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Genotypic variation in the response to high water temperature during vegetative growth and the effects on rice productivity under a cool climate

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ABSTRACT

We examined the effects of high water temperature (T_w) during early vegetative growth on dry matter production, grain yield, and grain quality in a 2-year field trial in northern Japan using two rice cultivars: 'Hitomebore', a standard cultivar for this region, and 'Koshihikari', a late-maturing cultivar. The heading date of 'Koshihikari' was 8–9 days later than that of 'Hitomebore'. Heading date was significantly earlier for both cultivars (by 2–5 days) in the high T_w treatment, without a significant cultivar × T_w interaction. High T_w significantly increased dry matter production before heading, and there was a significant cultivar × T_w interaction: 'Koshihikari' responded more than 'Hitomebore' to high T_w. This genotypic difference was explained by the daily rate of dry matter increase rather than by the growth duration. After heading, leaf senescence measured as the reduction of the SPAD value was greater at high T_w for both cultivars. Radiation-use efficiency after heading was significantly reduced by high T_w for both cultivars. Consequently, the positive effect of high T_w on dry matter production was reduced for both cultivars at harvest. Grain yield was significantly increased by high T_w (by 1–20%), but without a significant T_w × cultivar interaction. These results suggest that to increase grain yield above that for the standard cultivar 'Hitomebore', manipulation of the accelerated leaf senescence caused by high T_w will be a key factor in efforts to adapt rice to future global warming.

1. Introduction

Rice (*Oryza sativa* L.) is one of the world's major crops, and supplies 21% of the calories consumed by the world's people (Pritchard and Amthor, 2005). As it is grown around the world, cultivars have been developed for use at a wide range of growing temperatures, ranging from tropical to cool climates (Yoshida, 1981). However, global warming (IPCC, 2007) threatens to decrease rice productivity and grain quality (Peng et al., 2004; Easterling et al., 2007).

Most plant physiological processes are promoted by increasing temperature, but the response is not linear and there are complex interactions among processes. In areas with a tropical warm climate, with temperatures close to the maximum value for optimal rice growth, excessively high temperatures can severely decrease rice productivity as a result of sterility induced by heat during flowering (Baker and Allen, 1993; Matsui et al., 1997; Moya et al., 1998; Ohe et al., 2007) and as a result of poor grain filling (Morita et al., 2005; Shimono and Ishii, 2012).

At temperatures below the optimal range for rice in areas with a cool-temperate climate, the response of biomass production is the key factor that determines yield variations. Biomass production is determined by a combination of canopy development and radiation-use efficiency (RUE), both of which are affected by temperature (Sinclair and Muchow, 1999). After canopy closure, increasing temperature can decrease growth and yield as a result of increasing respiration losses (Arai-Sanoh et al., 2010; Matsushima et al., 1964), which reduce RUE (De Costa et al., 2006). Before canopy closure, the enhanced canopy development caused by high temperature can increase biomass production by promoting leaf area development (Matsushima et al., 1964; Shimono et al., 2002; Ishii et al., 2011). On the other hand, the acceleration of each growth stage and the resulting shortened growth duration caused by high temperatures can reduce total canopy radiation capture during each growth stage, leading to decreased biomass. The overall impact of these expected negative and positive effects of high temperature before canopy closure on rice productivity in

Abbreviations: CT, control water temperature; DAT, days after transplanting; HT, high water temperature; LAI, leaf area index; RUE, radiation-use efficiency; T_w, water temperature.

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cool-temperate areas are difficult to predict. Thus, researchers have been unable to propose a satisfactory strategy for adapting rice to changing climates so as to protect or improve its productivity.

Nitrogen (N) fertilization, as an important management practice, might promote rice productivity under increasing temperatures, since increasing leaf area can decrease the N content of leaves if the plant grows faster than the soil can provide N (a dilution effect). However, Ishii et al. (2011) examined the role of N fertilization in the responses of rice to high water temperature (T_w, an increase of 2.7–2.8 °C) during vegetative growth and the effects on rice productivity, and found that although high T_w increased canopy radiation capture by up to 72% before the heading stage at all levels of N fertilization, it shortened the total growth period and reduced post-heading RUE by up to 100%. Consequently, high T_w during vegetative growth had only a small positive effect on final biomass and grain yield, irrespective of the amount of N fertilization. Thus, the hypothesis that N fertilization could compensate for the proposed dilution effect was rejected.

Another important option to adapt rice culture to the predicted future temperature increase in cooler regions is the selection of appropriate cultivars. Horie (1988) developed a simple empirical simulation model, SIMIRW, to predict the impact of global warming on rice productivity in the Hokkaido region of northern Japan. Horie simulated a future climate scenario with double the modern CO_2 level plus a higher temperature, and found that this increased the yield of the standard cultivar ‘Ishikari’ by only 5% above current levels, but that using a later-maturing cultivar such as ‘Koshihikari’ increased the yield by 23–25%. Later-maturing cultivars, which are more photoperiod sensitive than earlier-maturing cultivars, would benefit from a less negative impact of increasing temperature on canopy radiation capture. The later-maturing cultivars would therefore be good candidate for increasing rice yield under future global warming conditions in regions with a cool climate.

