Rice grain quality degradation and economic loss due to global warming in Japan

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Abstract

Global warming is predicted to have significant impacts not only on crop productivity but also on crop quality, leading to economic loss. In the present study, focusing on grain quality of rice in Japan, we assessed the impact of global warming on the occurrence of low quality rice grain called ‘chalky rice grain’, and the incurred economic loss. Using 10 future climate scenarios and a simulation model to estimate the occurrence of chalky rice grain, we showed that global warming will double the occurrence of chalky rice grain by the 2040s under RCP8.5. This corresponds to one third of paddy rice fields in Japan showing a decrease in grain grade. This would produce an annual economic loss of 401.4 million US$/yr under RCP8.5 in the 2040s. These results suggest that the development and implementation of national and local adaptation strategies are urgently needed for rice production in Japan.

1. Introduction

Previous studies have revealed that global warming will have significant impacts not only on crop productivity [1–5] but also on crop quality [6–9]. In Japan, there have been many studies showing that high temperatures during the growing period drastically degrade rice grain quality [8]. Thus, degradation of rice grain quality due to global warming is an urgent issue in Japanese rice production, and adaptation strategies should be immediately implemented.

The most significant phenomena that degrades rice grain quality in Japan is the occurrence of chalky rice grain (CRG) [10]. CRG contains an opaque part within the endosperm. Because the starch granules of endosperm in CRG are loosely packed, the numerous air spaces between starch granules cause random light reflections to create a chalky appearance [8]. Several studies have shown that high temperatures during the ripening period of rice increase the occurrence of CRG [8,11–13] due to the lack of starch substrates in the endosperm [14], down-regulation of some starch synthesis-related genes [15], and up-regulation of starch-degrading amylase-encoding genes [15, 16]. Hence, there is a great concern that global warming will increase the occurrence of CRG in Japan.

CRG is not considered a whole grain in Japan because it decreases palatability [17, 18] and increases loss in the milling process [11, 19]. Therefore, high occurrence of CRG decreases grain grade, thereby decreasing farmers’ income, because the price of rice grain is generally determined by grain grade. Thus, the increase in the occurrence of CRG due to global warming is a major issue that can cause economic loss.
To assess the effects of high temperatures on the occurrence of CRG, several types of models for estimating the occurrence of CRG have been developed. A major type of the models is statistical models of non-linear relationship between the occurrence of CRG and temperatures during the ripening period [8, 13, 20]. A feature of these simple statistical models is that they can be easily developed for any variety and applied to any area without much loss of accuracy in estimations, if input data, including temperature, CRG occurrence, and flowering date, are available for the varieties and regions. As an improvement of these simple statistical models, Takimoto et al. (2019) suggested that the consideration of radiation can improve the accuracy of estimations [21].

As other types, Wakiyama et al. (2010) proposed a non-linear regression model between dry matter weight per grain and the occurrence of milky-white grain, which is a type of CRG [20], and Yoshida et al. (2016) developed a model combined with a rice growth simulation model [22].

While there have been a few studies on the impact of global warming on the ratio of first grade grain [6, 9], no studies on the occurrence of CRG under predicted global warming conditions. Furthermore, there have been no studies on the economic loss caused by degradation of crop quality due to global warming, although many studies have assessed the economic loss through reduction in crop yields [23–25].

The objective of the present study was to quantify the occurrence of CRG in Japan under future global warming conditions and to assess the incurred economic loss. In addition, we discuss effective adaptation strategies to combat the occurrence of CRG in Japan.

2. Materials and methods

2.1. Assessment framework

First, we developed a model for estimating the occurrence of CRG across Japan, using CRG data collected from rice paddy fields across Japan (Step 1 in figure 1). Second, using the model, we estimated the occurrence of CRG in 1 km grids (Step 2 in figure 1). Third, using the estimated occurrence of CRG in 1-km grids and the gridded data on the area of paddy fields, we estimated the occurrence of CRG averaged across Japan and the areas of the first and second grain grades (Step 3 in figure 1). Finally, using the estimated areas of the second grade grain, we estimated the economic loss due to the occurrence of CRG (Step 4 in figure 1).

