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To cite this article: Yoshihiro Hirooka, Koki Homma, Tatsuhiko Shiraiwa, Yuki Makino, Tian-sheng Liu, Zhengjin Xu & Liang Tang (2018) Yield and growth characteristics of erect panicle type rice (*Oryza sativa* L.) cultivar, Shennong265 under various crop management practices in Western Japan, *Plant Production Science*, 21:1, 1-7, DOI: [10.1080/1343943X.2018.1426993](https://doi.org/10.1080/1343943X.2018.1426993)

To link to this article: <https://doi.org/10.1080/1343943X.2018.1426993>



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Published online: 24 Jan 2018.



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# Yield and growth characteristics of erect panicle type rice (*Oryza sativa* L.) cultivar, Shennong265 under various crop management practices in Western Japan

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## ABSTRACT

Erect panicle rice cultivars utilize solar energy effectively and have improved ecological growing conditions. Among such cultivars, Shennong265 has been grown successfully throughout Northern China. Nevertheless, no studies have yet examined the relationships between crop dry matter productivity, weather conditions, and nitrogen uptake of the erect panicle type rice cultivar in Japan. The objective of our study was to evaluate the productivity of erect panicle rice Shennong265 in Western Japan under varied conditions. Three rice cultivars, Shennong265, Nipponbare, and Takanari were grown in the field under different fertilizer and plant density conditions in Western Japan; using this information, we compared yield and growth characteristics of Shennong265 with those of Nipponbare and Takanari. Although Shennong265 had radiation use efficiency similar to that of the high yielding cultivar (Takanari) and much higher leaf nitrogen content than Takanari and Nipponbare, the average grain yield of Shennong265 grown under normal fertilizer and plant density conditions was approximately 6.9 t ha<sup>-1</sup> as against 6.2 t ha<sup>-1</sup> for Nipponbare and 9.6 t ha<sup>-1</sup> for Takanari. These results suggest that, while Shennong265 has a high yield potential, the environmental conditions including climate, fertilizer, and planting period provided in this study were not suitable for achieving its maximum yield. The reduced performance of Shennong265 may be caused by insufficient fertilizer after heading and by shorter growth periods, as well as by the climate of Western Japan. Additional fertilizer application during the heading stage and earlier transplanting may be needed to obtain higher Shennong265 yields in Western Japan.

**Abbreviations:** LAI: leaf area index; NF: normal fertilizer level; LF: low fertilizer level; LD: low plant density level; ND: normal plant density level; HD: high plant density level; TDW: total dry weight at maturing stage; HI: harvest index; PN: panicle number; GN: grain number per panicle; SSR: seed setting rate; TGW: 1000-grain weight; RUE: radiation use efficiency; LNC: leaf nitrogen content; LNW: leaf nitrogen weight

## ARTICLE HISTORY

Received 14 October 2017  
Revised 15 December 2017  
Accepted 23 December 2017

## KEYWORDS

Rice; erect panicle; yield; radiation use efficiency; leaf area index; leaf nitrogen content

## CLASSIFICATION

Agronomy & Crop Ecology

## Introduction

Rice is the second most widely grown cereal crop worldwide and serves as a carbohydrate source for more than half of the world's population. The production of rice is likely to increase because of population and economic growth (Maclean et al., 2013); in recent years, however, it has become difficult to increase the area of cultivated rice as most of the arable land used for rice production has been converted into urban infrastructure (Horie et al., 2005). As a result, annual increases in rice yield have begun to slow down in many countries. Therefore, the

yield per unit area must now be increased to enhance rice production.

Increasing rice yield potential has been the main objective of breeders in rice improvement programs (Li et al., 2009; Peng et al., 2008). Among various breeding strategies, rice ideotype breeding is essential to increase rice production. Panicle angle is considered to be one of the most important agronomic traits in designing 'new plant type' of high-yielding rice varieties (Kong et al., 2007; Xu et al., 2010). After nearly 30 years endeavors, breeders have exploited erect panicle rice as a new germplasm resource (Tang et al., 2017). Rice panicle architecture contributes not

only to grain yield but also to the ecological conditions of a canopy and the physicochemical properties of different varieties (Xu et al., 1996). Erect panicle rice cultivars tend to have greater lodging and fertilizer resistance because of their characteristic plant canopy structure (Qiao et al., 2011). Erect panicle rice cultivars also utilize solar energy effectively, accelerate CO<sub>2</sub> diffusion, and have improved ecological growing conditions in the middle and lower part of the rice canopy (Tan et al., 2001). Thus, the erect panicle cultivars generally provide a genetic repository for increasing biomass and harvest index, offering a sustainable yield improvement option for further breeding programs (Tang et al., 2017).

