IMPACT OF CLIMATE CHANGE ON RICE PRODUCTIVITY AND ADAPTATION STRATEGY IN JAPAN

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ABSTRACT

The recent trend of increasing temperatures has affected agriculture in many ways, including the productivity and quality of rice, which is the staple food in Japan. These effects are predicted to be even more frequent and more severe under climate change projections. This study aimed to evaluate the impact of the projected increasing temperatures due to climate change on the yield and quality of rice and to present the regional differences in the effectiveness of moving the transplanting date, which has been one of the most effective adaptation measures, to avoid the negative effects of high temperatures on rice yield and quality. As an indicator of rice quality, we used the heat stress index HD_m26, calculated as the cumulative temperature within 20 days after the heading date, which is related to the decreased percentage of first-grade rice caused by high temperatures. As the impact assessment model, a process-based rice growth and yield projection model (the Hasegawa/Horie model) was employed. Simulations were conducted based on 18 multiple projected climate scenarios (six GCMs × three RCPs) obtained from CMIP-5 during 1981–2100. Transplanting date for each grids were obtained from the statistics data from 2006 of sub-prefectural regions and were moved at 7-day intervals within the range from −70 to +70 days from the standard transplanting date. The predominant cultivar in each prefecture in 2006 was assigned to grids in the respective prefectures. The estimated yield was categorized into three classes with different degrees of quality decrease risk according to the values of HD_m26. The results showed that when the transplanting date was not changed, total rice production was predicted to increase until the middle of *this century and subsequently to decrease slightly toward the end of this century; however, the proportion of rice at high risk of quality decrease (following exposure to high temperatures within the early ripening period) was predicted to increase. In the case of selecting the transplanting date that provides the maximum yield without heat stress negatively affecting the quality, the increased risk of a decrease in quality can be avoided while maintaining total productivity. However, a large decrease in yield was predicted in some areas, suggesting that the current rice-producing regions would be separated into distinctly suitable and unsuitable areas as the temperature increases.*

Keywords: Climate change adaptation, rice yield, rice quality, moving transplanting date

INTRODUCTION

Rice is one of the most important crops in Japan, and stable rice production under changing climatic conditions is an important issue in terms of national food security. In the past, the main target of climate change impact measures regarding rice production in Japan was to prevent damage due to low temperatures. However, with the tendency toward the increasing frequencies of high-temperature summers since the 1990s, the apparent decline in rice quality, as indicated by the decrease of first-grade rice caused by the increase in the proportion of immature grains due mainly to high temperatures, has emerged, particularly in western Japan. In extremely hot summers such as that of 2010, decreases in rice yield due to high temperatures were observed in some prefectures. The negative effects of high temperature on rice productivity and quality have already been reported in Japan. On the other hand, in recent years, carbon dioxide (CO_2) levels in the atmosphere have exceeded 400 ppm, an increase which is due largely to human activities. In the future, global warming progression associated with an increase in greenhouse gases is certain to occur. In this situation, it is necessary to clarify how predicted climate changes will affect rice productivity and quality and to examine practical and feasible adaptation measures to mitigate the negative impacts and the expected effects of these measures.

In this study, we first describe the effects of high temperature that have already been observed on rice production in Japan. We additionally introduce some recent research results related to the impact assessment of projected climate change on rice productivity and quality in Japan at a national scale, followed by an evaluation of the impacts of moving the transplanting date as an adaptation measure to mitigate the effects of heat stress on rice yield and quality.