These estimations were conducted every year from 2011 to 2050. The results of the estimations are shown by decades (2010s: 2011–2020; 2020 s: 2021–2030; 2030 s: 2031–2040; 2040 s: 2041–2050). For climate data from 2011 to 2015, we used the Mesh Agro-Meteorology Data (Mesh AM [26]), which was developed from observations at meteorological sites across Japan, and from 2016 to 2050, we used NIAESv2.7r [27], which is bias-corrected and 1 km-downscaled climate data from General Circulation Models (GCMs). To account for uncertainty in future climate projections, we used 10 future climate scenarios from 2 RCPs (RCP2.6 and RCP8.5) and 5 GCMs (CSIRO-Mk3-6-0, MIROC5, MRI-CGCM3, HadGEM2-ES, GFDL-CM3). Figure S1 is available online at stacks.iop.org/ERC/1/121003/mmedia shows air temperatures in August over rice-growing
areas in Japan for Mesh AM from 2001 to 2015 and NIAESv2.7r from 2010 to 2030 to check the coherency in the 2010s between the two data. It can be seen that there was no large gap between the two data.

The model developed in the present study focuses on the Japanese rice variety 'Koshihikari', which is planted in over 35% of rice paddy fields in Japan [28]. Okinawa Prefecture was excluded from the model because it has a predominantly subtropical climate, in contrast to the other prefectures, which have a temperate one.

2.2. Model for estimating chalky rice grain (CRG) (Step 1)
According to Masutomi et al (2015) [13], the occurrence of CRG, I [%], is estimated by the following equation:

\[ I = \max\{0, k(T_{20} - T_{crit})\} \] (1)

where, \( T_{20}[^\circC] \) is the daily temperature averaged over 20 days after the flowering date, which is the same date as the heading date for rice, \( T_{crit}[^\circC] \) is the critical temperature at which CRG begins to occur, and \( k\) [%/^\circC] is a parameter for the sensitivity of I to increases in \( T_{20} \). In the model, \( I = 0 \) if \( T_{20} \leq T_{crit} \), otherwise \( I > 0 \). In the case of \( T_{20} > T_{crit} \), \( I \) linearly increases with \( T_{20} \) according to \( k \) (figure 2). \( T_{crit} \) and \( k \) are parameters that are estimated with observed data on CRG. The input data for estimating I are daily temperature and the flowering date. The data required for model calibration are occurrence of CRG, daily temperature, and flowering date.

2.3. Gridded estimation of CRG occurrence (Step 2)
The occurrence of CRG was estimated at each 1 km grid across Japan from 2011 to 2050, applying the model described in Step 1. The data required for the estimation are 1 km gridded data on daily air temperature and flowering date. Until 2015, we used air temperature data from Mesh AM and reported values of flowering date for each agricultural region. From 2016, we used air temperature data from NIAESv2.7r [27], which are bias-corrected and downscaled to 1 km grid from 10 GCMs (2 RCPs and 5 GCMs). Flowering dates from 2016 for each grid were estimated according to the method of Fukui et al (2015) [29], where the development rates for vegetative and reproductive stages are given as a function of temperature and daylength. Daylength is determined by the latitude of each grid, and reported values of each agricultural region in 2010 were used for the transplanting date.

2.4. Average occurrence of CRG and area estimation on grades of grain quality (Step 3)
The CRG occurrence averaged across Japan was estimated from 1 km gridded data on CRG occurrence and rice paddy area. In addition, the area of the first and second grades was estimated by the following procedure. First, all grids were classified into each grade according to the occurrence of CRG. Second, the area of rice paddies for each grid is summed up by grades. Regarding the classification of the first and second grades, we optimised the threshold for the occurrence between the first and second grades using the reported values for the ratio of grains below the second grade due to the occurrence of
The optimised threshold was 16.9%, which is consistent with the inspection standard for brown rice grain of the Ministry of Agriculture, Forestry, and Fishery [30].

The 1 km gridded rice paddy area, which was used in the estimation above, is provided from the Mesh AM, and was originally developed by the Ministry of Land, Infrastructure, Transport and Tourism. The data represents rice paddy area in 2009.

