1)	6.02 (0.1)	7.02 (0.2)	7.02 (0.2)
2.0	3.02 (0.1)	4.02 (0.1)	5.02 (0.2)	5.02 (0.2)	2.0	3.02 (0.1)	4.02 (0.1)	5.02 (0.2)	5.02 (0.2)	2.0	3.02 (0.1)	4.02 (0.1)	5.02 (0.2)	5.02 (0.2)	2.0	3.02 (0.1)	4.02 (0.1)	5.02 (0.2)	5.02 (0.2)
2.5	2.02 (0.1)	3.02 (0.1)	4.02 (0.2)	4.02 (0.2)	2.5	2.02 (0.1)	3.02 (0.1)	4.02 (0.2)	4.02 (0.2)	2.5	2.02 (0.1)	3.02 (0.1)	4.02 (0.2)	4.02 (0.2)	2.5	2.02 (0.1)	3.02 (0.1)	4.02 (0.2)	4.02 (0.2)

Fukuoka				Ibaraki				Tochigi				Gunma							
HT	HTA	HTB	HTC	HT	HTA	HTB	HTC	HT	HTA	HTB	HTC	HT	HTA	HTB	HTC				
10	23	2317.26	5222.10	7933.46	10	81	3725.16	6747.18	13709.16	10	64	4137.26	8781.16	11851.38	10	66	4462.16	8963.15	13581.85
10	17	1917.72	4118.12	8224.12	10	81	4157.12	8114.12	11487.12	10	77	4633.12	7144.12	10771.12	10	66	5123.12	8218.12	11754.87
10	10	1264.64	3042.16	4483.10	10	77	2736.16	6648.16	987.16	10	64	2106.68	5722.68	82.63.11	10	10	4164.18	6627.18	966.18
10	10	2104.10	2104.10	2104.10	10	77	2474.12	2474.12	2474.12	10	64	2469.12	2469.12	2469.12	10	10	2104.10	2104.10	2104.10
10	10	5451.12	15934.18	23026.68	10	77	2471.67	3924.64	62292.13	10	64	1504.64	2404.64	521.10	10	10	2105.18	3951.18	6722.13
10	10	321.16	1309.22	1414.14	10	77	1055.22	2404.64	4143.13	10	64	1932.4	2404.64	521.10	10	10	2105.18	2105.18	2105.18
10	10	321.16	1309.22	1414.14	10	77	1055.22	2404.64	4143.13	10	64	1932.4	2404.64	521.10	10	10	2105.18	2105.18	2105.18

Sakana				Oiba				Nigata				Toyama			
HT	HTN	HTM	HTL	HT	HTN	HTM	HTL	HT	HTN	HTM	HTL	HT	HTN	HTM	HTL
01	116	118	117	01	117	119	118	01	116	118	117	01	116	118	117
02	816	817	817	02	816	818	816	02	816	818	816	02	816	818	816
03	741	742	742	03	741	743	741	03	741	743	741	03	741	743	741
04	560	562	562	04	560	562	560	04	560	562	560	04	560	562	560
05	100	101	101	05	100	102	100	05	100	102	100	05	100	102	100
06	321	323	323	06	321	323	321	06	321	323	321	06	321	323	321
07	215	216	216	07	215	217	215	07	215	217	215	07	215	217	215
08	10	10	10	08	10	12	10	08	10	12	10	08	10	12	10
09	10	10	10	09	10	12	10	09	10	12	10	09	10	12	10
10	10	10	10	10	10	12	10	10	10	12	10	10	10	12	10
11	10	10	10	11	10	12	10	11	10	12	10	11	10	12	10
12	10	10	10	12	10	12	10	12	10	12	10	12	10	12	10
13	10	10	10	13	10	12	10	13	10	12	10	13	10	12	10
14	10	10	10	14	10	12	10	14	10	12	10	14	10	12	10
15	10	10	10	15	10	12	10	15	10	12	10	15	10	12	10
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95	10	10	10	95	10	12	10	95	10	12	10	95	10	12	10
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99	10	10	10	99	10	12	10	99	10	12	10	99	10	12	10
100	10	10	10	100	10	12	10	100	10	12	10	100	10	12	10