RECENT TREND OF HIGH TEMPERATURES AND ITS EFFECT ON RICE PRODUCTION

The average temperature in summer (June–August), which greatly affects rice production in Japan, has risen by 0.97°C over the past 100 years, with an increase in annual mean temperature of 1.36°C (Fig. 1). Particularly, since the 1990s, unprecedented extremes of high temperatures have been reported. In 2007, the highest recorded temperature of 40.9°C was simultaneously observed at the Kumagaya observation station in Saitama Prefecture and at the Tajimi observation station in Gifu Prefecture, which broke the previous highest temperature record in Japan (40.8°C in Yamagata, 1933) since 74 years. In 2013, only 6 years later, a temperature of 41.0°C was recorded at the Ekawasaki observation station in Kochi Prefecture. Five years later, in 2018, a new highest temperature of 41.1°C was recorded again at the Kumagaya observation station; this is the current record of the highest temperature in Japan. Because the observation instruments, the environment around the observation site, and the method of detecting extreme temperatures have all changed over time, these frequent increases in the highest temperature recorded is not necessarily due to climate change. However, the trend of increasing temperatures in recent years is clear from the fact that a majority of the years that have been ranked in the top ten in terms of the highest average summer temperature have occurred since 1990, with 2010 being the year with the current highest average temperature.

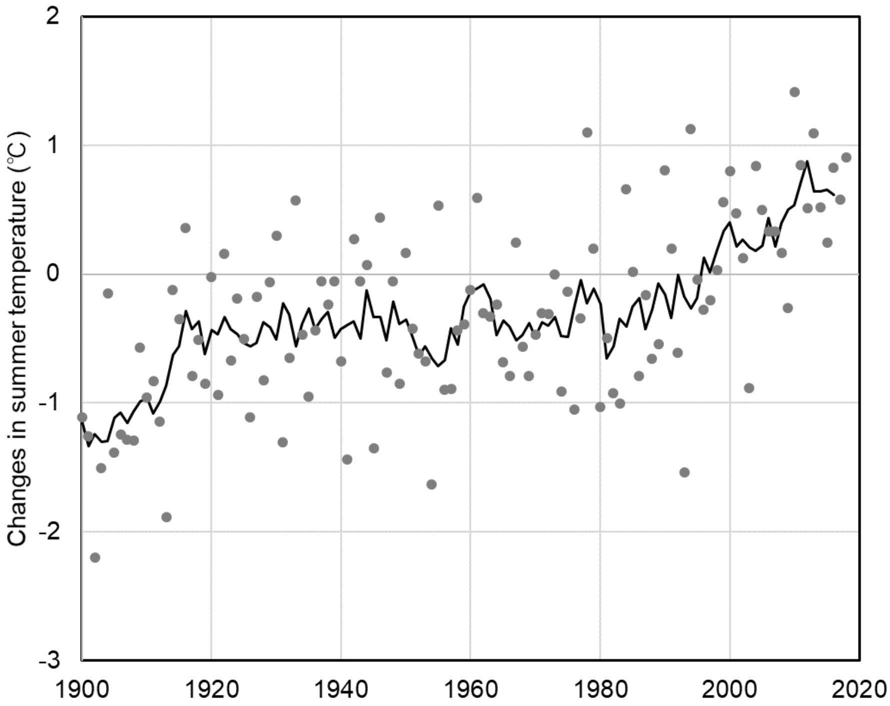

Fig. 1. Time-series change in the mean summer temperature (June–August). The values represent the difference from the average for the period 1971–2000. The curve represents the 5-year moving average. Data were obtained from the website of the Japan Meteorological Agency (https://www.data.jma.go.jp/cpdinfo/temp/list/mon_jpn.html).

In this situation, especially since the 1990s, the warming trends have already significantly affected nearly all types of crops in Japan (Sugiura *et al.*, 2012). In the case of rice, the decrease in quality caused by the high temperatures is extremely serious. Particularly in the Kyushu region, the decline in the proportion of first-grade rice since 2000 has been remarkable. The grade of rice quality is based on the percentage of undamaged grains; therefore, the increasing frequency of white immature grains or spotted grains causes a decrease in the grade of rice quality. The main cause of white immature grains (chalky grains) is considered to be high temperature during the early ripening period; the frequency of immature grains increases when the average temperature within 20 days after the heading date is more than 26~27°C (Morita *et al.*, 2016). In 2010, the average summer temperature was the highest historically, with high-temperature injuries occurring in rice crops throughout the country. In particular, the impact on the quality of rice grain has been severe; in most regions with the exception of Hokkaido, a decrease in the proportion of first-grade rice has been observed, especially in

Niigata Prefecture, Gunma Prefecture, and Saitama Prefecture, where the lowest level of rice quality in the past 30 years was recorded. As the decline in quality leads to a decrease in farmers' income, it is necessary to mitigate these detrimental effects as soon as possible.

