Research article

Application of Probabilistic Risk Assessment to the Chalky Rice Grain Issue in Japan

HIROKI ODA*
Graduate School of Frontier Sciences, The University of Tokyo, Kashiwa-city, Chiba, Japan
Email: 2215920513@edu.k.u-tokyo.ac.jp

MOMOKA MASANO
Shizuoka Prefectural Office, Shizuoka-city, Shizuoka, Japan

TAKASHI NOBUOKA
Tokyo Electric Power Service Corporation, Koutou-ku, Tokyo, Japan

KOSHI YOSHIDA
The University of Tokyo, Kashiwa-city, Chiba, Japan

Received 19 November 2023 Accepted 26 November 2023 (*Corresponding Author)

Abstract In recent years, extreme weather events have become more frequent, and there are concerns about the increase of chalky rice grains. Therefore, it is important to understand the frequency and severity of high-temperature injuries to rice grains occurring nationwide in Japan. Thus, the objective of this research was to analyze the hazard of high temperature through a probabilistic method using big weather data and to assess the risk of chalky rice grain. In this research, we analyzed air temperature data from approximately 800 stations of the AMeDAS (Automated Meteorological Data Acquisition System) in Japan and checked the chronological changes. To assess the risk of chalky rice grain, the Probabilistic Risk Assessment (PRA) method was applied and the risk for each of the 20 years from 1980 to 1999 and from 2000 to 2019 was compared. Chalky rice grains, which reduce rice quality, increase when the average temperature exceeds 26℃ during the first 20 days after the heading date of rice. A comparison of the areas with air temperatures exceeding 26℃ at least once per three years (33.3%) between the past and the recent 20 years shows that the risk of high temperatures has increased in the inland areas of the southern Tohoku region and the southern part of Ibaraki Prefecture. Subsequently, a multiple regression model was applied to identify the factors affecting high temperature risk. The 20-day averaged daily mean temperature, which has a probability of 33.3%, was set as the dependent variable, and longitude, altitude, and urban area ratio were set as explanatory variables. As a result, regions located further north experience greater temperature increases due to climate change, and regions with higher urban rates also experience greater temperature increases due to anthropogenic effects.

Keywords climate change, climate hazard, agricultural damage, paddy rice quality

INTRODUCTION

In recent years, there have been many reports of high-temperature injury in rice (Terashima et al., 2001). The main symptoms are a decrease in grain filling rate and a decrease in grain weight per grain (MAFF, 2006), which can reduce the inspection grade and yield, respectively, thereby decreasing farmer income (Morita, 2008). The inspection grade is determined by the minimum grain filling rate and the maximum proportion of rice classified as a chalky rice grain or other non-grain filling categories (National Food Safety and Quality Association, 2002).

The reason CRGs appear "chalky" is due to empty spaces between starch granules in the endosperm, which cause light to scatter randomly (Tashiro and Ebata, 1975). In fact, in "chalky" areas caused by high temperatures, there have been observations of empty spaces between amyloplasts, normally polyhedral amyloplasts that are round, and small amyloplasts that only contain two or a few single-grain starches (Tashiro and Wardlaw, 1991; Zakaria et al., 2002).

Masutomi (2019) revealed that CRG begins to occur when the average temperature exceeds 26°C during the 20 days after rice heading. The study also presented the predicted spatial distribution of this damage under future climate conditions. However, in analyzing the risk of agricultural damage, it is important to consider not only the severity of the damage but also the probability (frequency) of its occurrence.

OBJECTIVE

This study aims to use a probabilistic method and weather big data to analyze the risk of high temperatures and assess the risk of CRGs in Japan.

