REGULAR PAPER

Changes in developmental duration of direct-seeded rice in a well-drained paddy field in response to late planting

Satoko Yasumoto, Natsumi Maki, Makoto Kojima and Yasuo Ohshita
National Agriculture and Food Research Organization, Central Region Agricultural Research Center, Tsukuba, Japan

ABSTRACT
We investigated changes in the developmental duration of rice cultivars with a wide range of maturities in response to late planting. Elucidating the relationship between cropping season and the progress of growth stages is important for establishing direct-seeded cultivation and creating growth models. Late planting of the intermediate to late maturing cultivars Akidawara and Hoshijirushi decreased the time from emergence to panicle formation and decreased the cumulative effective temperature (CET) and cumulative effective soil temperature (CEST). In the very early maturing cultivars Ichibanboshi and Fusakogane, the changes in number of days, CET, and CEST from emergence to panicle formation with late planting were small. From emergence to heading and maturity, the number of days, CET, and CEST of many cultivars tended to increase until mid-May and then decreased. The changes in the number of days, CET, and CEST caused by late planting were greater for the intermediate to late maturing cultivars than for the very early maturing cultivars. The differences between cultivars were greatest with early May sowing, and then decreased with later planting. Short-day condition revealed significant differences in the duration of vegetative growth and CET among cultivars, but long-day condition erased these differences. These results demonstrate that the photosensitivity and thermosensitivity of cultivars are especially important in crop planning and for creating growth models of direct-seeded rice.

Abbreviations: CET: cumulative effective temperature; CEST: cumulative effective soil temperature; DTH: days to heading

Rice is a major food crop in Japan. Japan’s area of arable land is $4.5 \times 10^6$ ha, of which $2.4 \times 10^6$ ha (ca. 53%) was paddy fields in 2015 (Ministry of Agriculture, Forestry, and Fisheries [MAFF], 2015). In the current global economic context, Japan must strengthen its international competitiveness. To accomplish this in agriculture, it is important to investigate alternative planting systems that offer higher benefits, including lower costs. Direct seeding of rice can reduce costs since it eliminates the costs of raising and transplanting seedlings, which can account for up to 26% of the total cost of rice cultivation (Nourin Suisanshou Daizin Kanbou Toukeibu [NSDKT], 2014). It also allows farmers to spread cropping seasons over a longer period and to choose various cultivation systems. However, only 1.6% of the total rice cultivated in Japan is planted by direct seeding; most rice is grown from transplants (NSDKT, 2014). Direct seeding has not expanded, because establishment of seedlings is less stable than that after transplanting, an optimal weed management system has not been established, and as the current paddy rice cultivars were bred for transplant cultivation, basic knowledge of the progress of growth stages in direct-seeded cultivation is lacking. Umetsu et al. (1992) reported that poor establishment was one reason for unstable yields in direct-drilled rice cultivation and concluded that securing stable initial growth from sowing to establishment was important for stable cropping. Nakagawa and Horie (1995) reported a model for the period from emergence to heading of rice that divides crop growth into ‘before’ and ‘after’ panicle initiation. But basic knowledge about the progress of growth stages and cropping seasons in direct-seeded rice cultivation remains poor.

To identify the relationship between the date of direct seeding, notably late planting, and the progress of growth stages of cultivars in different maturity groups, including newly bred cultivars, we conducted experiments over two years in central Japan using eight cultivars and two to five sowing dates, recording growth over the entire crop life, from seeding to maturity. This basic information will be useful for expanding the use of direct seeding.

CONTACT Satoko Yasumoto ysatoko@affrc.go.jp
© 2017 The Author(s). Published by Informa UK Limited, trading as Taylor & Francis Group. This is an Open Access article distributed under the terms of the Creative Commons Attribution License (http://creativecommons.org/licenses/by/4.0/), which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.
1. Materials and methods

1.1. Effects of sowing date on crop developmental stages

The effects of sowing date on crop developmental stages were examined in the summers of 2014 and 2015 in a well-drained paddy field in Tsukuba-mirai City, Ibaraki, Japan (36°02′N, 140°0′E, 20 m a.s.l.). The soil was gray lowland soil. Daily mean temperatures during the growing seasons ranged from 12.1 to 29.5 °C in 2014 and 11.9 to 29.6 °C in 2015, respectively.

