Recent Warming Trends and Rice Growth and Yield in Japan

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Abstract: Climate change will affect various aspects of rice production. Both gradual changes in mean temperature and CO_2 concentration will likely change the potential productivity of the regions determined by available climatic resources. Increases in extreme events such as heat or dry spells will be a serious concern for growers and may become a source of vulnerability of the crop production system. There is an urgent need for assessment of the climate change impacts on crop production at the field and regional scale, but no single method can give us an overall picture of the impacts. We need to combine knowledge obtained from different methods and at different temporal and spatial scales to understand the likely impacts of climate change. Analysis of the past climatic variation on crop growth and yield is one of the key areas of the study, which help to estimate the potential impacts of climate change on crop production. In this paper, we firstly examine the recent temperature and yield trends at widely different geographical sites all over Japan. Secondly, we present results of the field survey we conducted in an extremely hot summer of 2007. Climate records obtained at different climatic and geographic zones in Japan since 1980 clearly suggested a strong warming trend typically between 1 and 2 °C per quarter century. The rate of temperature rise is generally more pronounced in the western part than in the north. The trend is not just a result of global warming caused by greenhouse gases, but may involve a periodic temperature fluctuation and urbanization effects. Nevertheless, the temperature increases have already been influencing rice growth. A preliminary analysis of long-term field trials indicates that days to heading become shorter by a nearly 1 week for the past 25 years. Up to present, no significant change in grain yield has occurred in both experimental station records and regional yield statistics. The percentage of the first-grade rice kernel (quality in terms of grain appearances) in the western part of Japan showed a declining trend. A number of factors are involved in this, but the recent warming trend can be considered as a triggering factor of the trend. The field survey on spikelet sterility in the hot summer of 2007 showed that extreme heat in mid summer can induce sterility in the open field conditions, but to a lesser extent than what was predicted from the previous chamber results. The lesson from the survey is that air temperature per se is not sufficient to predict the occurrence of heat-induced sterility, but factors influencing the heat budget of the panicles are needed to account for the crop damages under open field conditions. Systems understandings of the impacts of climate change on rice production are needed to effectively and efficiently develop adaptation measures to climate change.
Keywords: Climate change, Extremely hot summer, Grain quality, Grain yield, Phenology, Rice, Warming trends

1. Introduction

Predicted levels of global warming will have a marked effect on the growth, yield, and quality of the crop. Both positive and negative effects of climate change are expected: Increasing atmospheric CO_2 concentration will have a positive influence on crop growth and yield via promoting photosynthesis and reducing the water use due to reduced stomatal conductance. Increases in temperature may reduce the low temperature limitations on growth particularly in high-latitude and/or high altitude regions, but will shorten crop life cycle and increase occurrences of heat stress and water use. These counteracting effects will determine the magnitude and even the direction of the impacts of climate change.

A number of experiments and simulations have been conducted to determine or predict the likely impacts of climate change on yields of major crops, including rice (*Oryza sativa.* L), the most important food crop in Asia. A summary of these simulation results by the Intergovernmental Panel of Climate Change [1] indicated that the effects of climate change on crop yields will be different depending on the region or the current level of temperature. In low-latitude regions, crop yields may drop even with a 1 °C increase in air temperature from the current level. In mid-high latitude regions, negative effects of climate change may appear where air temperature rises by 3 °C or more.

However, these predictions include large uncertainties not just in a magnitude but in the direction of the impacts. The uncertainties in the predictions resulted from a number of sources, such as those in the carbon emission scenarios, global climate models (GCM) and gaps between global and local climates. Options in land use, crops, varieties and management practices may also make climate change impacts very different. In addition, crop models themselves contain uncertainties. Many of the crop models were developed based on small-scale experiments typically those conducted in environmental controlled chambers. While these experimental results are highly valuable in understanding the mechanisms of crop responses to the environmental changes, extrapolating to the field or regional conditions under variable climatic conditions creates another major source of uncertainties in the prediction of the future crop production.

