Relationship between recent trends in climate conditions and rice quality in the Southern Tohoku region

Hiroyuki MATSUDA*, †, Tsuyoshi HAYASAKA**, Takahiro KONTA***, Masumi ASANO****, Shizuka MORI***** Ho ANDO******, Hiroshi FUJI******, and Hiromitsu KANNO******

*Rice Breeding and Crop Science Experiment Station, Yamagata General Agricultural Research Center, 25 Yamanomae, Fujishima, Tsuruoka, Yamagata, 999–7601, Japan
**Agricultural Technique Improvement Research Office, Shonai Area General Branch Administration, Yamagata Prefectural Office, 51 Yamanomae, Fujishima, Tsuruoka, Yamagata, 999–7601, Japan
***Utilization Crop Research Division, Yamagata General Agricultural Research Center, 6060-27 Minorigaoka, Yamagata, Yamagata, 990–2372, Japan
****Utilization Crop Research Division, Furukawa Agricultural Research Center, 88 Fukoku, Furukawa-Oosaki, Oosaki, Miyagi, 989–6227, Japan
*****Faculty of Agriculture, Yamagata University, 1-23 Wakabamachi, Tsuruoka, Yamagata, 997–8555, Japan
******NARO, Tohoku Agricultural Research Center, 4 Akahira, Shimokuriyagawa, Morioka, Iwate, 020–0198, Japan

Abstract

In the southern part of the relatively cool Tohoku region of Japan, the mean temperature during the rice cropping season rose at Shonai and Murayama from 1974 to 2004, yet the amount of solar radiation showed no significant trend. Higher mean temperature and solar radiation during the first half of the cropping season advanced the heading date, exposing ripening rice to higher temperatures and more solar radiation. These meteorological influences on paddy rice were different at every site. At Shonai, the heading date advanced with the increase of mean temperature from transplanting to heading after 1980. Other sites did not show these phenomena. The mean temperatures during the latter half of the ripening period increased over time at Shonai and Murayama. Those during the first half of the ripening period exceeded 27℃ several times at Shonai and Murayama, increasing the rate of white immature grains at Shonai. The amount of solar radiation during the ripening period showed no trend, but that at Natori was lower than that at Shonai and Murayama.

Key words: Growth stage of rice, Solar radiation, Southern part of the Tohoku region, Temperature, White immature grains.

1. Introduction

Air temperatures in Japan have risen since the 1990s (JMA, 2005), possibly affecting agricultural production and the quality of brown rice (MAFF, 2009). Studies of the relationships between air temperature and the growth, yield, and quality of brown rice in Kyushu reveal that higher temperatures and shorter sunshine duration (due to the advancement of heading date) during the ripening period increased the rate of white-backed grains and reduced grain production. In Hokuriku, high rates of white-cored grains and white-bellied grains were caused by high temperatures during early ripening (Nagata et al., 2004; Matsumura, 2005; MAFF, 2006; Morita, 2008). Furthermore, the advance of the heading date reduced sunshine duration during ripening in Kyushu and Shikoku, which might reduce grain quality (Okada et al., 2009).

The year-to-year variation in summer temperatures increased after the 1970s in northern Japan, increasing
the frequency of both cold and hot summers (Kanno, 2008). High temperatures during ripening reduced the quality of the brown rice produced in 1994 and 1999 in the Tohoku region (NARC, 2001), but only in Miyagi and Yamagata prefectures, not in Aomori and Iwate prefectures (the northernmost part of the Tohoku region) or in Fukushima prefecture (the southern part of the Tohoku region) (Yamagata Prefectural Government, 1995, 2000). These facts indicate that the warming and reduced sunshine duration during ripening harm the growth and quality of brown rice to varying degrees in the Tohoku region, a relatively cool part of Japan.

The heading date has advanced by 2.5 days per decade in the Tohoku region since the 1980s (Shimono, 2008). Because the heading date is advanced, the temperature during the ripening period is higher (Matsumura, 2005). Thus, the advancement of the heading date in the Tohoku region might be a factor in the higher rates of white immature grains. Reduced sunshine duration during the first 20 days after heading might have affected the quality of brown rice in the Sen-Nan region of Miyagi prefecture (Miyano and Kokubun, 2009).