Eight cultivars of japonica rice (Oryza sativa L.) were used. Ichibanboshi (Okamoto et al., 2015) and Fusakogane (Shinoda & Koyama, 2007) were very early maturing cultivars. Moeminori (Kataoka et al., 2007) and Fukumaru were early maturing cultivars. Koshihikari and Yumehitachi (Suga et al., 2000) were intermediate maturing cultivars. Akidawara (Ando et al., 2011) and Hoshijirushi were intermediate to late maturing cultivars. In a preliminary trial, germination of all cultivars was greater than 95% after 7 days in the dark at 30 °C.

Seeds were sown on 25 April and 18 June in 2014 (with two replicates), and on 17 April, 1 and 14 May, and 2 and 16 June in 2015 (with three replicates), at 250 m−2 in both years. Seeds were sown at a depth of 1.4 cm with a model NSV600 no-till direct-seeding machine (Matsuyama Co., Ueda City, Japan) at 30 cm between ridges. Soil water was maintained at approximately 10 cm below the surface in both years until emergence, then the surface was flooded (<1 cm).

In both years, the early sowing plots had previously been used for summer paddy rice cultivation, but with no cultivation of winter crops. In 2014, the late sowing plot was established after summer soybean cultivation with no winter crop. In 2015, the early sowing plots (17 April, 1 May) and the late sowing plots (14 May, 2 and 16 June) had been cultivated with wheat as a winter crop, and the field was tilled with a model KJMI80T rotary tiller (Kobashi Co., Okayama City, Japan) to prepare the seedbed.

The seeds were not treated with fungicide in either year. Nitrogen was applied as types LP70 and LPS100 polyolefin-coated urea, which are controlled-release fertilizers that release 80% of their total nitrogen content at a uniform rate until 70 days and at a sigmoid curve rate until 100 days, respectively, at 20–30 °C. They were mixed at a weight ratio of two parts LP70 to 1 part LPS100. The application rate was similar to the standard regime used locally, 200 kg ha−1, containing 80 kg ha−1 of nitrogen. The fertilizer was applied in a trench of around 2 cm in depth near the seedbed. To control weeds, we sprayed glyphosate and butachlor just after sowing, and hand-weeded when necessary.

We recorded the dates of emergence, young panicle formation stage (date when flag leaf opens), maximum tiller number stage, heading stage, milk-ripe stage (when crushed seeds release milky sap), dough-ripe stage (when the glumaceous flower is opaque and the contents are soft), and maturity. We calculated the cumulative effective temperature (CET) above 11.5 °C (Ebata, 1990a, 1990b) from the daily mean temperature to show the relation between temperature and growth. Umetsu et al. (1992) found a high correlation between initial growth and soil temperature at 0.5 cm depth. Therefore, we also calculated the cumulative effective soil temperature (CEST) above 11.5 °C (Ebata, 1990a) measured at a depth of about 5 cm with a Thermo Recorder (TR-71Ui; T and D Inc., Nagano, Japan).

1.2. Effects of day length on the duration of vegetative growth

We studied the effects of day length on the duration of vegetative growth in growth chambers in 2015. We grew five cultivars: two very early heading cultivars (Ichibanboshi and Fusakogane), two intermediate maturing cultivars (Koshihikari and Yumehitachi), and one intermediate to late maturing cultivar (Akidawara). We sowed eight seeds of each in a 0.2 m2 Wagner pot. We used the same fertilizer and application rate as in the field trial. After establishment, we thinned the plants to five per pot, with three pots for each cultivar.

The temperature was held at 25 °C. The day length was 12 or 16 h. We recorded the time to the panicle formation stage as the duration of vegetative growth, and recorded CET.

1.3. Statistical analysis

All data are expressed as means and standard errors. All analyses were performed in SPSS v. 11.0 software (SPSS Inc., Chicago, IL, USA). The effects of sowing date on CET were assessed by t-test. The effects of day length and cultivar were assessed by two-way analysis of variance (ANOVA). Statistically significant differences between means were identified by Tukey’s multiple-range test.