The typical japonica cultivars have a curved panicle, such as in Nipponbare and Koshihikari (Tang et al., 2017). In China, especially in Liaoning province, erect panicle japonica rice cultivars have become predominant (Xu et al., 1995). In 1996, Shenyang Agricultural University successfully developed a super-high yielding erect panicle japonica rice cultivar, Shennong265, with grain yields of up to 12 t ha<sup>-1</sup>. This cultivar has been grown successfully throughout Northern China. Many studies have examined the mechanisms underlying the high grain yield of Shennong265 in China (e.g. Song et al., 2013; ZhenYu et al., 2010). Shennong265 has a more efficient canopy structure and higher nitrogen use efficiency than any other erect panicle rice cultivar in China. In Japan, Shennong265 has been found to have high nitrogen content in leaves and a high photosynthetic capacity (Urairi et al., 2016). Hirooka et al. (under submission) also reported that Shennong265 has a unique leaf canopy and relatively uniform leaf area index (LAI) distribution in Japan. The productivity of Shennong265 relative to other rice cultivars has been previously investigated in Northeastern Japan (Fukushima et al., 2011; Yamaguchi et al., 2009). However, no studies have been undertaken to examine the relationship between dry matter productivity, weather conditions, such as solar radiation and temperature, and nitrogen uptake in erect panicle rice in Western Japan.

The objective of our study was to evaluate the productivity of the erect panicle rice cultivar, Shennong265, and to analyze the characteristics of rice productivity in Western Japan. Three rice cultivars were grown in the field under different fertilizer and plant density conditions at Kyoto in Western Japan; we used the results from these experiments to compare the yield and growth characteristics of Shennong265 with those of Nipponbare and Takanari.

## Materials and methods

### Plant materials and growth conditions

The field experiments were conducted in experimental fields belonging to the Graduate School of Agriculture,

Kyoto University (35° 2' N, 135° 477' E; altitude 65 m above sea level) in 2013 and 2014. Three cultivars were selected for the experiment: Shennong265 is a japonica cultivar with erect panicles; Nipponbare is a standard cultivar of japonica rice; and Takanari is an indica-japonica crossbred high yielding cultivar. The sowing dates were 7 May 2013 and 8 May 2014. Seedlings of each cultivar were transplanted to the paddy field in alluvial loam soil classified as Haplaquept.

In 2013, fertilizer experiment was conducted. Twenty-nine-day-old seedlings were transplanted on June 6. Each plot was 12.15 m<sup>2</sup> (4.5 m × 2.7 m) and planting density was 22.2 plants per m<sup>2</sup> (.3 m × .15 m) with one plant per hill. For the normal-fertilizer treatment (NF), Eco-long (JCAM AGRI, Japan), a slow release fertilizer containing coated urea was applied at rates of 12.00, 9.43, and 11.14 g m<sup>-2</sup> for N, P<sub>2</sub>O<sub>5</sub>, and K<sub>2</sub>O, respectively. For the low-fertilizer treatment (LF), the same fertilizer was applied at rates of 3.00, 2.36, and 2.79 g m<sup>-2</sup> for N, P<sub>2</sub>O<sub>5</sub>, and K<sub>2</sub>O, respectively. Additionally, 5 g m<sup>-2</sup> of LP coat (JCAM AGRI, Japan), a coated urea fertilizer, was applied to the NF group as a basal fertilizer.

In 2014, plant density experiment was conducted. Twenty-eight-day-old seedlings were transplanted on June 5. Each plot was 10 m<sup>2</sup> (2.4 × 4.2 m). Eco-long was applied here too at the rates of 15.00, 11.79, and 13.93 g m<sup>-2</sup> for N, P<sub>2</sub>O<sub>5</sub>, and K<sub>2</sub>O, respectively, for all treatments. Additionally, 5 g m<sup>-2</sup> of LP coat was applied. Three plant density treatments were used: low plant density (LD; 16.7 plants per m<sup>2</sup>), normal plant density (ND; 22.2 plants per m<sup>2</sup>), and high plant density (HD; 44.4 plants per m<sup>2</sup>).