The eastern part of the Tohoku region faces the Pacific Ocean, where the cold Oyashio current flows. The western part faces the Sea of Japan, where the warm Kuroshio current flows. In addition to these temperature differences, many basins in the region can trap cold air. If the topography and geography of the region affect the local temperatures and sunshine duration, which affect the growth and quality of brown rice, then we need detailed information in order to analyze the climatic trends in the region.

The objectives of this study were to evaluate the actual circumstances of the warming and solar radiation in the Shonai and Murayama areas of Yamagata Prefecture and the Natori area of Miyagi Prefecture, all in the southern part of the Tohoku region, in order to elucidate the effect of air condition on heading date and on the quality of brown rice.

2. Materials and Method

The study region comprises Yamagata and Miyagi prefectures, in the northern part of mainland Japan (Fig. 1). Cropping data were collected in Shonai, near Sakata city, on the Sea of Japan; in Murayama, near Yamagata city, inland; and in Natori, near Sendai city, on the Pacific Ocean. All lie at around 38°N.

The mean temperatures and solar radiations during the rice cropping season were calculated from data collected by AMeDAS (Automated Meteorological Data Acquisition System) weather stations from 1974 to 2004 at Sakata, Yamagata, and Sendai cities. The cropping season runs from around May to September. We also calculated the seawater temperatures from April to September in the mid area of the Sea of Japan and in the East Kanto area of the Pacific Ocean from the AMeDAS data.

To evaluate the effects of temperature and solar radiation on the growth stage of rice (‘Sasanishiki’), we used data collected at the Yamagata General Agricultural Research Center (ARC) Rice Breeding and Crop Science Experiment Station (Shonai), at the Yamagata General ARC Utilization Crop Research Division (Murayama), and at the Natori ARC Utilization Crop Research Division (Natori), from 1974 to 2004. The Shonai data came from crop reports from 1974 to 2004; the Murayama data from crop reports from 1974 to 2000 and cultivar recommendations from 2001 to 2004; and the Natori data from crop reports from 1974 to 1999, when the program was cancelled. The ripening period was divided into two parts: from 1 to 20 days and from 21 to 40 days after the heading date.

The rice was transplanted during 8 to 12 May at
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Shonai, during 15 to 21 May at Murayama, and during 10 to 11 May at Natori. Heading dates ranged from 31 July to 15 August, from 30 July to 14 August, and from 31 July to 20 August, respectively. The dates of maturity ranged from 6 September to 4 October, from 9 September to 4 October, and from 11 September to 16 October, respectively.

To elucidate the relationships between rice quality and the air temperature and solar radiation during the ripening period, we evaluated the quality of brown rice (“Sasanishiki”) at Shonai from 1986 to 2004 from the rates of milky white, white-cored, white-bellied, white-backed, and basal white grains (collectively, “white immature grains”).

Time series trends were calculated using the Mann-Kendall test provided by Makesense version 1.0 Freeware.

Tests of regression equation lines were calculated using ANCOVA provided by covariance analysis DNA1 Freeware.

3. Results

3.1 Time series of air temperature and solar radiation during the rice cropping season

The air temperatures in the rice cropping season increased at Shonai and Murayama over the 31 years from 1974 (Fig. 2a). Natori data showed no significant trend. The y ranged from 19.1 to 22.2 °C (mean, 20.7 °C) at Shonai (measured at Sakata), from 19.0 to 22.0 °C (20.6 °C) at Murayama (measured at Yamagata), and from 18.7 to 22.0 °C (20.1 °C) at Natori (measured at Sendai). They were around 0.5 °C lower at Natori than at Shonai and Murayama. The 5-year-running temperature means at Shonai and Murayama were around 1 °C higher during the 2000s than during the early 1980s. That at Shonai was a little higher than that at Murayama from the mid-1980s. That at Natori was around 0.5-1 °C lower than those at Shonai and Murayama, except around the mid-1990s.