2.5. Assessment of economic loss (Step 4)
Economic loss due to the occurrence of CRG is estimated by using the area of each grade estimated in Step 3. The price of rice in Japan is generally determined by grain grade. The price decreases by 0.15 US$/kg from the first to the second grades [31]. We estimated the economic loss by the following equation:

\[
\text{Economic Loss} = \text{Pro} \times \text{AR}_2 \times \Delta P_2
\]

where, AR2 is the area ratio of the second grade of the total rice paddy area in Japan. \(\Delta P_2\) is the price decrease from the first to the second grades. We set this as \(\Delta P_2 = 0.15 \text{ US$/kg}\). Pro is rice production in Japan and is set as \(\text{Pro} = 8042 \times 10^6 \text{ kg}\), which is the value in 2016, reported by MAFF [32]. The assumption of constant rice production will overestimate future economic loss because rice production in Japan has been decreasing over the last 60 years.

2.6. Future climate scenarios
We used NIAESv2.7r [27] for the 10 climate scenarios, which are bias-corrected and statistically downscaled to 1 km grid from GCMs (2 RCPs (RCP2.6 and RCP8.5) and 5 GCMs (CSIRO-Mk3-6-0, MIROC5, MRI-CGCM3, HadGEM2-ES, GFDL-CM3)). Figure 3, tables S1(a) and (b) show average air temperature in August over rice areas in Japan from the 2010s to 2040s. August is the ripening period of rice in Japan. The figure and tables show that average air temperature will increase by 0.9 [°C] for RCP2.6 and by 1.6 [°C] for RCP8.5 from 2010s to 2040s in mean.

2.7. Field data on chalky rice grain
To estimate model parameters (Step 1), we collected data on the occurrence of CRG for ‘Koshihikari’ from 4 sites (6 treatments), which have different air temperatures, soil types and managements. Table 1 shows basic information for each site. The total number of samples was 55 and the number of samples for each treatment was 12, 5, 9, 9, 9, and 9. There were no treatments with extremely large number of samples and therefore the effect of specific treatment on model calibration was excluded. Soil types in each site were identified by Japan Soil Inventory [33]. Three soil types, including gley lowland soil, gray lowland soil, and andosol, are major soil types used for paddy rice fields in Japan. The amount of nitrogen application ranges from 50–80 kg/ha. These values are close to 60 kg/ha, which is the average amount of nitrogen application for paddy rice in Japan [34]. Plant density ranges from 15.2–24 hill/m². The range agrees with 17–23 hill/m², which is the planting density of standard machines used in Japan [35]. Therefore, it can be thought that the model calibrated by the collected data estimates the occurrence of CRG under major soils and standard managements in Japan. The occurrence of CRG ranges from 2.55% to 37%. Note that the occurrence of CRG in all samples was measured with grain discriminators. The flowering date was measured in the 4 sites (6 treatments).
### Table 1. Sites for the estimation of model parameters.

| Site       | Lon   | Lat   | Years          | T20 [°C]          | Soil                    | Nitrogen [kg/ha] | Plant density [hill/m²] | CRG [%]          |
|------------|-------|-------|----------------|-------------------|-------------------------|------------------|--------------------------|------------------|
| Nagaoka    | 138.87| 37.44 | 2004–2015      | 26.86 (25.23–25.85) | Gray lowland soil       | 50 (30–20)      | 18.2–19.6               | 8.68 (2.55–18.7) |
|            |       |       | 2012–2016      |                   |                         | 50 (30–20) †     | 18.2–19.6               |                  |
| Mito       | 140.54| 36.36 | 2006–2014      | 25.55 (23.62–27.45) | Gray lowland soil       | 50 (60–0) †     | 15.2 ‡                   | 9.61 (5.1–20.5)  |
|            |       |       | 2006–2014      |                   |                         | 50 (50–0) †     | 15.3 ‡                   | 12.68 (3.2–21.8) |
| Tsukuba    | 140.04| 36.13 | 2006–2014      | 26.48 (25.27–27.77) | Andosol                | 80 (30–50)      | 24                       | 16.44 (3.16–37.0) |
| Kumagaya   | 139.35| 36.17 | 2008–2016      | 28.02 (26.29–29.91) | Gray lowland soil       | 75 (30–45)      | 22.2                     |                  |

Soil type is identified by Japan Soil Inventory.
The values in the column of nitrogen express total amount of nitrogen, and values in parenthesis indicate basal and top dressing.