METHODOLOGY

Probabilistic Risk Assessment

Probabilistic Risk Assessment (PRA) is a method of quantitatively evaluating risk using probability theory and is commonly used in the safety assessment of structures. For example, the International Atomic Energy Agency (IAEA) uses probabilistic risk assessment to evaluate the safety of nuclear facilities. PRA involves integrating probability fields that represent the predicted seismic forces at the construction site of the facility, represented as a hazard curve, with the load represented as a fragility curve when specific seismic forces are applied, and evaluating the risk in terms of annual damage probability (IAEA, 2010). In addition to structures, some studies quantitatively evaluate the risk that herbicides for rice fields pose to the surrounding ecosystem (Nagai et al., 2008). To assess the risk of CRGs, we applied the PRA method and compared the risk for two 20-year periods: 1980-1999 and 2000-2019. CRGs, which can negatively impact the quality of rice, are more likely to occur when the average temperature exceeds 26°C during the first 20 days after the heading date of rice.

We utilized daily mean temperature data from Japan's Automated Meteorological Data Acquisition System (AMeDAS), which consists of over 1600 observatories. However, due to the inclusion of recently established stations and the presence of missing values, we did not compute data for any station that had less than 90% data availability during the analysis period. After applying this criterion, the number of stations eligible for our calculations was approximately 830. The data of 20 days mean air temperature were extracted in descending order and the top five values per year were selected for further analysis. Using Eq. (1), the annual exceedance probability was calculated based on these values.

$$P_{(x)} = 1 - e^{\left(-\frac{n}{T}\right)} \tag{1}$$

where, x: 20 days mean air temperature (°C), T: observation period, n: The number of occurrences of mean temperatures above x°C.

Multiple Regression Analysis

To identify the factors that have the most significant impact on the increase in temperature resulting from global warming and anthropogenic effects, multiple regression analysis was conducted. The dependent variable was the 20-day averaged daily mean temperature with an annual exceedance probability of 33.3% (i.e., once in the 3-year probability of occurrence), while latitude and elevation were chosen as explanatory variables due to their well-established negative correlation with temperature. The reason for adopting a threshold of 33.3% can be exemplified by Sompo Japan Thailand. This company has set the frequency of early drought coverage in its weather index insurance for rice drought damage in Thailand to about once every three years. Additionally, we included urban land use coverage as an explanatory variable due to its known role in raising temperatures. For latitude and elevation, we used the coordinates and elevation data of AMeDAS stations published by the Japan Meteorological Agency. For urban land use coverage, we utilized land use data in 2010 from JAXA, calculating urban land use coverage within a buffer of 10 km in diameter centered on the AMeDAS station being examined following Fujibe (2011).

RESULTS AND DISCUSSION

To analyze the risk of CRGs, we calculated the annual probability of 20-day averaged daily mean temperature exceeding 26°C for the recent 20 years (2000-2019) in Fig 1. The probability of exceeding 26°C is low in Hokkaido or the northern part of Japan, where temperatures are relatively low throughout the year, and in high-elevation areas (mountainous regions), indicating a low risk of high-temperature injury. In the areas south and western parts of Japan, the annual probability of exceeding 26°C frequently occurs, except in high-elevation areas.

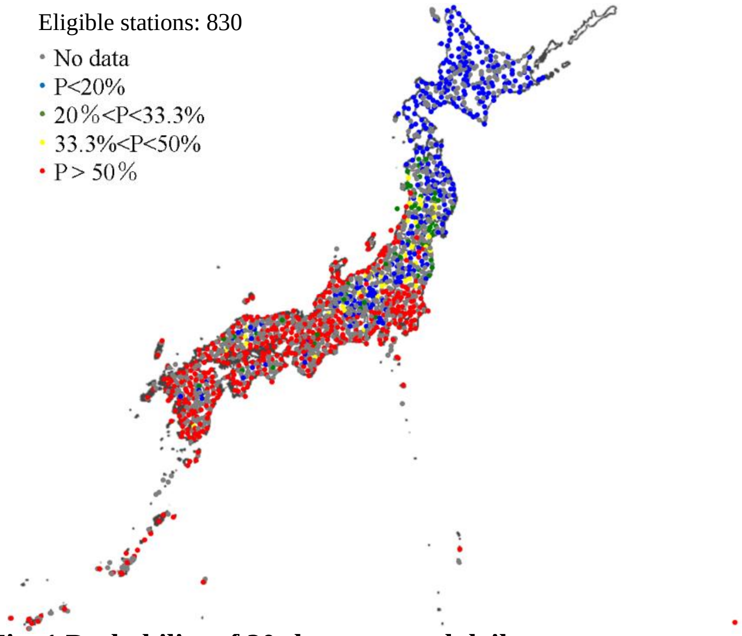

Fig. 1 Probability of 20-day averaged daily mean temperature exceedance by 26°C for the last 20 years (2000-2019)