Testing the climate change impacts on crop production at the field or regional scale is still difficult and no single method can give us an overall picture of the impacts. We need to combine knowledge obtained from different methods and at different temporal and spatial scales to understand the likely impacts of climate change. Analysis of the past climatic variation on crop growth and yield is one of the key areas of the study, which help to estimate the potential impacts of climate change on crop production.

During the past 100 years, there was a significant increase in the global surface temperature by 0.74 °C per century, and the rate of increase is accelerating [2]. The rate of the increase depends on local conditions of the regions. Detailed analysis is needed to interpret the changes in recent climate record. Japan extends more than 3000 km from south to north (from 20° to 46 °N) and has various climatic zones. According to Japan Meteorological Agency Report 2008 [3], annual mean temperature averaged for the 17 meteorological stations in Japan has increased at a rate of 1.11 °C per century over the period of 1898 and 2008. Particularly, the rate of temperature increase became more pronounced since 1980. The higher-than-global-average increase in Japan's annual temperature increase resulted not only from global warming caused by greenhouse gases, but also from a periodic temperature fluctuation. In addition, the observations at the 17 meteorological stations were not free from the effects of urbanization, although they were carefully selected to minimize them. The mechanisms underlying this warming trend are thus complex, but nevertheless, analysis of the effects of these changes on crop production will be an opportunity to detect any sign of the effects of warming on a real farm or regional scale.

In addition to the gradual temperature increases, occurrences of extreme heat events will likely increase as a result of global warming. Excessive heat, even if it is a short spell, might reduce yields of crops due to failure of reproductive growth, but the effects of such events have not been well accounted for by many crop models, so that we cannot assess the negative effect of rising temperature properly: This is one of the major uncertainties about the future yield prediction. Rice is highly adaptive to a range of environments, previous chamber experiments have shown that rice is also highly susceptible to heat [4, 5]. According to their studies, flowering is the most sensitive stage and heat-induced spikelet sterility (HISS) is the major reason for the yield loss. The threshold temperature for HISS was around 35 ºC at the time of flowering, which has already been reported even under current climates. The yield loss due to HISS, however, has not been well documented in the rice industry. Filling the gap between chambers and open-field is an important task for researchers working in the field of crop physiology and agricultural micrometeorology.

During the summer of 2007, many areas in the Kanto and Tokai regions of Japan experienced abnormal heat. In some areas, the daily maximum temperatures exceeded 40 ºC. Such abnormally high temperatures can cause HISS which has not yet been reported in Japan. To better understand the potential risk of crop failure and the possible impacts of future global warming on rice cultivation, we needed to determine the degree of crop damage in the open fields during the hot summer of 2007.

In this paper, we firstly examined the recent temperature and yield trends at widely different geographical sites all over Japan. Secondly, we present an outline of the results of the field survey we conducted in five prefectures in Kanto and Tokai regions.

2. Trends in temperature and yield analyses

1) Database for the analyses

To analyze trends in climate and rice production in various climatic and geographical zones in Japan, we used a database, called MeteoCrop developed for an analysis of the past climate variability and its association with crop growth and yield [6]. The MeteoCrop database contains daily meteorological data since 1980 obtained from Automated Meteorological Data Acquisition System (AMeDAS) stations (about 850 sites) and for 1961 to 2007 from surface meteorological stations (156 sites) (Outlined in Fig. 1. Currently, a Japanese version of the Web site is available at http://meteocrop.dc.affrc.go.jp/). These stations cover the whole of Japan and are the main components of the observation network of the Japan Meteorological Agency (JMA). The database includes some specific agro-meteorological elements (solar radiation, humidity, downward longwave radiation, FAO-56 reference evapotranspiration, and potential evaporation) in addition to basic elements such as air temperature, wind speed, and precipitation. For the specific agro-meteorological elements that are not observed at AMeDAS stations, MeteoCrop estimates them at each AMeDAS station from measured sunshine duration and the data at neighboring surface meteorological stations. Meteorological data at any AMeDAS (or surface meteorological) station, which are formatted as MS Excel 2003 (or CSV text) files, can be downloaded easily by selecting the point representing the station on Google Earth. In MeteoCrop, a micro-meteorological model of crop canopy and a simple rice growth model are coupled with the meteorological data. By applying these two models to the meteorological data at any stations we can evaluate the daily mean water temperature in a rice paddy during the growth period, the diurnal variation in rice panicle temperature during the flowering period [7], and the growth stage (heading date) and evolution of leaf area index in the main rice cultivar, Koshihikari. Performance of each model was tested at several experimental sites.

