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Can the cropping schedule of rice be adapted to changing climate? A case study in cool areas of northern Japan

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ABSTRACT

Adaptation of cropping schedules in response to climate change is essential for increasing rice productivity. In the present study, we analyzed yield, cropping schedule and cultivar characteristics records from 1958 to 2007 in a case study of four prefectures in northern Japan, where low temperatures can severely limit rice growth. Grain yield in all prefectures increased over time, with a higher increase from 1958 to 1982 (2.4 g m^{-2} y^{-1}) than from 1983 to 2007 (1.0 g m^{-2} y^{-1}). The transplanting date became 0.07–0.91 days y^{-1} earlier before 1983, but did not appear to change thereafter. The growing period duration from transplanting to harvesting increased over time, especially during the first 25 years. We observed a significant correlation between grain yield and transplanting date before 1983. The length of the potential growing period, defined as the period from the earliest potential date for transplanting and the latest potential date for harvesting, increased over time in all four prefectures. The gap between the actual growing period and the potential growing period increased after 1983. The safe reproductive period, which is defined as the duration within which rice can escape cold damage during its reproductive stage, did not appear to change over time. Based on these results, we discuss future cropping schedules capable of increasing rice productivity under a changing climate in the future.

1. Introduction

Rice (*Oryza sativa* L.), cultivated widely between 35°S and 53°N in latitude and at altitudes ranging from sea level to more than 2000 m (Yoshida, 1981), is grown under a wide range of environmental conditions, and has become one of the major crops for feeding the world's growing population. During the past 50 years, world rice production increased sharply, from 0.2 billion Mg to more than 0.6 billion Mg, mainly due to increasing productivity per unit of land area, and until recently, this production has been able to meet the increased demand resulting from population growth. However, during this period, concentrations of atmospheric greenhouse gases such CO_2 and methane have increased rapidly (IPCC, 2007), causing global atmospheric temperature to rise by an average of 0.74 °C per 100 years, and researchers predict a further increase of global temperatures by 1–5 °C, leading to potentially severe climatic change in many areas and to low rice productivity. Despite these changes, the world's population is predicted to increase to 9 billion by 2050 (UN, 2009), so that rice production is strongly expected to increase to meet future rice demand. To reliably predict future rice production, it is essential to accurately assess the impact of global climate change.

Temperature is one of the most important variables for determining rice productivity as a result of its impact on most physiological processes including ontogenetic changes, leaf expansion, photosynthesis, respiration, floret fertilization, and grain filling (Yoshida, 1981). Within the optimal temperature range at a growth stage, higher temperature generally accelerates these processes and improves productivity, but extreme temperatures that are lower or higher than this optimal range during any growth stage can inhibit these processes and reduce productivity (Kim et al., 1996; Matsui et al., 1997; Shimono et al., 2002, 2004, 2007; Peng et al., 2004). The sensitivity of rice to temperature is particularly high during developing panicle of reproductive growth stage; a supra-optimal temperature, over 33 °C (Kim et al., 1996; Matsui et al., 1997), or a sub-optimal temperature, less than 20 °C (Satake, 1976; Shimono et al., 2002), during this stage can damage florets or decrease fertilization, leading to severe decline of productivity.

On the other hand, when temperatures remain within the optimal range for longer durations, rice can produce a larger canopy that can capture more light, leading to higher productivity. The length of the potential growing season for rice is also restricted by the temperature, and especially by sub-optimal temperatures, during the

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seedling stage and during the grain-filling stage (Yoshida, 1981). Temperatures of less than 12 °C can prevent rice growth during the seedling stage by inducing chlorosis and leaf death, and can terminate the grain-filling process during the ripening stage. To prevent these problems, growers must adopt a suitable cropping schedule and must select a suitable cultivar to adapt rice cultivation to the local climate by minimizing the risk of damage especially during reproductive growth and by maximizing their utilization of the potential growing season.

Historical large-scale records of crop productivity (such as at the prefecture or state level) provide a robust data set that can be used to analyze the impacts of factors affected by climate on the performance of different cultivars, and the effects of management practices, including the cropping schedule, although it is difficult to distinguish the relative contributions of the individual factors responsible for the observed productivities. A number of studies have analyzed the contributions of various climatic factors (e.g., for rice, Peng et al., 2004; Shimono, 2008; for soybean, Egli, 2008a,b; for maize, Egli, 2008a) and of cultivar differences (e.g., for rice, Tanaka et al., 1968; Takeda et al., 1984; Saitoh et al., 1993; Peng et al., 1999; Zhang and Kokubun, 2004; for wheat, Zhou et al., 2007; Ziska, 2008; for soybean, Ziska and Bunce, 2000). However, very few studies have evaluated the impacts of management practices on crop productivity even though these practices, especially the timing of sowing or transplanting, have important consequences for crop adaptation to local climate (e.g., for rice, Kawatsu et al., 2007; for maize, Kucharik, 2008). The data from these studies provides important insights into how rice and other crops will respond to future climate change.