With respect to the effect of high temperature on rice yield, the decrease in rice yield is caused by the increase in spikelet sterility as a result of fertilization failure at very high temperatures during the flowering period ("high-temperature sterility"), and by the decrease in the length of the growth period from transplanting to maturity by the acceleration of crop growth at high temperatures, resulting in a reduction in biomass accumulation as cumulative photosynthesis decreases. As for the high-temperature sterility, the National Institute for Agro-Environmental Sciences, and the Institute of Crop Science, National Agriculture and Food Research Organization, have investigated the rice crop damage caused by the very high temperatures in 2007 in the Kanto and Tokai regions. The results showed that spikelet sterility tended to be found largely in paddy fields which were exposed to high temperatures at the times of heading and flowering (Hasegawa *et al.*, 2009). So far, the large-scale decrease in rice yield caused by high temperature, which appears clearly in statistical literature, has not occurred in Japan. However, there is a possibility that the decrease in rice yield due to the high-temperature sterility will emerge as global warming progresses.

LARGE-SCALE IMPACT ASSESSMENT AND ADAPTATION MEASURES

Rice is the most important cereal crop in Japan, so that the impact of projected climate change on rice productivity has attracted much attention. Therefore, impact assessment studies on rice have been carried out at the regional or national scale in many previous studies. Here we introduce a case study with respect to the impact assessment on Japanese rice production and quality under the projected climate conditions (Ishigooka *et al.*, 2017), with this study examining the effects of moving the transplanting date as an adaptation measure for preventing the high-temperature impacts on either yield or quality. We outline the research process and present some major results from this study; please refer to the original paper (Ishigooka *et al.*, 2017) for more details.

As an impact assessment model, a process-based model that allows the identification of individual impact factors and the setting of adaptation options is appropriate to evaluate not only the climate impact but also the effects of adaptation. In this study, we employed the Hasegawa–Horie model, a process-based rice simulation model for estimating rice phenological development and yield developed by Hasegawa and Horie (1997) and modified by Fukui *et al.* (2015) and Yoshida *et al.* (2015). This model consists mainly of the growth process and the photosynthetic process; the former calculates the developmental stage (panicle formation period, heading period, maturity period, etc.), while the latter calculates the amount of biomass (dry matter production) by the net assimilation product formation process (the balance between carbon fixation by photosynthesis and respiratory consumption). In the photosynthetic process, the biomass increase due to the CO_2 fertilization effect is also taken into account.

The model was implemented based on the “second-order mesh,” which had been standardized by the Japanese Industrial Standards and defined as a resolution of 5′ latitude by 7.5′ longitude (approximately 10 km × 10 km). Japan as a whole is covered by about 4700 grids. The evaluation period was 120 years from 1981 to 2100, and the climate change scenarios as inputs (daily) were obtained from six global climate models (GCMs) with three greenhouse gas emission scenarios (Representative Concentration Pathways; RCPs) (18 scenarios in total). To clarify the effect of moving the cropping calendar as an adaptation measure to reduce the negative impact of climate change on rice production and quality, the transplanting date in 2006 was considered to be the standard, being assigned to each mesh from the statistical data and was moved at 7-d intervals within the range of–70 to +70 days from the standard transplanting date as the starting point. The purpose of this study was to clarify the effect of moving only the transplanting date as an adaptation measure under the climate change conditions, so that the other conditions, such as the cultivars planted, the fertilizer application strategies, etc., were fixed under the current conditions.