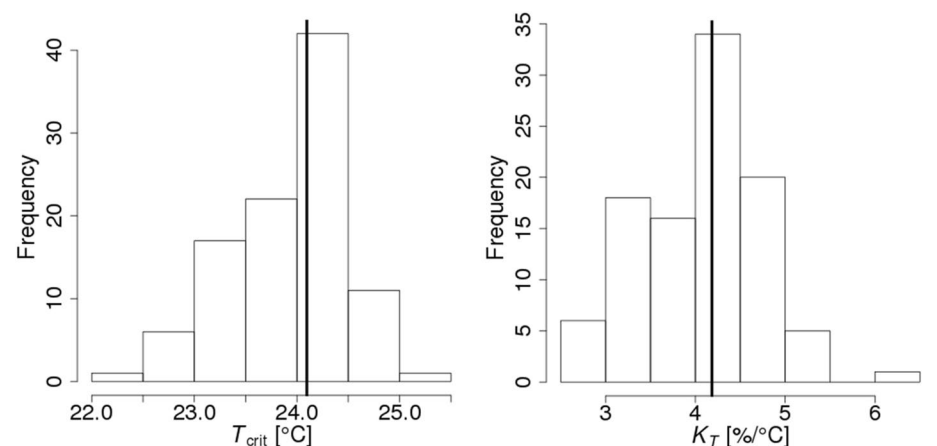
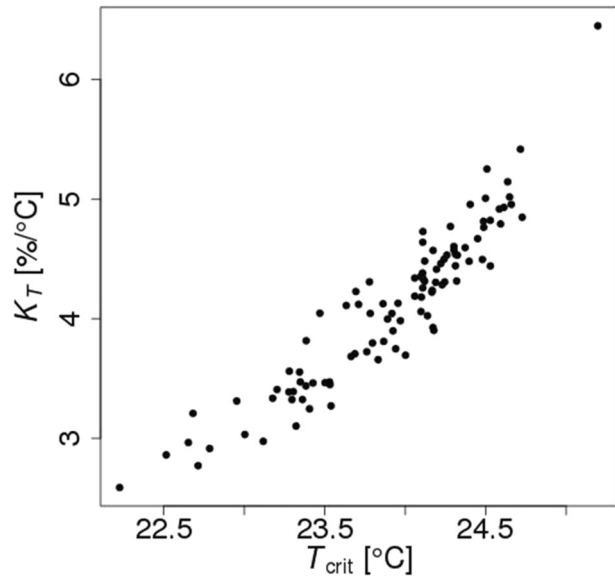


Fig. 10 Plots of 100 parameter values of T_{crit} [$^{\circ}\text{C}$] and k_T [$\%/^{\circ}\text{C}$]



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Data availability All data and material are open for public.

Code availability Not available.

Declarations

Competing interests The authors declare no competing interests.

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References

- Akune Y, Okiyama M, Tokunaga S (2015) Economic evaluation of dissemination of high temperature-tolerant rice in Japan using a dynamic computable general equilibrium model. Japan Agricultural Research Quarterly: JARQ. <https://doi.org/10.6090/jarq.49.127>