In northern Japan, temperatures remain close to the critical lower threshold for rice production throughout the growing season, and a slight temperature decrease during any growth stage can seriously affect rice productivity. The window for the potential growing season is therefore limited. Because the potential growing season in this region is tightly restricted by climatic factors, it may expand in the future as a result of global warming. In the present study, we tested this hypothesis by analyzing historical changes in grain yield at the prefectural level in a case study of four prefectures in northern Japan.

2. Materials and methods

The present study analyzed data from four prefectures in northern Japan (Fig. 1): Hokkaido, Aomori, Iwate, and Miyagi prefectures. These prefectures, cover latitudes from 38°N to 45°N, are major rice-producing areas, and account for 19% of Japan's national production (in 2007).

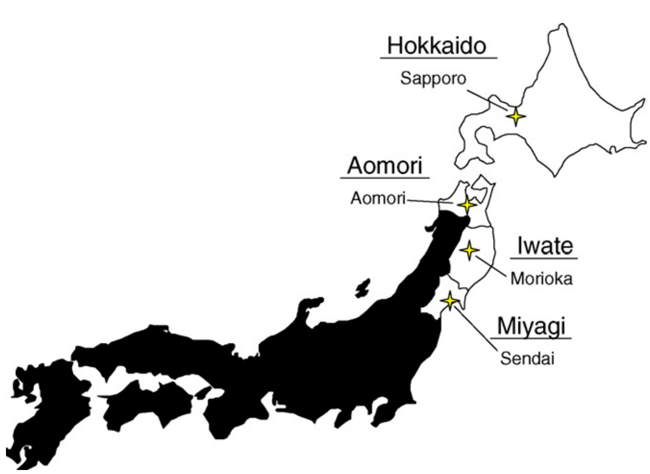

Fig. 1. Locations of the four prefectures used in the case study in northern Japan. Stars indicate the locations of the meteorological stations that provided data for this study.

2.1. Data used in the analysis

The transplanting, heading, and maturity dates and the cultivars used in the four prefectures were obtained from crop statistics collected by Japan's Ministry of Agriculture, Forestry and Fisheries (MAFF) from 1958 to 2007. Monthly air temperature and solar radiation and daily air temperature for this period were derived from Japan Meteorological Agency data collected in Hokkaido Prefecture (Sapporo, 43°04′N, 141°20′E), Aomori Prefecture (Aomori, 40°49′N, 140°46′E), Iwate Prefecture (Morioka, 39°42′N, 141°10′E), and Miyagi Prefecture (Sendai, 38°16′N, 140°54′E). Monthly air temperature and solar radiation was used to calculate their mean during the rice cropping season from May to October. Daily air temperature was used to calculate the temperature parameters that affected rice growth below (Section 2.2), but we did not include years before 1961 in the temperature analysis because digital data for daily values were not available. Amount of N fertilization was obtained from report of economic investigation for rice production collected by MAFF from 1961 to 2006.

2.2. Temperature parameters for rice growth

The earliest limit for transplanting was defined as the first date when the 5-day moving-window average air temperature was higher than 12 °C, which is the physiologically critical temperature for early rice growth (Yoshida, 1981). The latest limit for maturity was defined as the last date when the 5-day moving-window average air temperature was higher than 12 °C. We defined the potential growing season as the period between the early limit for transplanting and the late limit for maturity. We defined the safe reproductive period as the period when the 30-day moving-window average air temperature remained higher than 22 °C, which is the lower critical temperature for this phase of development (Shimono et al., 2002).

2.3. Characteristics of the cultivars used during the study period

We classified the cultivars used in the study area into (1) plant type (from 1 for the heavy panicle-weight type to 5 for the many panicle-number type), (2) maturity groups (from 1 for the earliest-maturing cultivar to 5 for the latest-maturing cultivar), (3) cold-tolerance groups based on how likely low temperatures at the booting stage were to induce sterility (from 1 for the weakest cold resistance to 6 for the strongest cold resistance), (4) lodging tolerance (from 1 for the weakest lodging resistance to 6 for the strongest lodging resistance) and (5) blast disease tolerance (from 1 for the weakest blast disease resistance to 6 for the strongest blast disease resistance) for the period from 1961 to 2007. The cold tolerance was determined based on the data of Tanno et al. (2000) for Hokkaido Prefecture and the data of Sasaki (1996) and Matsunaga and Sasaki (1985) for the other prefectures, and the other characteristics were determined by web system for searching rice characteristics developed by National Institute of Crops Science, Japan (http://ineweb.narcc.affrc.go.jp/search/hinsyu_top.html).

Fig. 2 illustrates the changes in the percentage of the total cultivated area accounted for by the leading cultivars in each prefecture during the study period. This percentage was mostly greater than 70% after 1990, whereas before 1990, the leading cultivar accounted for less than 40% of the total area, especially in Hokkaido and Iwate prefectures. This means that two or more cultivars have been grown in each prefecture in all years, but that the number of cultivars has tended to decline in recent years. To quantify the overall cultivar characteristics in each prefecture based on their plant type (*PT*),