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Climatic responses of biomass production and grain yield in Japanese high-yielding rice cultivars under different transplanting times

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ABSTRACT

Planting time is one of the management methods determining yield potential in rice. The aims of the present study were to determine whether early transplanting improves yield potential in temperate regions of Japan, and to identify quantitative influences of climatic factors on crop productivity. We evaluated differences in biomass production and yield formation under three transplanting times for high-yielding cultivars having different heading characteristics. Early transplanting extended growth duration, but did not increase biomass production before heading, resulting in no improvement in total spikelet number and yield potential. For all the cultivars, cumulative air temperature better explained differences in biomass production under different transplanting times than did cumulative solar radiation. The results indicate that early-transplanted plants could not effectively utilize solar radiation for CO_2 assimilation and that early biomass production in early-transplanted plants was constrained by low temperature. On the other hand, biomass production after heading and grain filling in late-heading cultivars were reduced with late transplanting time, owing to lower solar radiation and lower temperature. These results suggest that avoiding late transplanting can increase final biomass as well as acquire stable and high grain yield in late-heading cultivars in temperate regions, even if early biomass production after transplanting is reduced by low temperature. Two *indica*-dominant cultivars showed the highest grain yield and biomass productivity in the present study, but showed higher base temperature for biomass production, indicating that *inidica*-dominant cultivars were susceptible to low temperature. Development of a management method and genetic modification to promote early biomass productivity at low temperatures is necessary for further improvement of yield potential of high-yielding cultivars in temperate regions.

1. Introduction

Rice production and consumption as a staple food has decreased with the changes in dietary habit in Japan since the 1960s, and the food self-sufficiency ratio on a calorie-supply basis has decreased to 39% in 2012 (MAFF, 2013). Targeting 50% as a food security ratio for 2020, the government has promoted rice production for use in flour and livestock feed in place of a large quantity of imported crops. A reduction in production cost is indispensable for the expansion of the new uses of domestically produced rice, because of the lower prices of imported crops, and yield increase is a strategy aimed at this goal. Several rice cultivars showing high grain yield and high biomass production have been released in Japan in recent years, but the cultivation methods able to exploit the yield potential in these cultivars have not been established.

One of the cultural factors determining yield performance is planting time. Planting time changes growth duration, given that days to heading is influenced by concurrent changes in air temperature and photoperiod during rice vegetative growth (Horie and Nakagawa, 1990; Vergara et al., 1965). Early planting can extend days to heading via lower temperature and longer photoperiod during the vegetative growth (Ghosh et al., 2004; Gravois and Helms, 1998; Horai et al., 2013; Maruyama and Tanaka, 1985), and is effective for increasing biomass production (Nakano et al., 2008), panicle number (Nakano and Morita, 2009; Samoto et al., 1959a,b) and grain yield (Samoto et al., 1959a) in warm temperate regions. Because increased rice yield in Japan after the mid 1950s has been achieved by acceleration of transplanting time (Horie et al., 2005), whether the standard transplanting time in temperate regions has

Abbreviations: DAH, days after transplanting; LAI, leaf area index.

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reached its optimum for maximum biomass and grain yield remains to be elucidated.

In contrast, in cool regions, longer growth duration did not increase grain yield and decreased shoot dry weight at maturity when rice plants were transplanted 10 days earlier than the usual planting time (Horai et al., 2013). This result indicates that the effects of early transplanting on biomass production and grain yield vary with climate, because the biomass productivity and yield formation are affected by climatic conditions (Matsushima et al., 1963). Several reports have proposed optimum planting times to achieve maximum grain yield, and claimed that earlier or later planting decreases grain yield (Blanche and Linscombe, 2009; Sha and Linscombe, 2007; Slaton et al., 2003). However, the quantitative influences of climatic factors on biomass productivity and yield formation have not been fully evaluated for rice transplanted at different times. Characterizing differences in climatic response of biomass productivity and yield traits among rice genotypes may lead to a strategy for the further improvement in yield potential of high-yielding cultivars.

The objectives of the present study were (1) to determine whether early transplanting improves yield potential in high-yielding rice cultivars in temperate regions in Japan, and (2) to clarify the relationship between climatic factors and crop productivity, and their difference among rice genotypes. We conducted field experiments with high-yielding cultivars having different heading characteristics transplanted at three different times in 2 years. For the analysis of the relationship between climatic factors and crop productivity, we focused on cumulative solar radiation and air temperature after transplanting, and evaluated the genotypic differences in biomass productivity at given cumulative and base temperatures for biomass production.