- Bao J (2019) Rice milling quality in Bao J (Ed.) Rice - Chemistry and Technology. Woodhead Publishing, Duxford, UK, pp. 339–369
- Bernardo R (2008) Molecular markers and selection for complex traits in plants: learning from the last 20 years. *Crop Sci* 48:1649–1664. <https://doi.org/10.2135/cropsci2008.03.0131>
- Challinor AJ, Koehler AK, Ramirez-Villegas J, Whitfield S, Das B (2016) Current warming will reduce yields unless maize breeding and seed systems adapt immediately. *Nat Clim Chang* 6(10):954–958. <https://doi.org/10.1038/nclimate3061>
- Chiba M, Terao T, Watanabe H et al (2017) Improvement in rice grain quality by deep-flood irrigation and its underlying mechanisms. *Japan Agricultural Research Quarterly: JARQ* 51:107–116. <https://doi.org/10.6090/jarq.51.107>
- Chun A, Song J, Kim K-J, Lee H-J (2009) Quality of head and chalky rice and deterioration of eating quality by chalky rice. *J Crop Sci Biotechnol*. <https://doi.org/10.1007/s12892-009-0142-41007/s12892-009-0142-4>
- Efron B (1979) Bootstrap methods: another look at the jackknife. *Ann Stat* 7(1):1–26. https://doi.org/10.1007/978-1-4612-4380-9_41
- Fahad S, Hussain S, Saud S et al (2016a) A combined application of biochar and phosphorus alleviates heat-induced adversities on physiological agronomical and quality attributes of rice. *Plant Physiol Biochem* 103:191–198. <https://doi.org/10.1016/j.plaphy.2016.03.001>
- Fahad S, Hussain S, Saud S et al (2016b) Responses of rapid viscoanalyzer profile and other rice grain qualities to exogenously applied plant growth regulators under high day and high night temperatures. *PLoS ONE* 11:e0159590. <https://doi.org/10.1371/journal.pone.0159590>
- Fukui S, Ishigooka Y, Kuwagata T, Hasegawa T (2015) A methodology for estimating phenological parameters of rice cultivars utilizing data from common variety trials. *J Agric Meteorol* 71(2):77–89. <https://doi.org/10.2480/agrmet.D-14-00042>
- Hayashi M, Sugiura K, Kuno C et al (2011) Reduction of rice chalky grain by deep and permanent irrigation method: effect on growth and grain quality of rice. *Plant Prod Sci* 14:282–290. <https://doi.org/10.1626/pp.s.14.282>
- Ishigooka Y, Fukui S, Hasegawa T et al (2017) Large-scale evaluation of the effects of adaptation to climate change by shifting transplanting date on rice production and quality in Japan. *J Agric Meteorol* 73:156–173. <https://doi.org/10.2480/agrmet.D-16-00024>
- Ishigooka Y, Hasegawa T, Kuwagata T et al (2021) Revision of estimates of climate change impacts on rice yield and quality in Japan by considering the combined effects of temperature and CO₂ concentration. *J Agric Meteorol* 77:139–149. <https://doi.org/10.2480/agrmet.D-20-00038>
- Ishimaru T, Hirabayashi H, Sasaki K, Ye C, Kobayashi A (2016) Breeding efforts to mitigate damage by heat stress to spikelet sterility and grain quality. *Plant Prod Sci* 19(1):12–21. <https://doi.org/10.1080/1343943X.2015.1128113>
- Kim SS, Lee SE, Kim OW, Kim DC (2000) Physicochemical characteristics of chalky kernels and their effects on sensory quality of cooked rice. *Cereal Chem*. <https://doi.org/10.1094/CCHEM.2000.77.3.376>
- Kinose Y, Masutomi Y, Shiotsu F, Hayashi K, Ogawada D, Gomez-Garcia M, Matsumura A, Takahashi K, Fukushi K (2020) Impact assessment of climate change on the major rice cultivar Ciherang in Indonesia. *J Agric Meteorol*. <https://doi.org/10.2480/agrmet.D-19-0004510.2480/agrmet.D-19-00045>
- Krishnan P, Ramakrishnan B, Reddy KR, Reddy VR (2011) High-temperature effects on rice growth yield and grain quality. *Advances in Agronomy* (1st ed. Vol. 111). Elsevier Inc. <https://doi.org/10.1016/B978-0-12-387689-8.00004-7>
- Lenaerts B, Collard BCY, Demont M (2019) Review: improving global food security through accelerated plant breeding. *Plant Sci* 287:110207. <https://doi.org/10.1016/j.plantsci.2019.110207>
- Li XM, Chao DY, Wu Y, Huang X, Chen K, Cui LG et al (2015) Natural alleles of a proteasome $\alpha 2$ subunit gene contribute to thermotolerance and adaptation of African rice. *Nat Genet* 47(7):827–833. <https://doi.org/10.1038/ng.3305>
- Lyman NB, Jagadish KSV, Nalley LL, Dixon BL, Siebenmorgen T (2013) Neglecting rice milling yield and quality underestimates economic losses from high-temperature stress. *PLoS ONE* 8(8):e72157. <https://doi.org/10.1371/journal.pone.0072157>
- MAFF (Ministry of Agriculture Forestry and Fishery) (2019) Survey report on the impacts of global warming (in Japanese) available at <https://www.maff.go.jp/j/seisan/kankyo/ondanka/attach/pdf/report-47.pdf> (accessed 14 April 2020).
- Masutomi Y, Takahashi K, Harasawa H, Matsuoka Y (2009) Impact assessment of climate change on rice production in Asia in comprehensive consideration of process/parameter uncertainty in general