To examine the changes in the probability of annual exceedance of 26°C for the 20-day averaged daily mean temperature over the past 20 years and the recent 20 years, we calculated the difference of temperature with a probability of 33.3% between the two periods. Yoshida et al. (2019) indicated that the most frequent climate hazard in Northeast Thailand occurs once every four years. The concern of this research lies in high-frequency climate hazards that are not covered by insurance, hence setting a threshold of 33.3%, which means a frequency of once every three years. To identify locations with significant differences, we used color-coded observation points based on the significance of the difference. As shown in Fig. 2, locations with insufficient data are represented in gray, those with negative change are depicted in blue, locations with no change are represented in green, locations with a change greater than 0°C and less than 0.3 are depicted in yellow, and locations with a change greater than 0.3°C are depicted in red. Notably, Fig. 2 has more 'No Data' points than Fig. 1. This is because each station needed to have over 90% data availability in both time periods. This stricter rule reduced the number of sites with sufficient data, resulting in an increased number of locations categorized as 'No Data'. With a few exceptions, most of the sites depicted in red are located slightly inland from the coast. This is likely due to the high heat capacity of the oceans in coastal areas, which makes it difficult for temperature changes to occur. There are many locations in the southern part of the Ibaraki prefecture where the risk of high-temperature injury has increased, consistent with the findings of Masutomi et al. (2019), who observed a decreasing trend in the ratio of first-class rice in future climates.

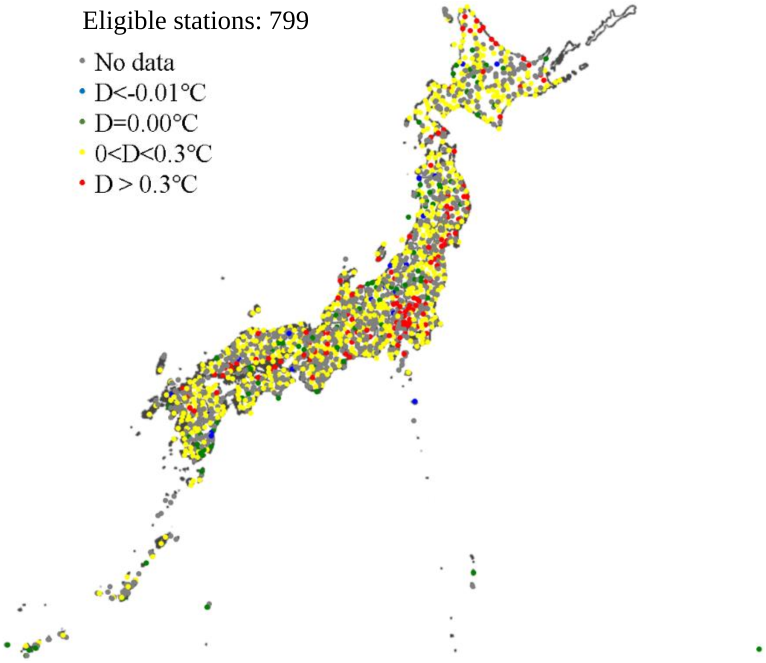

Fig. 2 Difference in temperature for two periods with a yearly exceedance probability of 33.3%

The data were organized for multiple regression analysis with the dependent variable being the difference of past and recent 20-day averaged daily mean temperature which occurs in 33.3% probability of the year and the explanatory variables being latitude, elevation, and urban land use ratio within a 10 km diameter buffer centered on the AMeDAS observatory. In the analysis, points with more than 90% of the observation period for substantial explanatory variables were extracted and examined. Applying this rule reduced the sample size to 799. The explanatory variables were standardized using the following Eq. (2), and multiple regression analysis was conducted using the standardized variables.

$$x' = \frac{x-\bar{x}}{s} \quad (2)$$

where, $\bar{x}$: mean value in sample, *s:* standard deviation in sample.