In both years, the experiments were conducted in a randomized block design with three replications; water, weeds, insects, and disease were controlled as required to avoid yield loss.

### Measurements

The above-ground parts of twelve plant samples were harvested from each plot, when they were at the maturing stage. The grain yield (Yield), total dry weight (TDW), and harvest index (HI) were calculated from these samples. The grain yield was adjusted to a moisture content of 14%. The TDW was measured after oven drying for 72 h at 80 °C. The yield components (panicle number [PN], grain number per panicle [GN], seed setting rate [SSR], and 1000-grain weight [TGW]) were also measured for each sample.

At the heading stage, four plant samples were harvested to calculate their above-ground dry weight, LAI, and leaf nitrogen content. The samples were chosen to be representative of the rice canopy, based on plant height and the number of tillers among twelve plants. The above-ground dry weight was measured after oven drying for 72 h at 80 °C. Green leaf blades were separated from the plant samples and their area was measured using an area meter (LI3080, Li-COR; destructive measurement) to calculate the

LAI. The leaf nitrogen content was quantified by the indophenol method after Kjeldahl digestion (Kjeldahl, 1883). In 2014, four plant samples were also harvested 2 weeks after heading to calculate their aboveground dry weight and LAI.

Meteorological data (daily solar radiation and air temperature) were measured by QMS101 and QMH101 (VAISALA, Tokyo, Japan). Canopy coverage was measured once or twice per week for two weeks after transplanting to maturation with an LAI-2200 (Li-COR, Inc., Lincoln, NE) to calculate daily solar interception.

### Data analysis

HI was calculated using Yield and TDW (Yield/TDW). The mean solar radiation use efficiency (RUE) across the growing period was calculated using the cumulative value of intercepted solar radiation and TDW obtained in this study (cumulative intercepted radiation/TDW). The daily light interception was estimated by interpolation of LAI-2200 measurements. The leaf nitrogen content (LNC:  $\text{g m}^{-2}$ ) was calculated using the LAI and the leaf nitrogen weight (LNW;  $\text{g m}^{-2}$ ) at heading stage (LNW/LAI). LAI defoliation was calculated as the difference between LAI at the time of heading and 2 weeks after heading.

The effect of the cultivar and treatment was analyzed for three cultivars (Shennong265, Nipponbare and Takanari) in five treatments (fertilizer treatments (NF and LF) in 2013 and plant density treatments (LD, ND, and HD) in 2014) using ANOVA. The data were subjected to an ANOVA with cultivar and treatment as the main effects. The LAI defoliation from heading to 2 weeks after heading and LNC at the heading of ND and HD mean values were compared by independent samples *t*-test. All statistical analyses were conducted using Microsoft Excel (Microsoft, Redmond, WA, U.S.A).

**Table 1.** Daily average temperature ( $^{\circ}\text{C}$ ) and solar radiation ( $\text{MJ m}^{-2} \text{d}^{-1}$ ) in 2013 and 2014.

		Temperature ( $^{\circ}\text{C}$ )		Solar radiation ( $\text{MJ m}^{-2} \text{d}^{-1}$ )	
		2013	2014	2013	2014
June	Early	22.0	23.1	24.6	21.3
	Middle	24.8	22.3	18.0	20.5
	Late	22.5	23.2	18.2	19.5
July	Early	27.0	24.4	20.0	14.7
	Middle	27.0	26.6	20.0	18.2
	Late	27.4	28.1	15.7	20.9
Aug.	Early	28.0	27.0	20.9	13.1
	Middle	29.8	27.4	25.8	16.6
	Late	26.6	25.1	14.1	14.0
Sep.	Early	23.3	23.2	12.3	11.0
Ave.		25.8	25.0	19.0	17.0

## Results

Table 1 shows the seasonal changes in the mean temperature and solar radiation during the rice growing periods in 2013 and 2014, that were measured in the Kyoto University field. The daily average temperature from June to August was higher in 2013 ( $25.8^{\circ}\text{C}$ ) relative to 2014 ( $25.0^{\circ}\text{C}$ ). The average daily solar radiation was also higher in 2013 ( $19.0 \text{ MJ m}^{-2} \text{d}^{-1}$ ) relative to 2014 ( $17.0 \text{ MJ m}^{-2} \text{d}^{-1}$ ). In particular, the mean temperature and solar radiations from early to mid-August were considerably lower in 2014 as compared to 2013. The transplanting, heading, and maturing dates of three different cultivars in the years 2013 and 2014 are shown in Table 2. This result shows that Shennong265 has remarkably shorter growth periods as compared to Nipponbare and Takanari.