- circulation models. *Agric Ecosyst Environ* 131(3–4):281–291. <https://doi.org/10.1016/j.agee.2009.02.004>
- Masutomi Y, Iizumi T, Takahashi K, Yokozawa M (2012) Estimation of the damage area due to tropical cyclones using fragility curves for paddy rice in Japan. *Environ Res Lett* 7(1). <https://doi.org/10.1088/1748-9326/7/1/014020>
- 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.’ *Agric for Meteorol* 203:11–16. <https://doi.org/10.1016/j.agrformet.2014.11.016>
- Masutomi Y, Kinose Y, Takimoto T, Yonekura T, Oue H, Kobayashi K (2019a) Ozone changes the linear relationship between photosynthesis and stomatal conductance and decreases water use efficiency in rice. *Sci Total Environ* 655:1009–1016. <https://doi.org/10.1016/j.scitotenv.2018.11.132>
- Masutomi Y, Takimoto T, Shimamura M, Manabe T, Arakawa M, Shibota N, Ooto A, Azuma S, Imai Y, Tamura M (2019b) Rice grain quality degradation and economic loss due to global warming in Japan. *Environ Res Commun* 1:121003. <https://doi.org/10.1088/2515-7620/ab52e7>
- Morita S, Nakano H (2011) Nonstructural carbohydrate content in the stem at full heading contributes to high performance of ripening in heat-tolerant rice cultivar, ‘Nikomaru.’ *Crop Sci* 51:818–828. <https://doi.org/10.2135/cropsci2010.06.0373>
- Morita S, Wada H, Matsue Y (2016) Countermeasures for heat damage in rice grain quality under climate change. *Plant Prod Sci* 19(1):1–11. <https://doi.org/10.1080/1343943X.2015.1128114>
- Nelder AJ, Mead R (1965) A simplex method for function minimization. *Comput J* 7:308–313. <https://doi.org/10.1093/comjnl/8.1.27>
- Nishimori M, Ishigooka Y, Kuwagata T, Takimoto T, Endo N (2019) SI-CAT 1 km-grid square regional climate projection scenario dataset for agricultural use (NARO2017). *SIMULATION* 38:150–154
- Ohno H, Sasaki K, Ohara G, Nakazono K (2016) Development of grid square air temperature and precipitation data compiled from observed forecasted and climatic normal data. *Climate in Biosphere* 16:71–79. <https://doi.org/10.2480/cib.j-16-028>
- Pardey PG, Connie CK, Steven PD, Jason MB (2016) Agricultural R&D Is on the Move. *Nature* 537(7620):301–303. <https://doi.org/10.1038/537301a>
- Porter JR, Liyong X, Challinor AJ, Cochrane K, Howden M, Iqbal M et al (2014) IPCC 2014: Climate Change 2014: Impacts Adaptation and Vulnerability. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. In: Field CB, Barros VR, Dokken DJ, Mach KJ, Mastrandrea MD, Bilir TE, et al., (Eds.) Chapter 7: Food security and food production systems. Cambridge United Kingdom and New York NY USA: Cambridge University Press.
- Ramirez-Villegas J, Heinemann AB, Pereira de Castro A, Breseghello F, Navarro-Racines C, Li T, Rebollo MC, Challinor AJ (2018) Breeding implications of drought stress under future climate for upland rice in Brazil. *Glob Change Biol* 24(5):2035–2050. <https://doi.org/10.1111/gcb.14071>
- Rosenzweig C, Elliott J, Deryng D, Ruane AC, Müller C, Arneth A, Boote KJ, Folberth C, Glotter M, Khabarov N, Neumann K, Piontek F, Pugh TA, Schmid E, Stehfest E, Yang H, Jones JW (2014) Assessing agricultural risks of climate change in the 21st century in a global gridded crop model inter-comparison. *PNAS USA* 111(9):3268–3273. <https://doi.org/10.1073/pnas.1222463110>
- Takimoto T, Masutomi Y, Tamura M, Nitta Y, Tanaka K (2019) The effect of air temperature and solar radiation on the occurrence of chalky rice grains in rice cultivars ‘Koshihikari’ and ‘Akitakomachi.’ *J Agric Met* 75(4):203–210. <https://doi.org/10.2480/agrmet.D-18-00039>
- Tanaka K, Onishi R, Miyazaki M et al (2009) Changes in NMR relaxation of rice grains kernel quality and physicochemical properties in response to a high temperature after flowering in heat-tolerant and heat-sensitive rice cultivars. *Plant Prod Sci* 12:185–192. <https://doi.org/10.1626/pp.s.12.185>
- Tanaka K, Miyazaki M, Uchikawa O et al (2010) Effects of the nitrogen nutrient condition and nitrogen application on kernel quality of rice. *Jpn J Crop Sci* 79:450–459. <https://doi.org/10.1626/jcs.79.450>
- Tanaka A, Takahashi K, Masutomi Y, Hanasaki N, Hijioka Y, Shioyama H, Yamanaka Y (2015) Adaptation pathways of global wheat production: importance of strategic adaptation to climate change. *Sci Rep* 5(August):2–11. <https://doi.org/10.1038/srep14312>
- Tanamachi K, Miyazaki K, Matsuo K et al (2016) Differential responses to high temperature during maturation in heat-stress-tolerant cultivars of Japonica rice. *Plant Prod Sci* 19:300–308. <https://doi.org/10.1080/1343943X.2016.1140007>
- Tashiro TT, Wardlaw IE (1991) The effect of high temperature on kernel dimensions and the type and occurrence of kernel damage in rice. *Aust J Agric Res* 42(3):485–496. <https://doi.org/10.1071/AR9910485>
- Usui Y, Sakai H, Tokida T, Nakamura H, Nakagawa H, Hasegawa T (2016) Rice grain yield and quality responses to free-air CO₂ enrichment combined with soil and water warming. *Glob Change Biol* 22(3):1256–1270. <https://doi.org/10.1111/gcb.13128>