Grain yield data were obtained from “Statistics on Crop and Statistics on Cultivated Land and Planted Area”, Statistics Department, Minister's Secretariat, Ministry of Agriculture, Forestry and Fisheries, MAFF. The data for rice kernel grading were from the Rice Kernel Inspection by the Staple Food Department, General Food Policy, MAFF. Fertilizer nitrogen input was estimated from the “Cost of Rice Production” by Statistics Department, Minister's Secretariat, Ministry of Agriculture, Forestry and Fisheries, MAFF. Additionally, a long-term growth data were from the database for the Performance Test for Recommendable Rice Varieties compiled by the National Institute of Crop Science, National Agricultural Research Organization.

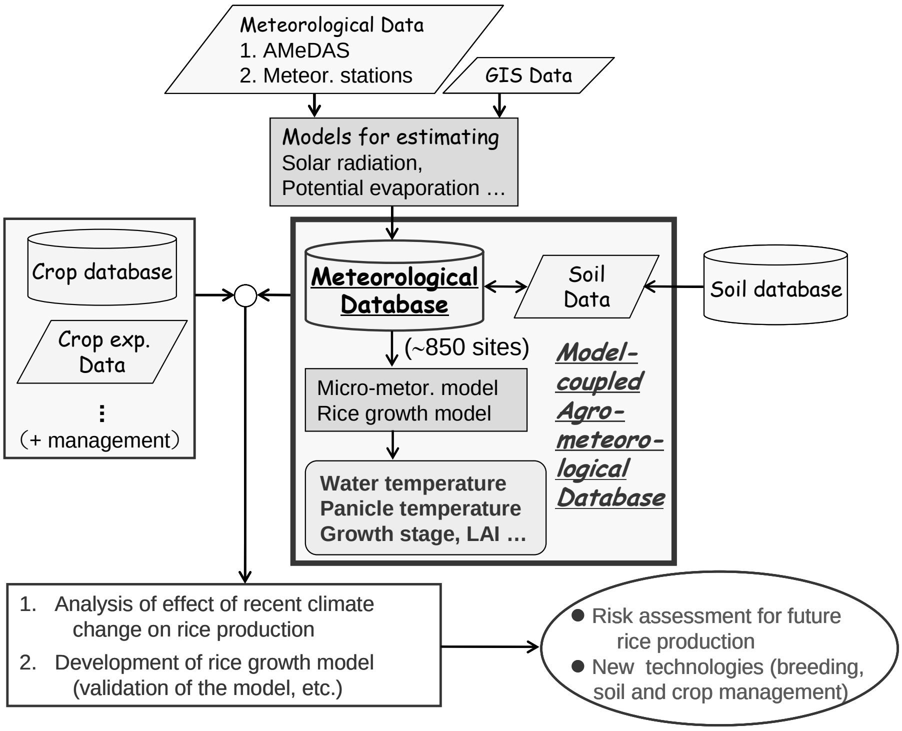

Fig.1. Structure of the model-coupled agro-meteorological database (MeteoCrop). The main body of the database is the yellow box enclosed by the red line. LAI: leaf area index. Adopted from Kuwagata et al [6]

2) Changes in air temperature since 1980

Amongst about 850 AMeDAS observation sites, we have selected 65 sites covering important climatic and geographic zones in Japan, but with modest urbanization effects. At each site, we calculated trends in both maximum and minimum temperatures for the period between 1980 and 2007 by regressing temperatures on years: the regression slopes were used to represent a degree of change for the period studied (Fig. 2).