The solar radiation in the rice cropping season showed no significant trend at any site after 1974 (Fig. 2b). It ranged from 15.4 to 18.2 MJ m⁻² (mean, 16.9 MJ m⁻²) at Shonai, from 13.9 to 17.2 MJ m⁻² (15.9 MJ m⁻²) at Murayama, and from 11.9 to 16.3 MJ m⁻² (14.3 MJ m⁻²) at Natori. It was 1.7-2.6 MJ m⁻² lower at Natori than at Shonai and Murayama. The 5-year-running mean was 2-3 MJ m⁻² lower at Natori than at Shonai and Murayama.

The seawater temperature from April to September in the mid area of the Sea of Japan increased after 1974, but that in the East-Kanto area of the Pacific Ocean showed no trend (Fig. 3).

3.2 Time series of air temperature and solar radiation from transplanting to heading

The mean air temperatures from transplanting to heading at Shonai showed an increasing trend after 1974 (Mann-Kendall, **P < 0.01, *P < 0.05). Natori data showed no significant trend. (a) Shonai and Murayama data after 1974 showed increasing trends (Mann-Kendall). (b) No trends were evident at all site after 1974 (Mann-Kendall).

Fig. 2. Time series of climate conditions from May to September at Sakata (Shonai) (N=31), Yamagata (Murayama) (N=31) and Sendai (Natori) (N=26). Solid line denotes Sakata. Short dashed line denotes Yamagata. Dotted line denotes Sendai. Thick line denotes five year running mean, thin line denotes the annual mean. (a) Shonai and Murayama data after 1974 showed increasing trends (Mann-Kendall, **P < 0.01, *P < 0.05). Natori data showed no significant trend. (b) No trends were evident at all site after 1974 (Mann-Kendall).
1980, although that at Murayama and Natori showed no trend (Fig. 4a). They ranged from 18.9 to 21.8°C (mean, 20.5°C) at Shonai, from 18.3 to 22.6°C (20.8°C) at Murayama, and from 17.7 to 20.9°C (19.4°C) at Natori. They were 0.3°C higher at Murayama than at Shonai, and 1.1-1.4°C higher at Shonai and Murayama than at Natori. The 5-year-running mean was higher at Murayama than at Shonai from the 1980s until the mid-1990s, when the difference decreased. That at Natori was consistently lower than those at Shonai and Murayama.

Solar radiation from transplanting to heading showed no trend at any site after 1974 (Fig. 4b). It ranged from 15.0 to 19.6 MJ m$^{-2}$ (mean, 17.5 MJ m$^{-2}$) at Shonai, from 14.7 to 18.4 MJ m$^{-2}$ (16.8 MJ m$^{-2}$) at Murayama, and from 12.6 to 17.0 MJ m$^{-2}$ (15.2 MJ m$^{-2}$) at Natori. It was 0.7 MJ m$^{-2}$ higher at Shonai than at Murayama, and 1.6-2.3 MJ m$^{-2}$ higher at Shonai and Murayama than at Natori. The 5-year-running mean was higher at Shonai than at Murayama, except in the mid-1980s. That at Natori was consistently lower than those at Shonai and Murayama.

The heading dates advanced significantly from 1980 to 2004 at Shonai, but showed no trend at Murayama and Natori (Fig. 5). They ranged from 31 July to 15 August (mean, 6 August) at Shonai, from 30 July to 14 August (5 August) at Murayama, and from 31 July to 20 August (9 August) at Natori. The mean was earlier at Murayama and Shonai than at Natori. The 5-year-running mean at Shonai was the same as or later than that at Murayama before 2000, but earlier after then. That at Natori was almost always later than those at Shonai and Murayama.

The relationships between heading date and mean temperature from transplanting to heading showed significant negative correlations at each site (Fig. 6a),
indicating that the higher mean temperatures from transplanting to heading advanced the heading date. Regression lines were not significantly parallel, indicating that the reaction of heading to temperature at Natori differs from that at other sites.

The relationships between heading date and solar radiation from transplanting to heading showed a significant negative correlation at Murayama and Natori (Fig. 6b), indicating that higher solar radiation from transplanting to heading advanced the heading date there. There was no correlation at Shonai. Regression lines were not significantly parallel at Murayama and Natori, indicating that the reaction of heading to solar radiation differ there.