† 50% of the input is organic.

‡ These are values in 2014, because no data in the other years are available.
2.8. Model calibration and validation

The parameters of the model were calibrated by using the site data explained in section 2.7. In this study, $T_{20}$ is used as the explanatory variable for estimating $I$, while $T_{40}$, which is the daily temperature averaged over 40 days after the flowering date, is used in Masutomi et al. (2015) [13]. This is because the target cultivars are different; ‘Koshihikari’ in the present study and ‘Sai-no-kagayaki’ in Masutomi et al. (2015). To select averaging period suitable for ‘Koshihikari’, we compared the estimation errors for models using $T_{10}$, $T_{15}$, $T_{20}$, $T_{25}$, $T_{30}$, $T_{35}$, and $T_{40}$. The model with $T_{20}$ was found to have the lowest error when estimating $I$. Morita et al. (2016) also concluded that $T_{20}$ is appropriate for estimating the occurrence of CRG for the variety Koshihikari, by analysing the data from 15 experimental stations in Japan [8].

The optimal values for the parameter $T_{crit}$ and $k_T$ were estimated from the observed data on the occurrence of CRG and the flowering date at four sites (six treatments) in Japan, and data on daily air temperature at the sites from Mesh AM [26]. The simplex method for optimization was used, as in Masutomi et al. (2015) [13].

We conducted two types of model validation. The first validation is a site-based method using the 53 samples of CRG and the flowering date at four sites across Japan (see section 2.7) and the second validation focused on the area below 2nd grade in Japan. In the first validation, one of the 53 samples was removed to test the data and the others were used to train the data (Leave-One-Out method). We optimised model parameters using the training data and estimated the occurrence of CRG and the errors using the test data and the optimised model. In the second validation, we compared the reported values [10] for the ratio of grains below 2nd grade due to the occurrence of CRG with the estimated ratio of area below 2nd grade.

3. Results

3.1. Calibration and validation

The optimised values were $T_{crit} = 24.17 \, ^\circ C$ and $k_T = 4.24 \% / ^\circ C$. Figure 4 shows the comparison of the occurrence of CRG between the observations and estimations with the Leave-One-Out method. Correlation coefficients (R) with significance, Root mean squared error (RMSE), Relative root mean squared error (RRMSE), and Nash-Sutcliffe model efficiency (NSE) are also shown in figure 4. This figure shows that there is agreement between the observations and estimations, and the model can accurately simulate the occurrence of CRG. R was 0.661 and the correlation was significant ($p \leq 0.001$). RMSE, RRMSE, and NSE were 5.30%, 0.44, and 0.43, respectively. Accuracy was similar to Masutomi et al. (2015) [13].

The model tends to underestimate when the observed occurrence of CRG is higher than 20%. This is because the collected data for model calibration contains only one sample of high $T_{20} (= 29.9 \, ^\circ C)$, which causes the occurrence of CRG higher than 20%. Hence, the applicable limit of the model is thought to be about 30.0 °C. Average air temperatures in August in the 2040s for all climate scenarios are below the limit (tables S1(a) and (b)). Therefore, the application of the model to the 2040s is almost valid.
Figure 5 shows the comparison of the ratio of area below 2nd grade due to CRG between the observations (OBS: black circle) and simulations (SIM: red dot) from 2003 to 2015 in Japan. Note that no observation are available for 2009.

Figure 6. Changes in the occurrence of CRG [%] averaged across Japan from the 2010s to 2040 s. Green and red boxes represent RCP2.6 and RCP8.5, respectively. The thick line in the boxes is the median; the lower and upper edges of the boxes are 25 and 75 percentiles; the lower and upper whiskers are the minimum and maximum values; the black dot is the mean.

Figure 5 shows the comparison of the ratio of area below 2nd grade due to CRG between the observations and simulations from 2003 to 2015 in Japan. The model accurately reproduces the high ratio of area below 2nd grade in 2010, which had extremely high air temperatures in summer across Japan. The correlation between the observations and simulations was 0.886 and significant ($P < 0.001$). Figure 5 also shows that the model underestimated the ratio of area below 2nd grade in years other than 2010 and 2013. These errors can be attributed to a model limitation from only considering air temperature as an explanatory variable.