We used the heat index (HD_m26: cumulative temperature above 26°C during the 20 days after the heading date) as the indicator of the risk of rice quality decrease due to high temperatures, based on the fact that there was a qualitative relationship between HD_m26 and the proportion of first-grade rice at the prefecture level, independent of cultivar (Ishigooka *et al.*, 2011). Here, referring to the relationship between the HD_m26 value summarized in each prefecture and the proportion of first-grade rice, it was decided to show the degree of risk by the following criteria:

0°C·days ≤ HD_m26 < 20°C·days: Low risk of heat-induced quality decrease (Class A)
20°C·days ≤ HD_m26 < 40°C·days: Middle risk of heat-induced quality decrease (Class B)
40°C·days ≤ HD_m26: High risk of heat-induced quality decrease (Class C)

By this standard, the calculated yield in each year was classified into three classes and an average value was calculated every 20 years. In other words, the average yield and the constituent ratio of each classification representing the risk of quality decrease due to high temperature for every 20-year period were calculated for each calculation unit (i.e., approximately 10 km × 10 km mesh). Based on these values, the optimal transplanting date was determined according to the following two adaptation types by moving the transplanting date for each 20-year period: the transplanting date was moved to maximize the 20-year average of total yield (adaptation 1: yield-oriented type), or the transplanting date was moved to maximize the 20-year average of Class A yield (adaptation 2: quality-oriented type).

Here, we show the yield estimation result based on HadGEM2-ES (a climate model) with RCP8.5 (a greenhouse gas emission scenario), which estimates a relatively large temperature increase as that the average temperature at the end of the 21st century increases by 5.3°C on the nationwide average compared to the end of 20th century, as an example of the simulation result by “no-adaptation.” Fig. 2 shows the distribution map of the percentage of the 20-year total yield average (2081–2100) relative to that in the baseline period (1981–2000). While the yield increases from northern Japan to the central mountainous region as a whole, there is no significant change in the west from Kanto or Hokuriku, and the decrease is observed in some inland basins and plains in south-central Japan. In the projection of future environmental conditions (the temperature increase and the CO_2 concentration elevation), the yield is increased by the CO_2 fertilizer effect and by the decrease in cold damage, while the yield is decreased by the shortening of the growth period and by the increase in spikelet sterility as the temperature increases. In the model, the yield is calculated as the balance of these factors. In the case of this example, the total increased-yield effects of CO_2 fertilization and decreased cold damage is significantly greater than the decreased-yield effects of shortened growing period, resulting in large yield increases in northern Japan, while the CO_2 fertilization effect seems to be cancelled out by the shortening in growing period, so that significant yield changes are not observed in many regions in the west from Kanto, with significant declines in yield being observed in some plains as a result of increased occurrence of spikelet sterility due to the high temperatures.

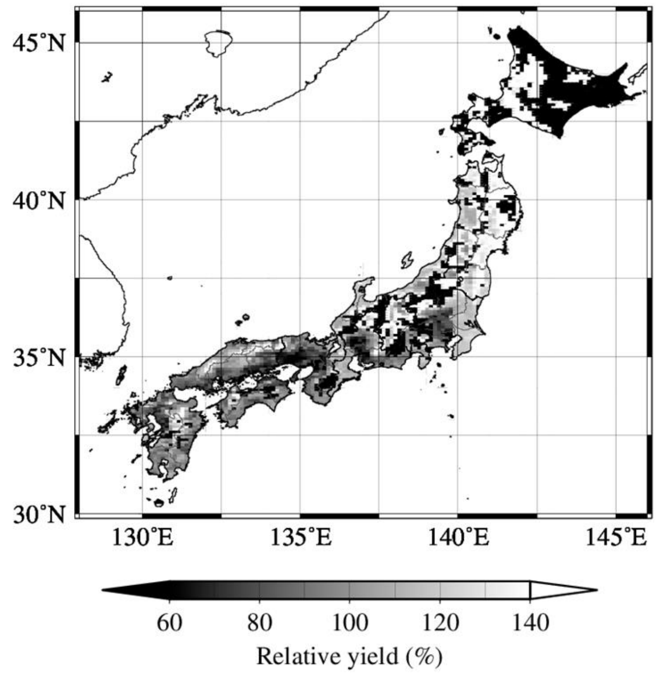

Fig. 2. Distribution maps of the percentage of the 20-year average of the total yield in 2081–2100 relative to that in the baseline period (1981–2000) based on HadGEM2-ES with RCP8.5 by "no-adaptation." Black areas indicate the areas where paddy fields do not exist (from Ishigooka *et al.*, 2017).