Thus, climate conditions from transplanting to heading differ at each site. At Shonai, only temperature showed a significant correlation to heading, because of more solar radiation due to the warm current. At other sites, both air temperature and solar radiation showed significant correlations to heading. At Natori, the slope of regression lines of temperature and solar radiation were larger than at other sites, which might be affected by the interaction of temperature and solar radiation because of the low temperature and lack of solar radiation. At Murayama, the influence on heading by solar radiation was smaller than at Natori, which might be affected by more solar radiation than at Natori because of a difference of location, i.e. Murayama is located in basin.

Fig. 5. Time series of heading date at Shonai, Murayama and Natori. Shonai and Murayama data after 1980 showed significant decreasing trend (Mann-Kendall, **P < 0.01, N as in Fig. 2). Natori data showed no significant trend.

Fig. 6. Relationships between climate conditions from transplanting date to heading date (day of year) and heading date from 1974 to 1999 (N is 26 at all sites). Solid line denotes Shonai, short dashed line denotes Murayama and dotted line denotes Natori. (a) All data showed significant negative correlation (***P < 0.001). Slope of regression lines were not parallel significantly (ANCOVA, P < 0.05). (b) Murayama and Natori data showed significant negative correlations (*P < 0.05, **P < 0.01). Slope of regression lines were not parallel significantly at Murayama and Natori (ANCOVA, P < 0.05).
3.3 Time series of air temperature and solar radiation during maturation period

The mean temperatures from heading to maturity increased at Murayama and Natori after 1980, although Shonai data showed no significant trend (Fig. 7a). They ranged from 19.7 to 27.2°C (mean, 23.4°C) at Shonai, from 19.6 to 25.8°C (22.6°C) at Murayama, and from 18.7 to 25.8°C (22.1°C) at Natori. The mean was 0.8°C higher at Shonai than at Murayama, and 0.5°C higher at Murayama than at Natori. The 5-year-running mean was higher at Shonai than at Murayama except in the mid-1990s, and was higher at Murayama than at Natori after the early 1980s.

The mean solar radiation from heading to maturity showed no trend at any site after 1974 (Fig. 7b). It ranged from 12.1 to 20.9 MJ m\(^{-2}\) (mean, 16.0 MJ m\(^{-2}\)) at Shonai, from 11.8 to 18.2 MJ m\(^{-2}\) (14.6 MJ m\(^{-2}\)) at Murayama, and from 9.6 to 17.4 MJ m\(^{-2}\) (13.1 MJ m\(^{-2}\)) at Natori. It was 1.4 MJ m\(^{-2}\) higher at Shonai than at Murayama, and 1.5 MJ m\(^{-2}\) higher at Murayama than at Natori. The 5-year-running mean was consistently higher at Shonai than at Murayama, and consistently higher at Murayama than at Natori.

The relationships between heading date and mean temperature during ripening showed significant negative correlations at each site (Fig. 8a), indicating that earlier heading exposed plants to higher temperatures during ripening. The intercept of the regression lines significantly differ at each site, indicating that temperature during ripening was higher in the order of Shonai, Natori, and Murayama when heading date was the same.

The relationships between heading date and solar radiation during ripening showed significant negative correlations at any site, indicating that earlier heading exposed plants to higher solar radiation during ripening (Fig. 8b), which was a phenomena differing from a previous report (Okada et al., 2009). The intercept of regression lines differ significantly at each site, indicating that solar radiation was greater in the order of Shonai, Murayama, and Natori, when heading date was the same.

Thus, both temperature and solar radiation during ripening increased with advance of heading at each site. The temperature at Murayama was lower than at other sites because of location, i.e. night temperature was lower in the basin. Solar radiation at Shonai was greater than at other sites because of location, i.e. sunshine hours were longer because of the warm current. Solar radiation at Natori was less than at other sites because of location, i.e. sunshine hours were shorter because of the cold current.