2. Results

2.1. Effects of sowing date on developmental stages

In 2014, although CET at heading was similar between sowing dates in most cultivars, the very early maturing Ichibanboshi headed at a significantly higher CET in late sowing than in early sowing, and the intermediate to late maturing Akidawara and Hoshijirushi headed at a
significantly lower CET in late sowing (short day length) than in early sowing (Figure 1). The differences at heading between sowing dates of other cultivars were not significant.

\[ \text{Figure 1. Cumulative effective temperature (CET) based on a basal temperature of 11.5 °C in relation to early (——) and late (- - -) sowing dates in 2014.} \]

Notes: *p < .05, **p < .01: significant difference between early sowing and late sowing by t-test; ns, not significant.

2.2. Effects of sowing date on each growth stage

The differences in heading date response among Ichibanboshi, Hoshijirushi and Akidawara in 2014 suggested differences in photosensitivity. We, therefore, examined the dates of key growth stages in detail in 2015. Daily mean temperature in relation to the heading and maturity dates following each of the five sowing dates is shown in Figure 2, and daily rainfall in relation to the same dates is shown in Figure 3. Cultivar heading and maturity dates ranged from very early maturing to intermediate to late maturing (Figures 2 and 3). The mean daily temperature at sowing across all plots increased most (by 5.5 °C) between the 17 April and 1 May sowings (Figure 4). Thereafter, it increased more slowly, by a total of only 3.7 °C, until the 16 June sowing. Conversely, the mean temperature at heading decreased: it was 4.0 °C lower following the 16 June sowing than following the 17 April sowing. The mean temperature at maturity also decreased, it was 5.2 °C lower following the 16 June sowing than following the 17 April sowing.

To assess whether soil temperature influenced initial growth in particular, we examined the relationship between the number of days from seeding to emergence and each of CET and CEST (Figure 5). The block sown on 17 April (encircled in Figure 5) had a greater number of days from direct seeding to emergence than the other blocks. Overall, CEST was more strongly correlated with the number of days than CET (Figure 5). Then we examined the relationships of sowing date with the duration of each period between growth stages and the associated CET and CEST for the eight cultivars grown in 2015. At each growth stage, the plants sown on 14 May showed a different pattern of changes in number of days, CET and CEST from those sown on the other dates (Figure 6).

The durations from seeding to emergence of all cultivars decreased with later sowing date (Figure 6(A)–(C)). But from emergence to panicle formation, there were
differences between cultivars in the patterns of change in number of days, CET and CEST. In most cultivars, the number of days, CET and CEST during the vegetative growth stage tended to decrease with later sowing date. However, in Ichibanboshi, the earliest-maturing cultivar, although the number of days tended to decrease, CET and CEST increased slightly did not change. Thus, the patterns of change in CEST were more similar to those of the number of days than of CET (Figure 6(D)–(F)). The decrease was larger for the intermediate to late maturing Akidawara (latest maturing) and Hoshijirushi than for Ichibanboshi. CET during this period also decreased with later sowing date for the medium to late maturing cultivars, but increased for the very early maturing cultivars (Figure 6(E)). Although CEST decreased slightly with later sowing date for the very early maturing cultivars, it decreased greatly for the intermediate to late maturing cultivars (Figure 6(F)). The differences among the cultivars in all three parameters decreased with later sowing date.

From emergence to heading, regardless of a cultivar’s maturity group, all three parameters tended to peak in mid-May and then decreased (Figure 6(J)–(L)). Although the duration of this period was longer in late maturing cultivars than in early maturing cultivars, eight cultivars
Figure 6. Number of days between growth stages, CET and CEST during each period for eight cultivars following each sowing date. Notes: Vertical bars indicate SEM (n = 3). △ - - - Ichibanboshi (earliest maturing); ◇ Fusakogane; ○ Moeminori; □ Fukumaru; ▲ Koshihikari; ● Yumehitachi; ■ Hoshijirushi; ● — Akidawara (latest maturing).
Table 1. Effect of day length on the duration of vegetative growth and cumulative effective temperature (≥11.5 °C) in the growth chamber experiment.