The total rice production was estimated by aggregating the yield calculated in each grid weighted by the percentage of paddy area in each grid in the whole country. The time-series change in total production and the components of each class for every 20-year period based on HadGEM2-ES with RCP8.5 is shown in Fig. 3. Here, the total production of each 20-year period is classified into Class A ~ C by different color according to the value of HD_m26. The total production increased throughout the former half of the period, while it declined slightly in the latter half of the period. On the other hand, the proportion classified into quality Class B or C increased continuously throughout the period, and the majority of all rice production was composed of Class C by the latter half of the period. In other words, most of the production will possibly be occupied by low-quality rice in some climate scenarios without introducing any adaptation measures, although the total rice production of the entire country is sufficiently secure.

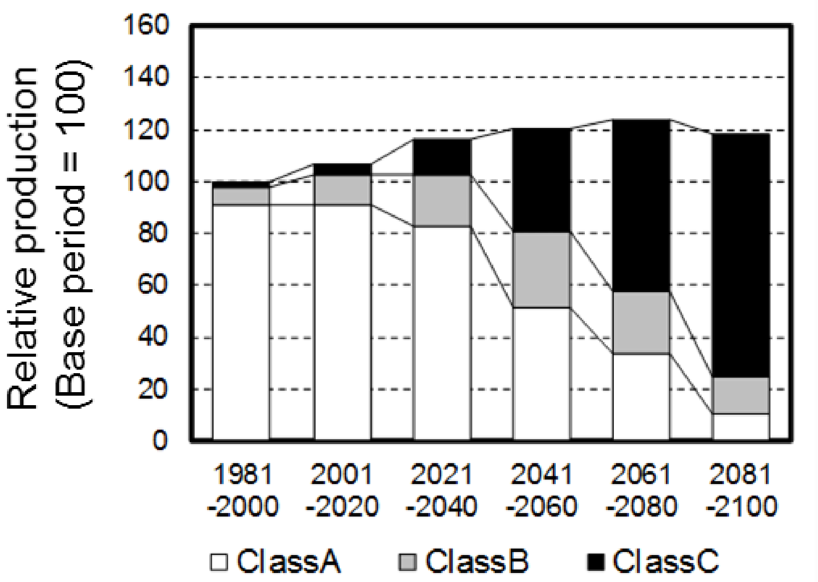

Fig. 3. Time series of changes in total rice production and components in each quality class based on HadGEM2-ES with RCP8.5 by "no-adaptation." Production levels are expressed as the percentage of those at the baseline (1981–2000) (from Ishigooka *et al.*, 2017).

Then, in order to evaluate the effect of the moving the transplanting date as an adaptation, the optimum transplanting date was selected for each mesh by every 20-year period, according to adaptation 1 (yield-oriented) or adaptation 2 (quality-oriented). In the above case, the total nationwide production and the percentage of the grain in each class were summarized. As an example, in the case of adaptation 2, based on HadGEM2-ES with RCP8.5, the distribution map of the percentage of the 20-year average for total yield (2081–2100) relative to that in the baseline period (1981–2000) is shown in Fig. 4, while the time-series change in the total production and quality components in each class by every 20-year period is shown in Fig. 5. As shown in Fig. 5, no marked increase or decrease in total production was found throughout the entire period, with no increased risk of quality loss, indicating that the predicted negative effects of temperature increase on both yield and quality can be avoided by selecting the appropriate transplanting date at the national level. However, it can also be seen that rice yield will be greatly reduced in some regions (Fig. 4), suggesting that it seems to be difficult to avoid the negative impact of increasing temperatures simply by moving the transplanting date in such regions. This is considered to be partly due to the narrow width of the selectable transplanting date as a result of the climatic restrictions. If, for example, a late transplanting date is required to avoid high temperatures, the crop will be unable to intercept sufficient solar radiation in the shortened ripening period by moving the transplanting date to after the autumn, causing a yield reduction. In such cases, it will be difficult to reduce the impact of the increased temperatures by only moving the transplanting date, but it will be necessary to consider the application of other adaptive technology options, such as the introduction of cultivars having different heading dates and of cultivars tolerant to high-temperature stress.