Overall, there were significant increases in both daily maximum and minimum temperatures averaged over the year, but the rate of increase in air temperatures was not uniform across the regions. Increases were generally greater in the western regions than in the northern region. The relatively small increase in air temperature in the north is in agreement with those reported by Sameshima et al [8] and Nishimori et al [9], who analyzed the long-term meteorological observations with a small urbanization effect. The rate of temperature increase was more pronounced in the daily maximum than in the daily minimum particularly in the western regions. These results seem somewhat different from the observations or predictions on a global scale, where the increase in minimum temperature was greater than in the maximum for the last 100 years [2] and a larger increase is expected in the higher latitudes compared to the lower latitudes. Analysis is still ongoing to determine the seasonal patterns of the temperature trends and their relation with meteorological disturbances over the past years, which will help to identify these reasons. What is evident at this moment is that Japan has experienced a substantial increase in both daily minimum and maximum temperatures, and the typical increase was between 1 and 2°C only for just about a quarter century.

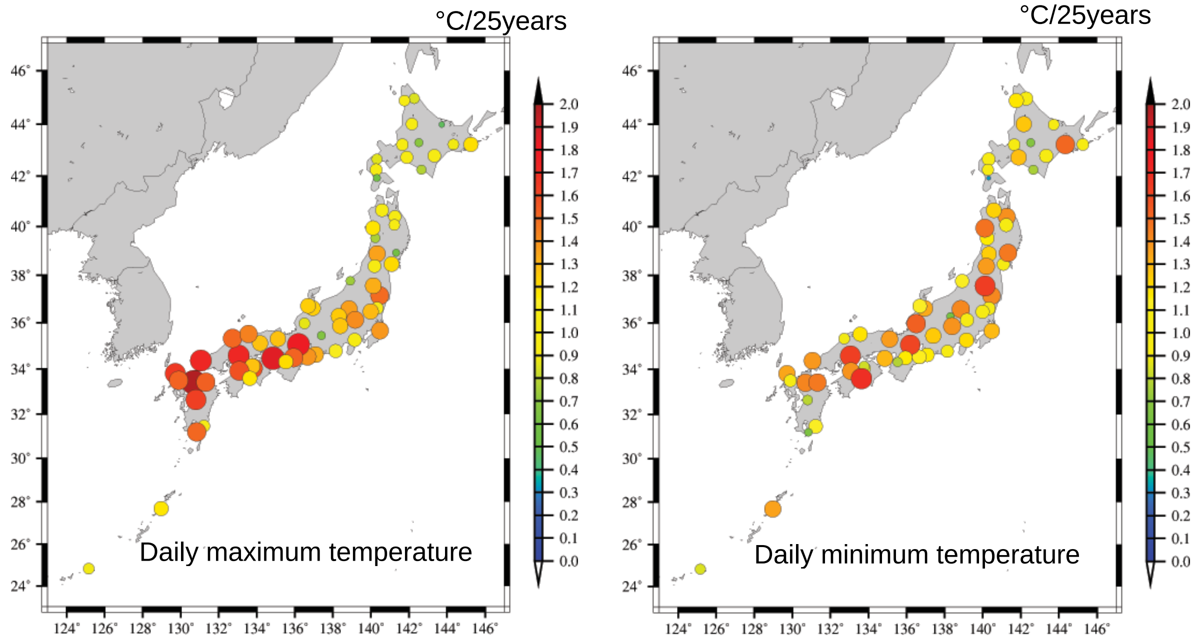

Fig.2. Distribution of the rate of increase in daily maximum temperature and minimum temperature recorded at 65 sites in Japan during the 1980-2007 period.