| Day length (h) | Cultivar       | Duration of vegetative growth (days) | Cumulative effective temperature during vegetative growth (°C) |
|---------------|----------------|------------------------------------|-------------------------------------------------------------|
| 12            | Ichibanboshi   | 29.0a                              | 391.5a                                                      |
|               | Fusakogane     | 29.3a                              | 396.0a                                                      |
|               | Koshikari      | 25.0b                              | 337.0c                                                      |
|               | Yumehtachi     | 26.7c                              | 360.0b                                                      |
|               | Akidawara      | 21.0d                              | 283.5d                                                      |
| 16            | Ichibanboshi   | 31.0                               | 418.5                                                       |
|               | Fusakogane     | 31.0                               | 418.5                                                       |
|               | Koshikari      | 31.3                               | 423.0                                                       |
|               | Yumehtachi     | 31.3                               | 423.0                                                       |
|               | Akidawara      | 31.0                               | 418.5                                                       |

ANOVA results
- Day length: **
- Cultivar: **
- Day length × cultivar: **

Notes: Values are the means of four replicates. Values within a column followed by the same letter do not differ significantly (p < .05, ANOVA followed by Tukey’s multiple-range test).
**Significant at p < .01.

The differences in CET and CEST between cultivars became larger for the late maturing cultivars (Koshihikari and Yumehtachi) and in the intermediate to late maturing cultivar Akidawara were shorter and lower under the 12-h day length than under the 16-h day length significantly. In addition, the duration and CET of the vegetative growth period both decreased significantly with later maturity under the 12-h day length. While under the 16-h day length, there were not significant differences among cultivars in the duration and CET.

2.3. Effects of day length on the duration of vegetative growth

In the growth chamber experiment, the differences in the duration of the vegetative growth period and in the CET of the very early maturing cultivars (Ichibanboshi and Fusakogane) were not significant between day lengths (Table 1). However, those in the intermediate maturing cultivars (Koshihikari and Yumehtachi) and in the intermediate to late maturing cultivar Akidawara were shorter and lower under the 12-h day length than under the 16-h day length significantly. In addition, the duration and CET of the vegetative growth period both decreased significantly with later maturity under the 12-h day length. While under the 16-h day length, there were not significant differences among cultivars in the duration and CET.

3. Discussion

We examined the effects of changing the sowing date on the progress of the growth stages from seeding to maturity of eight rice cultivars containing newly bred cultivars with different maturity. Although many cultivars headed at a similar CET regardless of sowing date, with early sowing the very early maturing Ichibanboshi headed at a lower CET, while the intermediate to late maturing Hoshijirushi and Akidawara headed at a higher CET (Figure 1). The timing of panicle formation and heading date represents major physiological changes that define the switch from vegetative to reproductive development. The differences among the cultivars in heading dates between the two sowing dates suggested high thermosensitivity in the very early maturing cultivars, advancing heading date by early sowing (Figure 1). And in the intermediate to late maturing cultivars, it was thought that their sensitivity to day length was high. Then they were thought to be advanced heading date in late sowing when day length was short (Figure 1).

The block sown on 17 April had a longer interval from direct seeding to emergence than the other blocks (Figure 5). The likely explanation is that the temperature on 17 April was lower from 5.5 to 9.2 °C than the other sowing dates (Figure 4). The relationship between number of days and each of CET and CEST was therefore different too. Overall, the relationship of number of days with CET was stronger than with CEST in all blocks (Figure 5), partly because soil temperature was more stable than air temperature. Soil temperature was likely to have had a stronger influence on the small rice seedlings than air temperature. Umetsu et al. (1992) reported a high correlation between
daily mean soil temperature during emergence and percentage establishment. Yoshino and Dei (1977) reported that the relationship between temperature and mineralization of soil organic nitrogen was important to the supply of nitrogen to paddy rice. Miyamoto (1958) reported that irrigation water temperatures below 20 °C caused cold injury to maturing spikelets. Our results show the important influence of soil temperature on the growth of very small rice seedlings (Figure 5).

From emergence to panicle formation, the differences among the cultivars in all three parameters decreased with later sowing date. This decrease is attributable to the shortening day length with later sowing date. The period from emergence to panicle formation for intermediate to late maturing cultivars with high sensitivity to day length were shortened with later sowing dates remarkably. In contrast, very early maturing cultivars with high sensitivity to temperature experienced constant CET and CEST from emergence to panicle formation, which minimized the differences between cultivars (Figure 6(D)–(F)). The differences among cultivars were due to differences in photosensitivity and thermostensitivity. The high photosensitivity of the intermediate to late maturing cultivars reduced the number of days, CET and CEST available for vegetative growth with later sowing date. Thus, both the photosensitivity and thermostensitivity of cultivars are critical for direct-seeded rice. After panicle formation, however, the changes in the number of days, CET and CEST were similar in all cultivars.