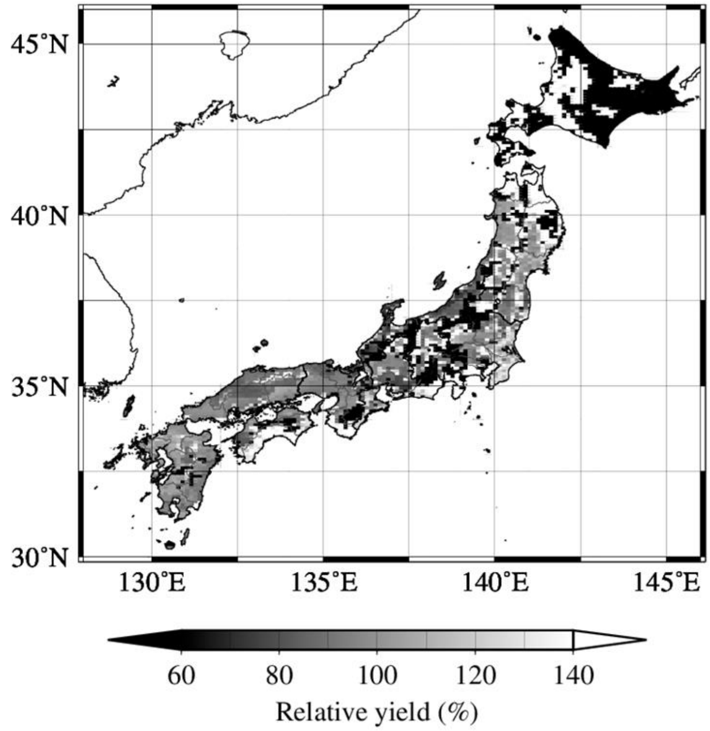

Fig. 4. Distribution maps of the percentage of the 20-year average of total yield in 2081–2100 relative to that in the baseline period (1981–2000) based on HadGEM2-ES with RCP8.5 by "adaptation 2." Black areas indicate the areas where paddy fields do not exist (from Ishigooka *et al.*, 2017).

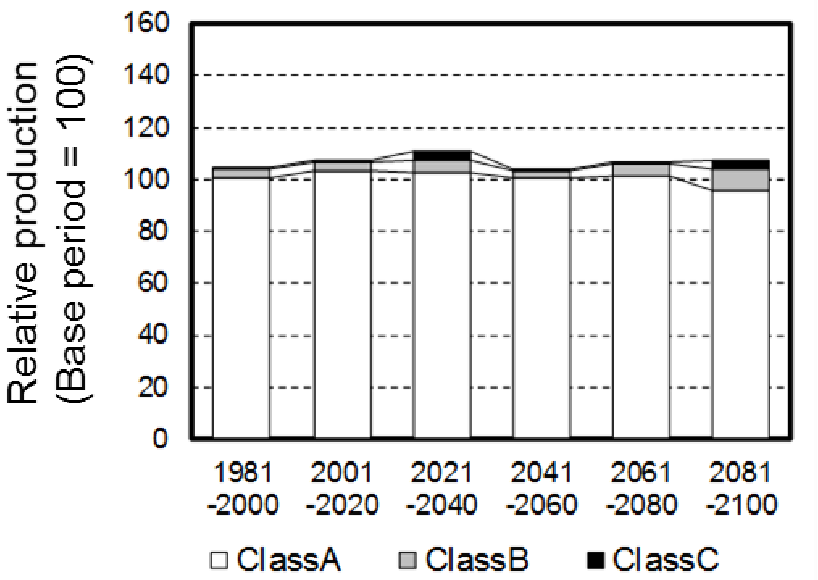

Fig. 5. Time series of changes in total rice production and components of each quality class based on HadGEM2-ES with RCP8.5 by "adaptation 2." Production levels are expressed as percentage of the baseline production (1981–2000) (from Ishigooka *et al.*, 2017).