2. Materials and methods

2.1. Plant cultivation

Field experiments were conducted in a paddy field of the Hokuriku Research Center, Jo-etsu, Japan (37°6′ N, 138°16′ E) in 2009 and 2010. The soil is well-drained heavy clay. Five rice (*Oryza sativa* L.) cultivars were used in the study: three *japonica*-dominant cultivars, Yume-aoba (early heading), Momiroman (late heading) and Kusanohoshi (very late heading) and two *indica*-dominant cultivars, Takanari (medium heading) and Hokuriku193 (late heading). An *indica*-dominant cultivar Hokuriku193 is suggested to be the latest-heading cultivar available in the study area (Goto et al., 2009), and achieved the highest grain yield in the warmer regions (Yoshinaga et al., 2013).

Rice seedlings with four leaves were transplanted on 1 May and 28 April for early transplanting in 2009 and 2010, respectively, transplanted on 15 May and 13 May for medium transplanting, and transplanted on 29 May and 27 May for late transplanting. Mid-May is the usual planting time for farmers in the study area. A split-plot design was used with planting date as main plot and cultivar as subplot. Main plots were not replicated in the field because random arrangement of the plots was difficult for tillage and water management. However, the main plots were rotated by year. Subplots of cultivar within each main plot were arranged in a randomized complete block design with three replications. Transplanting was performed at the rate of three plants per hill, and plant spacing was 15 cm between plants by 30 cm between rows. Plot size was larger than 9.5 m^2 with 10-plant rows in both years. Total amounts of fertilizer were 17 g m^{-2} N, 11 g m^{-2} P_2O_5, and 11 g m^{-2} K_2O in all the plots. Basal applications were of 3 g m^{-2} urea, and topdressings were composed of 6 g m^{-2} ammonium sulfate for tillering, 3 g m^{-2} urea at panicle initiation, and 5 g m^{-2} urea at 10 days before heading. Urea fertilization was applied in the form of complex chemicals including the same amounts of P_2O_5 and K_2O. Plants were grown under irrigated conditions with mid-term drainage for 2 weeks until panicle initiation of the earliest-heading cultivar, Yume-aoba, and protected from diseases and insects using chemicals.

2.2. Evaluation of biomass and yield components

Six plants were harvested for each plot at panicle initiation, 18 days after panicle initiation, heading, 20 days after heading (DAH) and maturity in 2009 and 2010. In addition, harvesting was performed for six plants in 2010 at maximum tillering stage, almost coinciding with panicle initiation of Takanari at each transplanting time. One third of the whole harvested plants were separated into green leaves, stems, senescent organs, and panicles, and their dry weights were determined after drying at 78 °C for 72 h, to calculate total biomass. Green leaf area was measured with an area meter (AAM-9, Hayashi Denko, Tokyo, Japan) at panicle initiation, heading, and maturity to calculate the leaf area index (LAI) for each cultivar. Oven-dried samples of stems, including culms and leaf sheaths, were powdered in a vibrating sample mill (TI-100, HEIKO Ltd., Fukushima, Japan). The content of nonstructural carbohydrates in stems (NSC) at heading, 20 DAH, and maturity were measured according to the gravimetric method by Ohnishi and Horie (1999).

At maturity, 24 plants were harvested from each plot, and used to determine yield and yield components. After the panicles were counted, all the spikelets were threshed from panicles, weighed to determine rough grain yield, and divided into halves. Filled grains were separated by submerging half of the harvested spikelets in salt solution with a specific gravity of 1.03 for all cultivars. Percentage of ripened grains was calculated as the number of submerged grains divided by the total spikelet number. The filled grains were hulled, counted, and weighed to determine hulled grain yield and 1000-grain weight at 14% moisture content. Harvest index is expressed as the ratio of hulled grain yield to biomass yield on a dry weight basis in the present study. Two-way analysis of variance was used to compare the effects of cultivar, transplanting date and their interaction, followed by Fisher's LSD. Statistical analyses were conducted using the statistical software, Cropstat 7.2 (IRRI, Los Banos, Philippines).

2.3. Estimation of biomass production based on effective cumulative temperature

Shoot dry weight exponentially increases until canopy closure, and then linearly increases (Graf et al., 1990). Given that in our experiments (see Section 3), increases in shoot dry weights were proportional to cumulative daily air temperature after panicle initiation, shoot dry weight was simply re-expressed as a linear function of effective cumulative temperature:

$$\text{Shoot dry weight} = a\sum_{i=0}^{n}(\text{Ta} - \text{Tb})\Delta t + b$$
$$\text{If Ta} < \text{Tb}, \quad \text{Ta} - \text{Tb} = 0$$

where Ta is daily average air temperature and Tb is base temperature. Δt is the time step of 1 day. Effective cumulative temperature, (Ta − Tb), is integrated after transplanting to the day before plant harvesting. The values of the three empirical constants, a, b and Tb, were estimated by applying the measured data set to the equation. One data set consists of daily average temperatures and shoot dry weights in the plants transplanted three times. A least-square methods for non-linear functions was applied for the regression