3) Trends in rice yield

The national rice yield in Japan has increased substantially from 2.2 t/ha (brown rice) in the last decade of the 19th century to 5.0 t/ha in that of the 20th century. The rate of increase has slowed since 1970's, when the supply met/exceeded demand. Two examples of the rice yield progress from 1961 to 2008 in the north (Tohoku Region) and in the west (Kyushu Region) indicated that the yield level has been higher in Tohoku than in Kyushu for this period (Fig. 3) but that the pattern of the change was similar: Grain yield has leveled off since around 1980 like in the national average. For this period, we have seen a substantial change in production technology, the major one being nitrogen fertilizer input. During the 1961-80 period, nitrogen fertilizer input had steadily increased, but during the1981-2000 period, on the other hand, there was a significant and consistent decrease in nitrogen use. The decrease in this period was greater than the increase in the 1961-1980 period, so that the current level of input was smaller than that in 1960. Despite the increase in temperature and the decrease in nitrogen input, we have not observed a change in the yield levels. Grain yield per unit fertilizer N input had been stable before 1990, but then markedly increased (Fig. 4). Interestingly, there was no major difference in this parameter between two regions. Therefore, we have not been able to detect negative signs of the recent warming trends on the grain yield and grain production efficiency at this point.

The percentage of kernels qualified as the 1st grade (the first grade rice %, hereafter) decreased to around 30 % for the recent 5 years in Kyushu Regions, while no major trend exists in Tohoku Regions. The first grade rice % reflects difference in grain appearance, which is often degraded by the occurrence of chalk and cracks of kernels. Occurrence of chalk and cracks involves a number of processes, which can be moderated by environmental and genotypic factors, so interpretation of the decline in the first grade rice % in observed in Kyushu region was complex. However, because high temperature during the grain filling period is well known to induce chalk and cracks [10, 11, 12], the recent warming trend can be considered as a triggering factor of the trend.

While statistical grain yield and quality data represent the changes occurring on a regional scale, these changes can be associated with those in cultivars and management practices in addition to those in climates. To detect the effects of change in climate on rice growth on a field scale, long-term field trials are useful. We have started a study utilizing the existing experimental data collected at the experimental stations covering a range of environmental conditions all over Japan. A preliminary analysis of the long-term growth and yield trials from eight experimental stations indicates that there was a significant reduction in the days to heading of the major variety at respective sites. Averaged across eight stations, days to heading became shorter by nearly 7 days during the 25-years period. The number of tested varieties is still small, but the reduction in days to heading was generally larger in the northern sites than in the south and western sites: this trend is opposite to the spatial distribution of the increase in temperat ure. Despite the significant change in growth duration, grain yield showed no significant change. This agrees with the observations in the regional yield levels being unchanged with recent warming. We are currently running phenology and growth models to test how much of these changes can be accounted for by the change in climate.