Yabuta et al. (2010) previously showed that the vegetative growth stage under short day length was considerably shorter in late maturing cultivars than in intermediate and early maturing cultivars. In addition, flag leaf emergence and the timing when the leaf emergence rate began to increase occurred earlier under short day length than under natural day length (Yabuta et al., 2012). They later reported that the vegetative growth stage was remarkably shorter in late maturing cultivars than in early maturing cultivars under short day length (Yabuta et al., 2015). In our study, late sowing greatly shortened the vegetative growth period in the intermediate to late maturing Hoshijirushi and Akidawara. On the other hand, it made little difference in the very early maturing Ichibanboshi, for number of days, CET and CEST with late sowing. Xue et al. (2008) reported that a quantitative trait locus called Ghd7, identified in an elite rice hybrid, strongly affects heading date: increased expression of Ghd7 under long-day conditions delays heading. Hori et al. (2013) reported that the rice flowering-time quantitative trait locus Heading date 16 (Hd16) acts as an inhibitor in the flowering pathway by enhancing the photoperiod response through phosphorylation of Ghd7, and the mechanisms that recognize day length in several plant species were proposed by Osugi and Izawa (2014). In our study, it was thought that Hd16 was responsible for an enhanced photoperiod response and for greater sensitivity to day length. We suspect that the function of Hd16 is weakened in early maturing cultivars. This would explain why even if the sowing times are different, CEST during vegetative growth was similar in the early maturing cultivars. We hypothesized that the function of Hd16 in the very early maturing cultivars was weakened and it makes their photosensitivity weaker than their thermostensitivity. And the function in the intermediate to late maturing cultivars was thought to be increased. Then the vegetative growth stage of the intermediate to late maturing cultivars was greatly shortened by short day treatment, but not shortened in the early maturing cultivars (Table 1). Yabuta et al. (2015) similarly reported that photoperiod sensitivity during both vegetative and reproductive growth was more sensitive in late maturing cultivars than in early maturing cultivars.

Though the changes in duration, CET and CEST from panicle formation to heading by sowing dates were small, these are long and high in cultivars that sown on 14 May and on 16 June. It was thought as one of the reasons that a lot of rain fell at the panicle formation time of that sown on 14 May and 16 June, and it was also thought as one of the reasons that daily mean temperature was decreased at the panicle formation time of that sown on 16 June (Figures 2 and 3). Then in the stage from panicle formation to heading, it was thought that though the influence by sowing dates was small, the stage was influenced great by environment such as temperature or the rain (Figures 2, 3, and 6(G)–(I)). The duration and CEST from emergence to heading peaked in early May, and CET peaked in mid-May and then tended to decrease in all maturity groups. Regardless of the sowing date, the differences among cultivars in the durations of each growth stage were about 20 days, the differences in CET were about 300 °C, and the differences in CEST were about 700 °C: these differences, and the order among cultivars from emergence to heading, were roughly constant (Figure 6(J)–(L)).

Unlike other stages, the ripening period tended to lengthen with later sowing. Among plants sown after 14 May, the CET and CEST of very early and early maturing cultivars were higher than those of mid to late maturing cultivars. One explanation for the reverse is that the ripening stage of the mid to late maturing cultivars sown after 14 May became delayed and the temperatures dropped. Thus, although the ripening period became longer, the CET and CEST decreased (Figures 2 and 6(M)–(O)). In contrast, even when very early and early maturing cultivars were sown after 14 May, they were ripening in warm temperatures in early to mid-August (Figures 2 and 6(M)–(O)). Thus, their CET and CEST during ripening did not change greatly among cropping periods. Then it was thought as one of reasons for the reverse.
These results show the importance of the photosensitivity and thermosensitivity of cultivars and the importance of taking into account environmental conditions in crop planning and for creating growth models of direct-seeded rice. Horie and Nakagawa (1990) quantified rice development by a continuous variable termed the developmental index (DVI). The value at which a crop becomes sensitive to photoperiod was estimated to be $DVI = .2$. Yajima (1996) reported the need to use crop models for monitoring and forecasting rice development and spikelet sterility in areas affected by cool-temperature damage.