3.2. Assessments

Figure 6, tables S2(a) and (b) show changes in the occurrence of CRG averaged over Japan from the 2010s to 2040 s. It can be seen from these figure and tables that the occurrence of CRG will increase from the 2010s to 2040 s. With respect to the mean values, the occurrence of CRG in the 2040 s under RCP8.5 will be approximately double that of the 2010s (2.03 = 12.6/6.2). The difference in the occurrence of CRG between RCP2.6 and RCP8.5 will be small until the 2030 s, but will be large in the 2040 s (RCP8.5–RCP2.6: 1.7%). The range of occurrence of CRG will increase in both the RCP scenarios from the 2010s to 2040 s.

Figures 7(a) and (b) shows the occurrence of CRG in 1 km grids across Japan under RCP2.6 and RCP8.5 from the 2010s to 2040 s. It can be observed that the area with a high occurrence of CRG will expand from coastal areas. No large difference was observed in the spatial distribution of occurrence of CRG between RCP2.6 and RCP8.5 until the 2030 s. In the 2040 s, CRG occurrence will be high in the northern parts of Japan under RCP8.5. This was not observed under RCP2.6.

Figure 8 shows the lowest (left: MRI-CGCM3 under RCP2.6) and highest (right: GFDL-CM3 under RCP8.5) occurrence of CRG across Japan in the 2040 s. It can be observed that there is a large difference in the occurrence of CRG between two future scenarios. In the scenario of the highest occurrence, areas of the second grade rice were spread over Japan. In contrast, in the scenario of the lowest occurrence, those are small.
Figure 7. (a): The occurrence of CRG across Japan under RCP2.6 from the 2010s to 2040s. (b): The occurrence of CRG across Japan under RCP8.5 from the 2010s to 2040s.
Figure 9, and tables S3(a) and (b) show changes in the ratio of area below 2nd grade from the 2010s to 2040 s. The ratio of area below 2nd grade will drastically increase from the 2010s to 2040 s. With respect to the mean values, one third of the rice paddy fields in Japan will have a high occurrence of CRG, which would produce rice grains below the second grade in the 2040 s under RCP8.5. This is because rice paddy fields are predominantly located in coastal areas across Japan.

Figure 10, and tables S4(a) and (b) show the annual economic loss due to the occurrence of CRG from the 2010s to 2040 s. The annual economic loss will increase from the 2010s to 2040 s, and reach 318.9 million US $/yr under RCP2.6 and 401.4 million US$/yr under RCP8.5, with respect to the mean values. These values are equivalent to 2.91 (RCP2.6) and 5.15 (RCP8.5) times than those in the 2010s.

4. Discussions

It is strongly established that not only mitigation but also adaptation must be taken into account to reduce the impacts of global warming [1]. In the Paris Agreement adopted in 2015, it is stipulated that the parties, as appropriate, engage in adaptation planning processes and implementation of actions [36]. To the best of our knowledge, the present study is the first to assess the future occurrence of CRG in Japan due to global warming and can be used as scientific evidence to support discussions and development of effective adaptation strategies.

Figures 7(a) and (b) show that the future occurrence of CRG will be spatially heterogeneous. In the near future, i.e. the 2020 s, several regions in coastal areas will have high occurrence of CRG. Hence, prioritising
regions where adaptive options can be immediately implemented is an effective adaptation strategy. In addition, in the 2020 s, the uncertainty in the estimations is considerable (4.0%–12.2%). To reduce the uncertainty, monitoring the variations in CRG occurrence will be an important adaptive action.

We show that the degradation of rice grain quality due to global warming will likely cause large economic losses. Quantification of economic loss will facilitate discussion and implementation of adaptive options. For example, the annual economic loss in the 2020 s will be approximately 160 million US$/yr. If the occurrence of CRG can be minimised by adaptive actions with costs below the economic loss, these actions would be economically advantageous. Our findings can be used in these economic analyses for discussing adaptation strategies. Furthermore, degradation of crop quality due to global warming is likely to occur in other countries and regions. The approach presented in the study can be used as an informative guide globally.