- Wada H, Masumoto-Kubo C, Gholipour Y, Nonami H, Tanaka F, Erra-Balsells R, Tsutsumi K, Hiraoka K, Morita S (2014) Rice chalky ring formation caused by temporal reduction in starch biosynthesis during osmotic adjustment under Foehn-induced dry wind. *PLoS ONE* 9(10):e110374. <https://doi.org/10.1371/journal.pone.0110374>
- Xiong D, Ling X, Huang J, Peng S (2017) Meta-analysis and dose-response analysis of high temperature effects on rice yield and quality. *Environ Exp Bot* 141:1–9. <https://doi.org/10.1016/j.envexpbot.2017.06.007>
- Zhao X, Fitzgerald M (2013) Climate change: implications for the yield of edible rice. *PLoS ONE* 8(6):e66218. <https://doi.org/10.1371/journal.pone.0066218>
- Zhao C, Piao S, Wang X, Huang Y, Ciais P, Elliott J, Huang M, Janssens IA, Li T, Lian X, Liu Y, Müller C, Peng S, Wang T, Zeng Z, Peñuelas J (2016) Plausible rice yield losses under future climate warming. *Nature Plants*. <https://doi.org/10.1038/nplants.2016.202>
- Zhu C, Xiao Y, Wang C, Jiang L, Zhai H, Wan J (2005) Mapping QTL for heat-tolerance at grain filling stage in rice. *Rice Sci* 12(1):33–38

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