The difference in temperature between two periods with a yearly exceedance probability of 33.3% was used as the dependent variable, and latitude and urbanization rate were used as explanatory variables in a multiple regression analysis. Table 1 shows the coefficients and p-values for the results. The coverage of urban land use within a 10 km buffer is represented by the percentage of JAXA land use maps classified as "urban," so it is referred to as the "urban rate" in the table. From this multiple regression analysis, it was found that there were statistically significant results for latitude and urban land use coverage at the 1% level. The partial regression coefficients for the explanatory variables were 0.124 for latitude and 0.279 for urban land use coverage. This indicates that regions located further north experience greater temperature increases due to climate change and that regions with higher levels of urbanization also experience greater temperature increases due to anthropogenic effects. Among these, it was also shown that urbanization has a greater contribution to temperature increases. Also, the analysis suggested that the impact of urbanization on temperature rise is more pronounced in northern regions compared to southern regions. In Fig. 2, most points near cities in northeastern regions are shown in red, while there are fewer red points near cities in southern regions. This means that cities in different places are affected differently by urbanization when it comes to temperature changes.

Table 1 Results of the multiple regression analysis

	coefficients	P-value
Intercept	0.000	1.000
Elevation	-0.029	0.401
Latitude	0.124	0.000
Urban rate	0.279	0.000

CONCLUSION

In this study, hazard curves were probabilistically created from nationwide AMeDAS data mainly using temperature as a meteorological factor, and based on the results, the risk of chalky rice grain was examined using a probabilistic risk assessment method. The 26°C yearly exceedance probability of the 20-day averaged daily mean temperature was calculated for the past 20 years (1980-1999) and the recent 20 years (2000-2019) at all AMeDAS observatories in Japan, and the change in the two periods was calculated to analyze the change of high-temperature risk. When the acceptable frequency of damage for farmers was set to 33.3%, it was shown that the risk of high-temperature damage in inland areas of the southern Tohoku region and the southern area of Ibaraki Prefecture has increased in the recent 20 years. The characteristics of points where the risk of high-temperature damage has greatly increased were inland areas slightly away from the coast. On the other hand, the risk of high-temperature damage decreased in the northern part of the Tohoku region, especially surrounding areas near the ocean. To quantitatively measure regional differences in temperature increases due to climate change, multiple regression analysis was conducted with the change in temperature with a yearly exceedance probability of 33.3% as the dependent variable and latitude, elevation, and urbanization rate as dependent variables. It was found that there were statistically significant results for latitude and urban land use coverage at the 1% level. The partial regression coefficients for the explanatory variables were 0.124 for latitude and 0.279 for urban land use coverage. This shows that climate change affects the northern part more and might become significant in the agricultural land located near the urban city area. In this study, we just used 26°C Celsius as a threshold of CRG and 33.3% probability as a farmer's acceptable frequency level, however further research is needed about the rice varieties or farmer's perception.

To tackle the issue of Chalky Rice Grains (CRGs), various strategies have been suggested. Morita et al. (2015) recommended applying enough nitrogen during or after the panicle initiation stage. Similarly, Chiba et al. (2013) suggested using deep-flood irrigation to control the temperature at the surface of rice paddies. In addition to these immediate solutions, Masutomi (2019) proposed the development and use of rice varieties that can better withstand high temperatures, as a long-term approach. Although these methods have been effective in reducing CRGs, they often involve significant costs. Therefore, it is important for future research to include detailed cost-benefit analyses to identify the most cost-effective adaptation strategies.

ACKNOWLEDGEMENTS

This research was supported by the MEXT/JSPS Grant-in-Aid for Scientific Research (KAKENHI) no.19H03069 and no.20KK0346.