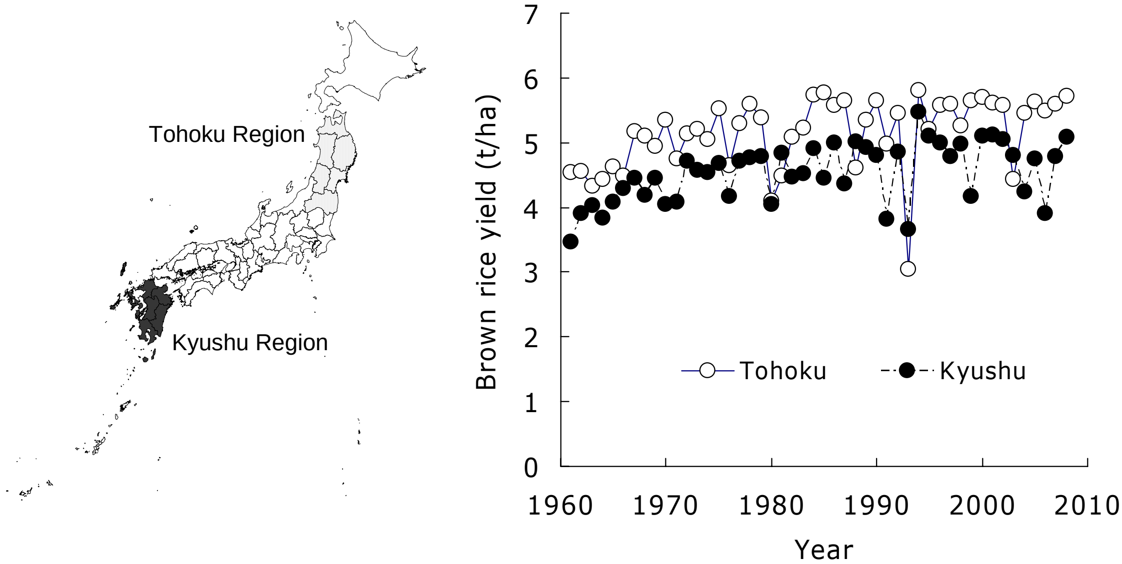

Fig.3. Changes in grown rice in two different regions in Japan during the 1961-2008 period. Data were from "Statistics on Crop and Statistics on Cultivated Land and Planted Area", Statistics Department, Minister's Secretariat, Ministry of Agriculture, Forestry and Fisheries, MAFF.

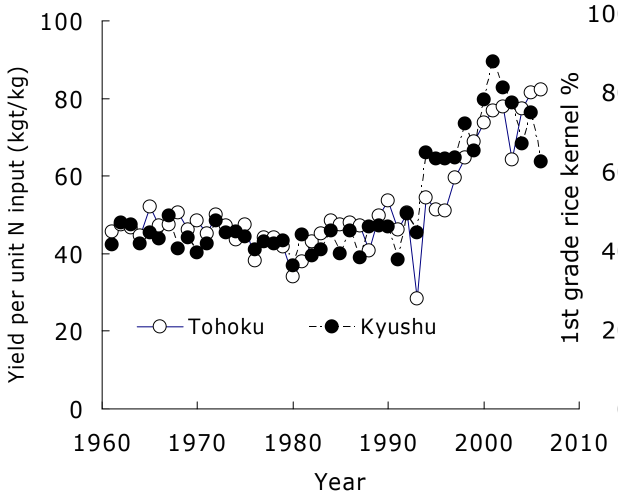

Fig.4. Changes in grain yield per unit fertilizer N input in Tohoku and Kyushu regions during the 1961-2008 period. The fertilizer N input was estimated from the Report of Statistical Survey on Farm Management and Economy (Production Cost of Rice) by Statistics Department, Minister's Secretariat, Ministry of Agriculture, Forestry and Fisheries, MAFF.

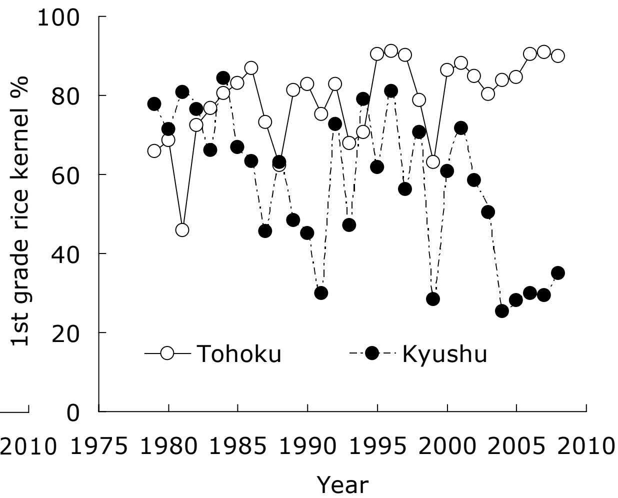

Fig.5. Changes in % of rice kernels qualified as the 1st grade in Tohoku and Kyushu regions during the 1961-2008 period. The grade inspection data were from the Staple Food Department, MAFF.