In this paper, we describe the results of a 2-year field trial with ‘Hitomebore’, a standard cultivar for northern Japan, and ‘Koshihikari’, a late-maturing cultivar. Increased air temperatures will increase the paddy water temperature, and rice, whose shoot meristems lie below water level, will be more sensitive to T_w than to air temperature (Matsushima et al., 1964; Shimono et al., 2002). Thus, we simulated the effects of increased temperature by warming the water rather than the air during vegetative growth before canopy closure. The treatment period followed historical trends for the temperature increase in this region; air temperature has not increased uniformly throughout the season, and the magnitude of the increase has been greater during vegetative growth (May and June) than during reproductive growth (July and August) based on an analysis of data from 1937 to 2007 (Shimono, 2008).

2. Materials and methods

2.1. Crop history

Our field experiment was conducted in 2010 and 2011 in a paddy field of the Faculty of Agriculture, Iwate University, Morioka, Japan (39°42′ N, 141°8′ E). We used two *japonica* cultivars (*O. sativa* L.) from different maturity groups: ‘Hitomebore’, which is the major cultivar grown in areas with a cool climate such as the study area, and which belongs to the normal maturity group; and ‘Koshihikari’, a cultivar that matures about 1–2 weeks later and that is more photoperiod-sensitive than ‘Hitomebore’. Germinated seeds were sown at three seeds per cell in a seed tray on 20 April 2010 and 19 April 2011. The seedlings were raised in a greenhouse for 1 month. They were transplanted into the paddy field on 17 May 2010 and 10 May 2011 at a planting density of 22.2 hills m^{-2} (15 cm between hills × 30 cm between rows, at 3 plants per hill) in both years.

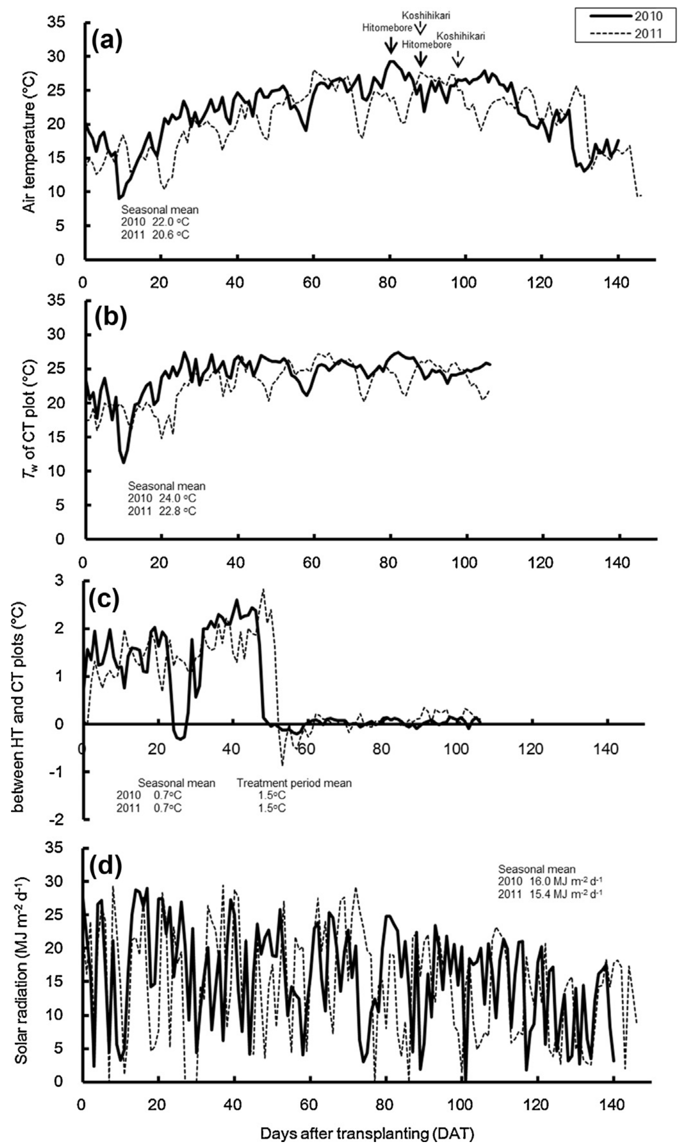

Fig. 1. Seasonal changes in (a) air temperature and (b) water temperature (T_w) in the control T_w plot, (c) the difference in T_w between the control and high T_w plots, and (d) solar radiation in 2010 and 2011. Arrows indicate the heading dates of each cultivar in the control T_w plot.

Weather conditions during the growing season in both years were favorable for rice growth (Fig. 1): the seasonal average air temperature was 20.6–22.0 °C, T_w of the control plot averaged 22.8–24.0 °C, there were no severe cold spells during reproductive growth (Fig. 1a and b), and the mean difference in T_w between the two plots was 0.7 °C in both years for the whole season and 1.5 °C during the warming period in both years (Fig. 1c); solar radiation averaged 16.0 MJ m^{-2} d^{-1} in 2010 and 15.4 MJ m^{-2} d^{-1} in 2011 (Fig. 1d). The regional rice yield attained by local farmers in the study area in 2010 did not differ from the long-term mean, and was only 1% higher than that mean in 2011 (Ministry of Agriculture, Forestry and Fisheries of Japan, 2013). The air temperature at 1.5 m above the soil and T_w at the soil surface were measured with a TR-52 sensor (T&D Co., Nagano, Japan) that had been carefully calibrated against a standard temperature sensor, and provided measurements with an accuracy of ±0.01 °C. The air temperature at 1.5 m was measured inside an aspirated-tube radiation shield.