In this study, we paid attention during a longer period, from seeding to maturity, than that was reported above. As well as the responses of the growth stages to changes in sowing date, we collected preliminary data on yield, which decreased with later sowing date by up to 24% of the best yield from about 14% of the best yield (data was not shown) according to cultivars. To increase yields, it is important to increase the optimal spikelet density (Horie et al., 1997), as a large sink capacity results from a high sink production efficiency per unit of absorbed nitrogen (Yoshinaga et al., 2013). Our results also show that it is important to consider when a plant matures for establishing of rotational cropping systems. However, most current paddy rice cultivars in Japan were selected for their suitability for transplanting, and much remains unknown about their suitability for direct seeding. Then the results of this study will be useful for establishing of rotational cropping systems and for creating crop growth models for direct-seeded rice. To identify or breed cultivars that are highly suited to direct seeding, our results will be useful for creating crop growth models for direct-seeded rice.

In this study, we paid attention during a longer period, from seeding to maturity, than that was reported above. As well as the responses of the growth stages to changes in sowing date, we collected preliminary data on yield, which decreased with later sowing date by up to 24% of the best yield from about 14% of the best yield (data was not shown) according to cultivars. To increase yields, it is important to increase the optimal spikelet density (Horie et al., 1997), as a large sink capacity results from a high sink production efficiency per unit of absorbed nitrogen (Yoshinaga et al., 2013). Our results also show that it is important to consider when a plant matures for establishing of rotational cropping systems. However, most current paddy rice cultivars in Japan were selected for their suitability for transplanting, and much remains unknown about their suitability for direct seeding. Then the results of this study will be useful for establishing of rotational cropping systems and for creating crop growth models for direct-seeded rice. To identify or breed cultivars that are highly suited to direct seeding, our results will be useful for creating crop growth models for direct-seeded rice.

In this study, we paid attention during a longer period, from seeding to maturity, than that was reported above. As well as the responses of the growth stages to changes in sowing date, we collected preliminary data on yield, which decreased with later sowing date by up to 24% of the best yield from about 14% of the best yield (data was not shown) according to cultivars. To increase yields, it is important to increase the optimal spikelet density (Horie et al., 1997), as a large sink capacity results from a high sink production efficiency per unit of absorbed nitrogen (Yoshinaga et al., 2013). Our results also show that it is important to consider when a plant matures for establishing of rotational cropping systems. However, most current paddy rice cultivars in Japan were selected for their suitability for transplanting, and much remains unknown about their suitability for direct seeding. Then the results of this study will be useful for establishing of rotational cropping systems and for creating crop growth models for direct-seeded rice. To identify or breed cultivars that are highly suited to direct seeding, our results will be useful for creating crop growth models for direct-seeded rice.

In this study, we paid attention during a longer period, from seeding to maturity, than that was reported above. As well as the responses of the growth stages to changes in sowing date, we collected preliminary data on yield, which decreased with later sowing date by up to 24% of the best yield from about 14% of the best yield (data was not shown) according to cultivars. To increase yields, it is important to increase the optimal spikelet density (Horie et al., 1997), as a large sink capacity results from a high sink production efficiency per unit of absorbed nitrogen (Yoshinaga et al., 2013). Our results also show that it is important to consider when a plant matures for establishing of rotational cropping systems. However, most current paddy rice cultivars in Japan were selected for their suitability for transplanting, and much remains unknown about their suitability for direct seeding. Then the results of this study will be useful for establishing of rotational cropping systems and for creating crop growth models for direct-seeded rice. To identify or breed cultivars that are highly suited to direct seeding, our results will be useful for creating crop growth models for direct-seeded rice.

4. Conclusions

Late sowing affected both the duration of the growth stages and the CET and CEST of rice, dependent on the maturity group of the cultivars. These results demonstrate that it will be necessary to account for the effects of a cultivar’s maturity group when planning cultivation schedules for direct seeding. Further research will be needed to identify factors in addition to photosensitivity and thermosensitivity that are responsible for these differences and to determine the impacts on plant growth, yield and grain quality.

Acknowledgements

We thank the staff of the National Agricultural Research Center for their help in data collection. We thank Dr. Tomoko Shibuya, of the National Agriculture and Food Research Organization (NARO), for her advice on our growth chamber experiment. This research was supported by grants from the Project of the Bio-oriented Technology Research Advancement Institution, NARO (Special Scheme Project on Advanced Research and Development for Next-Generation Technology). The manuscript has been edited by two English-speaking professional editors from ELSS, Inc. (elss@elss.co.jp, http://www.elss.co.jp).