Although many adaptive actions in response to the occurrence of CRG have been proposed [8], the development and adoption of varieties with high temperature tolerance (HTT) will be crucial to mitigate impacts of global warming [37]. Hence, there is an urgent need for research to develop new varieties with HTT. However the development and adoption of new varieties often time consuming and incurs high costs [3, 38]. In Japan, the rate of adoption of varieties with HTT is low (6.6%), although such varieties have been already developed [39]. Therefore, national and local systems and framework to support the adoption of new varieties with HTT are needed. In addition, changes in agricultural management, which are easily implemented by farmers, should be executed until new varieties with HTT are adopted. Thus, it is important to develop adaptation strategies, which include both long- and short-term adaptive options. In order to develop effective adaptation strategies, quantitative assessments of the effect of each adaptive option are necessary, which is challenging.

Regarding the model for estimating the occurrence of CRG, the model used in the study has some advantages. The model is a simple statistical model that only considers air temperature as an explanatory variable. The data required for model calibration are the occurrence of CRG as an objective variable, and temperature and flowering date for estimating \( T_{25} \) as an explanatory variable. Therefore, it is easy to calibrate the model for other varieties and apply the model to other regions. However, it should be noted that the statistical relationships can be valid in different environments when models are calibrated using reliable and representative set of data for the conditions to be explored [40]. In the calibration process, the optimal duration after the flowering date for averaging air temperature differs among varieties [13, 21]. The calibrated parameters, \( T_{\text{crit}} \) and \( k_j \), represent quantitative characteristic of each variety for the occurrence of CRG [13]. For example, higher \( T_{\text{crit}} \) indicates a strong tolerance to a high temperature. The information is useful for selecting varieties adapted to global warming.

There are some limitations and challenges in the model. The occurrence of CRG is known to depend on not only air temperature, but also radiation [21, 41], wind speed [42], CO2 concentration [43], and management, including nitrogen application [44] and planting density [45]. Although our simple model was accurate enough for estimating the occurrence of CRG under current conditions, it is an important challenge to develop and use a model that considers the other factors. In particular, CO2 concentration will definitely increase in the future. Usui et al. (2015) showed that elevated CO2 conditions increase the occurrence of CRG [43]. Therefore, our estimations might be underestimated. Improvement on this aspect is one of the very important challenges.

Agricultural managements are known to affect the occurrence of CRG. Wakamatsu et al (2008) found that higher nitrogen applications decrease the occurrence of white-back kernels [44], a type of CRG. Takahashi (2006) found that there is an optimal planting density to reduce the occurrence of CRG [45]. The consideration
of these management factors into the model allows the model to estimate the effect of changes in agricultural
managements as adaptations to global warming.

Shi et al (2017) suggested that there are different mechanisms in low rice grain quality induced by high day
and night temperatures [46]. Therefore, the usage of climate data with higher time resolution and the
consideration of the mechanisms suggested by Shi et al (2017) could improve the accuracy of estimation. For
further improvement, coupling of a quality model with a crop growth model is an interesting challenge. Farmers
care about not only grain quality but also yield. Therefore, a model that can simulate grain yield and quality
would be useful. In fact, Yoshida et al (2016) developed such a coupled model [22].

Our method to account economic loss is straightforward. We did not consider changes in the price for each
grade and its impact on economic loss. Decreases in the amount of the available 1st grade grain may increase its
price. To take this type of variation into account, it is necessary to develop an economic model that includes
grain quality. In addition, we did not consider socio-economic changes. The development of national and local
scenarios that correspond to global RCP-SSP scenarios is an important challenge.

Rice production in Japan has been decreasing for the past 60 years. Therefore, the assumption of constant
rice production in the economic assessment would overestimate the economic loss. Furthermore, the effect of
global warming on rice production was not considered in the estimation, although global warming will change
future rice production [9]. This is one of the limitations of the present study.

We found that the projected degradation of rice grain quality due to global warming and the associated
economic loss will be inevitable in a large part of the rice paddy fields across Japan if urgent adaptive actions are
not implemented. The development of effective adaptation strategies that integrate short-term adaptations with
long term ones is urgently necessary to avoid economic loss.

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Author contribution

Y M designed the research, conducted the simulations and analyses, and wrote the paper; T T and M S designed
the research and developed the database; T M, M A, N S, A O, and S A conducted field experiments; Y I and M T
contributed to the interpretation of the results and the writing of the paper.

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