The mean temperatures from 1 to 20 days after heading showed no trend at any site (Fig. 9a). They ranged from 21.5 to 30.1°C (mean, 25.0°C) at Shonai, from 21.5 to 28.7°C (24.8°C) at Murayama, and from

![Fig. 7](image)

**Fig. 7.** Time series of climate conditions from heading date to maturation date at Shonai, Murayama and Natori (N as in Fig. 2). Murayama and Natori data after 1980 showed significant increasing trends (Mann-Kendall, \(^*P < 0.05\), \(^{**}P < 0.01\)). Shonai data showed no significant trend. (b) No significant trend was evident after 1974 at all sites.
Fig. 8.  Relationships between heading date and climate conditions from heading date (day of year) to matura- tion date after 1974 to 1999 (N and lines as in Fig. 6). (a) All data showed significant negative correlations (**P<0.01, ***P<0.001). Slope of regression lines were parallel, and intercept of regression lines differ, significantly (ANCOVA, P<0.05) . (b) All data showed significant negative correlations (**P<0.001, *P< 0.01). Slope of regression lines were parallel, and intercept of regression lines differ, significantly (ANCOVA, P<0.05).

Fig. 9.  Time series of climate conditions from 1 to 20 days after heading date at Shonai, Murayama and Natori (N as in Fig. 2). (a) No significant trends were evident after 1974 at all sites (Mann-Kendall). Line of 27°C incidates critical temperature for apparrance of white immature grains (Terashima et al., 2001). Temperatures exceeded 27°C in 1985, 1994 and 1999 at Shonai; in 1984, 1985, 1994 and 1999 at Murayama; and in 1994 at Natori. (b) No significant trends were evident after 1974 at all sites (Mann-Kendall).

18.6 to 26.2°C (23.7°C) at Natori. Temperatures exceeded 27°C in 1985, 1994, and 1999 at Shonai; in 1984, 1985, 1994, and 1999 at Murayama; and in 1994 at Natori. Mean temperatures of 27-28°C during the first 20 days after heading promote the appearance of white immature grains (Terashima et al., 2001).

The mean temperatures from 21 to 40 days after heading increased at Shonai and Murayama after 1974, but showed no trend at Natori (Fig. 10a). They ranged from 18.5 to 25.3°C (mean, 22.4°C) at Shonai, from 18.0 to 24.5°C (22.0°C) at Murayama, and from 18.1 to 24.3°C (21.6°C) at Natori. Mean temperatures from
21 to 40 days after heading were lower than those from 1 to 20 days after heading, and were lower than the critical value of 27°C.

Solar radiation during ripening showed no trends from 1 to 20 days or from 21 to 40 days after heading at any site after 1974 (Figs. 9b, 10b). From 1 to 20 days after heading, it ranged from 11.7 to 23.4 MJ m$^{-2}$ (mean, 17.7 MJ m$^{-2}$) at Shonai, from 11.0 to 21.9 MJ m$^{-2}$ (16.4 MJ m$^{-2}$) at Murayama, and from 8.5 to 20.1 MJ m$^{-2}$ (14.0 MJ m$^{-2}$) at Natori. It was 1.3 MJ m$^{-2}$ higher at Shonai than at Murayama, and 2.4 MJ m$^{-2}$ higher at Murayama than at Natori. From 21 to 40 days after heading, it ranged from 10.9 to 18.8 MJ m$^{-2}$ (mean, 14.7 MJ m$^{-2}$) at Shonai, from 10.0 to 19.1 MJ m$^{-2}$ (13.6 MJ m$^{-2}$) at Murayama, and from 8.8 to 15.8 MJ m$^{-2}$ (12.2 MJ m$^{-2}$) at Natori. It was 1.1 MJ m$^{-2}$ higher at Shonai than at Murayama, and 1.4 MJ m$^{-2}$ higher at Murayama than at Natori.