3. Lessons from spikelet sterility observed under the record hot summer of 2007

During the summer of 2007, many areas in the Kanto and Tokai regions of Japan experienced abnormal heat, with, for example, an unprecedented 40.9°C being recorded in August in Kumagaya of Saitama Prefecture and Tajimi of Gifu Prefecture. We collected panicle samples from 132 paddy fields located in five prefectures (Gunma, Saitama, Ibaraki, Gifu, and Aichi) where heading and flowering occurred between late July and late August to examine the occurrence of HISS. We did a similar survey in 2008, a year without climatic episodic events, to determine the reference level of sterility without heat damages.

Examination of data recorded at the government meteorological stations and AMeDAS points near the studied paddy fields revealed that more than 40% of the paddy fields experienced maximum temperatures of over 35°C around the time of flowering. About 20% of the paddy fields investigated showed sterility rates of over 10%. In a reference year (2008), on the other hand, sterility percentage was mostly less than 5 % (Fig. 6), indicating that sterility occurred in an extremely hot summer of 2007.

To examine in more detail about the relation between timing of the heat event and sterility in 2007, we collected panicle samples from 34 experimental plots at the NIAES paddy field, which differed widely in flowering dates depending on the plots, and measured the spikelet sterility. Sterility was below 10% in the plots where flowering occurred before August 10 and on August 20; the daily maximum temperatures were relatively low. A sterility rate as high as 23 % was observed in the plots where flowering occurred around the date when the maximum temperature of 38.6°C was recorded (Fig. 7). However, even in the plots where flowering occurred around the hottest day, sterility rates varied widely between 10% to 23% depending on the variety and management of the crop. This suggests that technical options may be available to reduce the adverse impacts of high temperature.

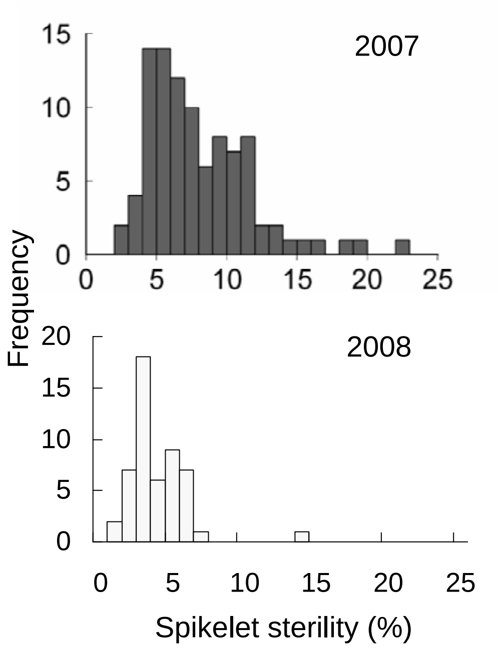

Fig.6. Frequency distributions of percentage of sterile spikelets collected from Kanto and Tokai regions in a hot summer of 2007 and a normal summer of 2008. Modified from Hasegawa et al [13].

Sterility rates of the same cultivar obtained from different prefectures tended to increase as temperature around flowering rose, but even where temperatures reached 38°C, sterility at some sites was not noticeably high (Data not shown). Previously, chamber experiments showed that sterility increases almost linearly with temperatures above 35°C at the time of flowering to reach almost 100% at 40°C or higher, but the sterility rates observed in paddy fields in 2007 were lower than those that could be expected from the response to increased temperature in the previous chamber experiments.