CONCLUSION

In this study, we illustrate the impact assessment and the effects of the introduction of adaptation measures based on only one climate scenario, but there is considerable width for each scenario in the future climate projection, and it is essential to take into account the uncertainty of climate projections. In the examples presented here, we used 18 climatic scenarios, each of them had been given different output results. However, it was observed that the regional distribution of rice yield and the time-series change in total production were relatively similar. On the other hand, the difference between the climatic scenarios was large in terms of the rice quality, and it can be said that the uncertainty is large at the present stage.

In addition to the uncertainties in climate projection, there are uncertainties inherent in the impact assessment model. Therefore, it is important to present the evaluation results that can be interpreted as multiple simulation results in a stochastic manner. Additionally, the effort to reduce the uncertainty of the impact assessment model itself is also important. As for the rice growth model, the uncertainty of the estimation result can be clarified by advancing the elucidation of the environmental response mechanism in each process and by reflecting the acquired knowledge into the model. In particular, in the case of impact assessment under future projected environmental conditions, it is important to clarify the interactive influences of high temperature and elevated CO_2 level.

In considering the implementation of adaptation measures in response to predicted global warming, it is not enough to develop adaptive technologies for individual phenomena, but it is essential to consider indirect impacts such as the combined effects of each impact and the costs associated with implementing adaptation measures and other risks that may arise. In the case of introducing the change in the transplanting date as the adaptation measure in rice cultivation, it can be said that it is a relatively low-cost adaptation, but actually in some cases it is difficult to move the transplanting period significantly due to irrigation practices or from the viewpoint of securing labor. It should also be considered that the late transplanting date will possibly lead to water resource scarcity at the puddling stage, interaction with the typhoon period, and other risks such as changes in agricultural ecosystems and pests.

REFERENCES

Fukui, S., Y. Ishigooka, T. Kuwagata, and T. Hasegawa. 2015. A methodology for estimating phenological parameters of rice cultivars utilizing data from common variety trials. *Journal of Agricultural Meteorology* 71(2): 77–89.

Hasegawa, T. and T. Horie. 1997. Modelling the effect of nitrogen on rice growth and development. In *Applications of systems approaches at the field level.* (ed. by Kropff MJ, Teng PS, Aggarwal PK, Bouma J, Bouman BAM, Jones JW, van Laar HH). Kluwer, Dordrecht, pp. 243–257.

Hasegawa, T., M. Yoshimoto, T. Kuwagata, Y. Ishigooka, M. Kondo, and T. Ishimaru. 2009. A study on the high temperature sterility of rice plants in summer 2007. *Agriculture and Horticulture* 84(1): 42–45. (in Japanese).

Ishigooka, Y., T. Kuwagata, M. Nishimori, T. Hasegawa, and H. Ohno. 2011. Spatial characterization of recent hot summers in Japan with agro-climatic indices related to rice production. *Journal of Agricultural Meteorology* 67(4): 209–224.

Ishigooka, Y., F. Fukui, T. Hasegawa, T. Kuwagata, M. Nishimori, and M. Kondo. 2017. Large-scale evaluation of the effects of adaptation to climate change by shifting transplanting date on rice production and quality in Japan. *Journal of Agricultural Meteorology* 73(4): 156–173.

Morita, S., H. Wada, and Y. Matsue. 2016. Countermeasures for heat damage in rice grain quality under climate change. *Plant Production Science* 19(1): 1–11.

Sugiura. T., H. Sumida, S. Yokoyama, and H. Ono. 2012. Overview of recent effects of global warming on agricultural production in Japan. *JARQ*

46(1): 7–13.

Yoshida, R., S. Fukui, T. Shimada, T. Hasegawa, Y. Ishigooka, I. Takayabu, and T. Iwasaki. 2015. Adaptation of rice to climate change through a cultivar-based simulation: a possible cultivar shift in eastern Japan. *Climate Research* 64: 275–290.