3.4 Relationships between air temperature and solar radiation during ripening and rice quality at Shonai

There were significant linear correlations between the mean temperatures during both the first and latter halves of the ripening period and the rate of white immature grains at Shonai (Fig. 11). On the other hand, there were no significant correlations between solar radiation during ripening and the rate of white immature grains (data not shown). These results indicate that higher temperatures during both the first and latter halves of the ripening period are the main factors promoting the increase in the rate of white immature grains at Shonai. However, the intercepts of regression lines at the latter halves of the ripening period were significantly lower than at the first halves.

4. Discussion

At 38°N, Shonai faces the warm Kuroshio current, Murayama is located in a basin, and Natori faces the
cold Oyashio current. Thus, air conditions at each site (located in a cold district in Japan) differ, respectively.

The rice cropping season’s temperatures have increased at Shonai and Murayama since 1974, and they were higher in the order of Shonai, Murayama, and Natori. In contrast, the solar radiation showed no trends at each site, but it too was higher in order of Shonai, Murayama and Natori, indicating that the climatic condition was better at Yamagata prefecture than at Miyagi prefecture. The lower temperatures at Natori might be due to the lower seawater temperatures nearby. The higher temperature at Shonai might be due to the higher seawater temperatures nearby. The higher temperatures at Shonai and Murayama or the lower solar radiation at Natori might affect the growth and quality of the rice (Miyano and Kokubun, 2009). Nevertheless, the rate of increase in summer temperatures in the Tohoku region was smaller than that in other regions in recent years (Kawatsu et al., 2007; Shimono, 2008), and so might not be expected to affect the quality of brown rice.

Higher temperatures from transplanting to heading advanced the heading date (Fig. 6) at each site, but the heading date advanced over time only at Shonai (Fig. 5), and the mean temperature from transplanting to heading increased only at Shonai after 1980 (Fig. 4). This means that the increase of temperatures over time advanced the heading date only at Shonai, which might be a factor to decline the quality of brown rice. On the other hand, heading showed no trend at Murayama and Natori, so temperature rising during ripening was caused by a net increase of temperature during ripening. The greater solar radiation at Murayama and Natori was partly responsible for the earlier heading dates there (Fig. 6). But solar radiation from transplanting to heading showed no trend at any site, so the heading date showed no trend at Murayama and Natori.

The advancement of heading date exposed plants to higher mean temperatures during ripening (Matsumura, 2005). The mean temperatures during ripening increased at Murayama and Natori over time, and those at Shonai were higher than at other sites. Shonai faces the warmer Sea of Japan, while Murayama lies in cool inland, which was cool at night, and Natori faces the colder Pacific Ocean.

These differences in location and the advancement of heading date at Shonai might be associated with the differences in temperature during ripening among Shonai, Murayama, and Natori. Solar radiation during ripening showed no trend. Therefore, higher temperatures during ripening might be the main cause of the decline in the quality of brown rice in recent years at Shonai and Murayama, more so at Shonai. In contrast, at Natori, where temperatures were lower, the lower amount of solar radiation during ripening might be the main cause of the decline in the quality of brown rice (Miyano and Kokubun, 2009).

The timing of high temperatures during ripening is critical to the quality of brown rice. The rates of white immature grains increased under high temperatures from the heading date to 15 days after heading (Ebata, 1961), from 4 to 20 and from 16 to 24 days after heading (Tashiro and Wardlaw, 1991), from 1 to 20 days after heading (Tashiro and Ebata, 1975) and from 11 to 20 days after heading (Nagato and Ebata, 1965). These intervals cover the first half of the ripening period. The mean temperatures during the first half of the ripening period showed no trend at each site. But the temperature at Shonai exceeded 27°C, the critical temperature for the appearance of white immature grains in 1985, 1994, and 1999 (Terashima et al., 2001). That at Murayama exceeded 27°C in 1984, 1985, 1994, 1999, and that at Natori exceeded 27°C in 1994. The high rate of white immature grains might be caused by the higher temperatures at any site. Actually at Shonai, the higher temperature during ripening caused a higher rate of white immature grains (Fig. 11).

The mean temperatures during the latter half of the ripening period increased over time at Shonai and Murayama, but remained below 27°C, yet there was a significant linear correlation between temperature and the rate of white immature grains at Shonai. There are no previous reports about the phenomenon, so the reason is unclear.

References


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