REFERENCES

Chiba, M., Matsumura, O., Watanabe, H., Takahashi, Y. and Terao, T. 2013. Deep-flood irrigation suppresses the occurrence of chalky grains through high source ability, despite the high percentage of secondary rachis grains. Japanese Journal of Crop Science, 82 (3), 223-232, Retrieved from DOI https://doi.org/10.1626 /jcs.82.223

Fujibe, F. 2011. Long-term climate changes in Japan and urbanization. Tenki, 58, 5-18. (in Japanese)

International Atomic Energy Agency. 2010. Development and application of level 1 probabilistic safety assessment for nuclear power plants. IAEA Safety Standards Series No. SSG-3, IAEA, Vienna, Retrieved

from URL https://www-pub.iaea.org/MTCD/Publications/PDF/Pub1430_web.pdf
Masutomi, Y., Takimoto, T., Shimamura, M., Manabe, T., Arakawa, M., Shibota, N., Ooto, A., Azuma, S., Imai, Y. and Tamura, M. 2019. Rice grain quality degradation and economic loss due to global warming in Japan. Environmental Research Communications, 1 (12), 121003, Retrieved from DOI https://doi.org/10.1088/2515-7620/ab52e7
Ministry of Agriculture, Forestry and Fishery, 2006. Overcoming high temperature distress in paddy rice, Report on measures to prevent high temperature distress. Retrieved from URL https://www.maff.go.jp/j/kanbo/kihyo03/gityo/g_kiko_hendo/suito_kouon/pdf/report.pdf (in Japanese)
Morita, S. 2008. Prospect for developing measures to prevent high-temperature damage to rice grain ripening. Japanese Journal of Crop Science, 77 (1), 1-12, Retrieved from DOI https://doi.org/10.1626/jcs.77.1 (in Japanese)
Morita, S., Wada, H. and Matsue, Y. 2016. Countermeasures for heat damage in rice grain quality under climate change. Plant Production Science, 19 (1), 1-11, Retrieved from DOI http://dx.doi.org/10.1080/1343943X.2015.1128114
National Food Safety and Quality Association. 2002. Handbook of agricultural product inspection, Rice. 157-201.
Schroer, S. and Modarres, M. 2013. An event classification schema for evaluating site risk in multi-unit nuclear power plant probabilistic risk assessment. Reliability Engineering and System Safety, 117, 40-51, Retrieved from DOI https://doi.org/10.1016/j.ress.2013.03.005
Tashiro, T. and Ebata, M. 1975. Studies on belly white rice-4-morphological characteristics of endosperm cells in white opaque parts. Japanese Journal of Crop Science, 44 (2), 205-214, Retrieved from DOI https://doi.org/10.1016/j.ress.2013.03.005
Tashiro, T. and Wardlaw, I.F. 1991. The effect of high temperature on kernel dimensions and the type and occurrence of kernel damage in rice. Australian Journal of Agricultural Research, 42 (3), 485-496, Retrieved from DOI https://doi.org/10.1071/ar9910485
Terashima, K., Saito, Y., Sakai, N., Watanabe, T., Ogata, T. and Akita, S. 2001. Effects of high air temperature in summer of 1999 on ripening and grain quality of rice. Japanese Journal of Crop Science, 70 (3), 449-458, Retrieved from DOI https://doi.org/10.1626/jcs.70.449
Yoshida, K., Surisutham, M., Sritumboon, S., Suanburi, D., Janjirauttikul N. and Suanpaga W. 2019. Evaluation of economic damages on rice production under extreme climate and agricultural insurance for adaptation measures in Northeast Thailand. Engineering Journal, 23 (6), 451-469, Retrieved from DOI https://doi.org/10.4186/ej.2019.23.6.451
Zakaria, S., Matsuda, T., Tajima S. and Nitta Y. 2002. Effect of high temperature at ripening stage on the reserve accumulation in seed in some rice cultivars. Plant Production Science, 5 (2), 160-168, Retrieved from DOI https://doi.org/10.1626/pps.5.160