Disclosure statement

No potential conflict of interest was reported by the authors.

References

Ando, I., Nemoto, H., Kato, H., Ohta, H., Hirabayashi, H., Takeuchi, Y., … Aoki, N. (2011). A new rice cultivar ‘Akidawara’ with high yield, good grain appearance, and good eating quality. Breeding Research, 13, 35–41.

Ebata, M. (1990a). Effective heat unit summation and base temperature on the development of rice plant. I. A method determining base temperature and its application to the vegetative development of rice plant. Japanese Journal of Crop Science, 59, 225–232. doi:10.1626/jcs.59.225

Ebata, M. (1990b). Effective unit summation and base temperature on the development of rice plant. II. On heading, flowering, kernel development and maturing of rice. Japanese Journal of Crop Science, 59, 233–238. doi:10.1626/jcs.59.233

Hori, K., Ogiso-Tanaka, E., Matsubara, K., Yamanouchi, U., Ebana, K., & Yano, M. (2013). Hd16, a gene for casein kinase I, is involved in the control of rice flowering time by modulating the day-length response. The Plant Journal, 76, 36–46. doi:10.1111/tpj.12268

Horie, T., & Nakagawa, H. (1990). Modelling and prediction of developmental process in rice. Japanese Journal of Crop Science, 59, 687–695. doi:10.1626/jcs.59.687

Horie, T., Ohnishi, M., Angus, JF., Lewin, LG., Tsukaguchi, T., & Matano, T. (1997). Physiological characteristics of high-yielding rice inferred from cross-location experiments. Field Crops Research, 52, 55–67.

Kataoka, T., Yamaguchi, M., Endo, T., Nakagomi, K., Takita, T., Yokogami, N., & Kato, H. (2007). Development of a new rice variety ‘Moeminori’ with high eating quality and adaptability for rotational cropping systems and for creating growth models of direct-seeded rice. Further research will be needed to identify factors in addition to photosensitivity and thermosensitivity that are responsible for these differences and to determine the impacts on plant growth, yield and grain quality.

MAFF (Ministry of Agriculture, Forestry, and Fisheries). (2015). Retrieved from http://www.maff.go.jp/j/tokei/kouihyou/sakumotu/index.html
Xue, W., Xing, Y., Weng, X., Zhao, Y., Tang, W., Wang, L., ... Zhang, Q. (2008). Natural variation in Ghd7 is an important regulator of heading date and yield potential in rice. *Nature Genetics, 40*, 761–767. doi:10.1038/ng.143

Yabuta, S., Minami, S., Hakoyama, S., & Kawamitsu, Y. (2010). Varietal difference in the duration of reproductive phase in *Oryza sativa* L. *Japanese Journal of Crop Science, 79*, 327–335. doi:10.1626/jcs.79.327

Yabuta, S., Hakoyama, S., Inafuku, S., Fukuzawa, Y., & Kawamitsu, Y. (2012). Effects of short-day treatment on leaf emergence rate and its turning point in several cultivars of rice. *Japanese Journal of Crop Science, 81*, 299–308. doi:10.1626/jcs.81.299

Yabuta, S., Hakoyama, S., Inafuku, S., Fukuzawa, Y., & Kawamitsu, Y. (2015). The photoperiodic sensitivity estimation at three growth phases of rice fractionated by turning point of leaf emergence and panicle initiation. *Japanese Journal of Crop Science, 84*, 64–68. doi:10.1626/jcs.84.64

Yajima, M. (1996). Monitoring regional rice development and cool-summer damage. 1996. *Japan Agricultural Research Quarterly, 30*, 139–143.

Yoshinaga, S., Takai, T., Arai-Sanoh, Y., Ishimaru, T., & Kondo, T. (2013). Varietal differences in sink production and grain-filling ability in recent developed high-yielding rice (*Oryza sativa* L.) varieties in Japan. *Field Crops Research, 150*, 74–82.

Yoshino, T., & Dei, Y. (1977). Prediction of nitrogen release in paddy soils by means of concept of effective temperature. *Journal of the Central Agricultural Experiment Station, 25*, 1–62.