One possible explanation for the fact that the actual sterility rate during the high temperature period in 2007 was below the sterility rate that could be expected from the maximum recorded temperature is that the temperature of the panicle that is the sensitive organ differed from air temperature. In fact, spatial distribution of the panicle temperatures estimated using a heat balance model [5] during the hours of rice flowering (10:00 - 12:00) does not necessarily match daily maximum temperature distribution (Data not shown). This is because, in addition to the temperature during flowering hours being lower than daily maximum temperature, other meteorological factors such as solar radiation, wind speed and humidity also affect ear temperature. The correlation between panicle temperature and sterility was higher than the correlation between daily maximum temperature and sterility. The above factors can be major reasons why the sterility rate was lower than expected given the high maximum temperature. It is also worth noting that within the whole region, the area of rice exposed to

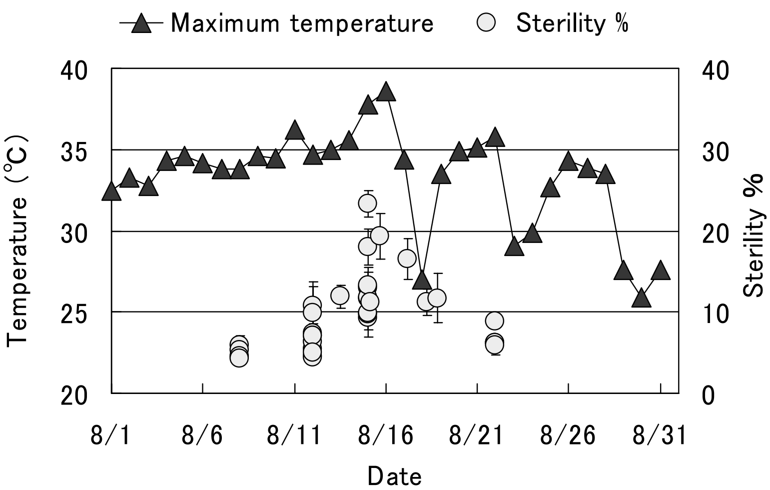

Fig.7. Daily maximum temperatures and sterility percentage sorted by flowering dates of NIAES experimental paddy field rice plants. Adopted from Hasegawa et al [13].

high temperatures during the flowering time was relatively small, and as a result, major yield losses due to heat-induced sterility did not occur.

To date, the impacts of future global warming on agriculture have been based on changes in air temperature, but this study demonstrates that impacts cannot be accurately assessed on the basis of changes in air temperature alone. In the case of the Kanto and Tokai regions in 2007, estimated panicle temperatures were not necessarily as high as air temperature. However, high humidity or windless conditions may cause panicle temperature to exceed air temperature. The risks of yield losses due to heat-induced sterility, therefore, need to account for the effect of panicle temperatures, which can vary depending on various micro-climatic conditions. It is also worth noting that there is a considerable variation in spikelet sterility under extreme heat conditions, depending on cultivars and management practices, suggesting the possibility of reducing the damage due to high temperature. We believe that understanding these mechanisms influencing the occurrence of sterility will help to contribute to the development of countermeasures against damage caused by high temperature events, which may occur more frequently in the future.

4. Conclusions

Climate records obtained at different climatic and geographic zones in Japan since 1980 clearly suggested a strong warming trend typically between 1 and 2 °C per quarter century. The rate of temperature rise is generally more pronounced in the western part than in the north. The trend is not just a result of global warming caused by greenhouse gases, but may involve a periodic temperature fluctuation and urbanization effects. Nevertheless, the temperature increases have already been influencing rice growth. A preliminary analysis of long-term field trials indicates that days to heading become shorter by a nearly 1 week for the past 25 years. Up to present, no significant change in grain yield has occurred in both experimental station records and regional yield statistics. The first-grade rice % (quality in terms of grain appearances) in the western part of Japan showed a declining trend. A number of factors are involved in this, but the recent warming trend can be considered as a triggering factor of the trend.

The field survey on spikelet sterility in the hot summer of 2007 showed that extreme heat in mid summer can induce sterility in the open field conditions, but to a lesser extent than what was predicted from the previous chamber results. The lesson from the survey is that air temperature per se is not sufficient to predict the occurrence of heat-induced sterility, but factors influencing the heat budget of the panicles are needed to account for the crop damages under open field conditions. Systems understandings of the impacts of climate change on rice production are needed to effectively and efficiently develop adaptation measures to climate change.

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