Table 3 shows the averaged values and two-way ANOVA results of grain yield (YIELD), TDW at maturing stage, HI, PN, GN, SSR, and TGW. The YIELD ranged from  $4.8 \text{ t ha}^{-1}$  (with LF for Shennong265) to  $10.4 \text{ t ha}^{-1}$  (with HD for Takanari) and TDW ranged from  $8.3 \text{ t ha}^{-1}$  (with LF for Shennong265) to  $16.6 \text{ t ha}^{-1}$  (with HD for Takanari), showing that there are significant cultivar, treatment, and their interaction effects. The effects of fertilizer and planting density on the YIELD and TDW of Shennong265 were higher than on those of Nipponbare and Takanari. The HI values were from .38 (with HD for Nipponbare) to .57 (with LF for Takanari). The HI showed a significant cultivar and treatment effects, but their interaction effect was not significant. The HI of Shennong265 was significantly higher than Nipponbare and significantly lower than Takanari. Figure 1 shows that the Shennong265 had relatively higher HI and lower TDW.

The range of PN was from  $153 \text{ m}^{-2}$  (with LF for Shennong265) to  $397 \text{ m}^{-2}$  (with HD for Nipponbare) and GN ranged from 69.1 (with HD for Nipponbare) to 204.4 (with LD for Takanari). Shennong265 had significantly lowest PN with a significant difference from the rest, and the GN of the cultivar was in between that of Nipponbare and Takanari. SSR ranged from .73 (with NF for Nipponbare) to .90 (with LF for Nipponbare) and the TGW ranged from 21.4 g (with NF for Shennong265) to 24.4 g (with LF for Nipponbare). The SSR and the TGW showed a significant cultivar effect and also an interaction between the cultivar and the treatment. The TGW of the Shennong265 cultivar was significantly lower than that of Nipponbare and Takanari.

The relationship between total radiation intercepted and TDW is illustrated in Figure 2. The cumulative value of intercepted solar radiation ranged from  $842 \text{ MJ m}^{-2}$  (with LF for Shennong265) to  $1452 \text{ MJ m}^{-2}$  (with HD for Nipponbare) and RUE ranged from  $.77 \text{ g MJ}^{-1}$  (with LF for Nipponbare) to  $1.38 \text{ g MJ}^{-1}$  (with LD for Shennong265). Under the same conditions, Shennong265 showed

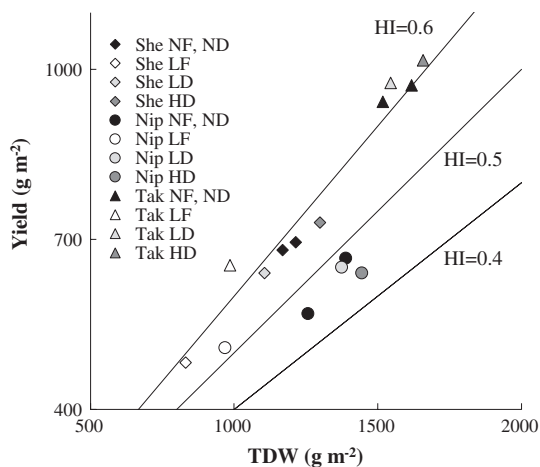
**Table 2.** The transplanting, heading, and maturing dates in the years 2013 and 2014.

	2013			2014		
	Transplanting	Heading	Maturing	Transplanting	Heading	Maturing
Shennong265	6-Jul	1-Aug	6-Sep	5-Jul	2-Aug	6-Sep
Nipponbare	6-Jul	16-Aug	26-Sep	5-Jul	17-Aug	1-Oct
Takanari	6-Jul	13-Aug	22-Sep	5-Jul	12-Aug	27-Sep

**Table 3.** Grain yield (YIELD) ( $t\ ha^{-1}$ ) and yield components of rice varieties grown under different fertilizer and plant density treatments in 2013 and 2014. TDW, total dry weight ( $t\ ha^{-1}$ ); HI, harvest index; PN, panicle number ( $m^{-2}$ ); GN, grain number per panicle; SSR, seed setting rate; TGW, 1000-grain weight (g). NF, normal-fertilizer treatment; LF, low fertilizer treatment; LD, low plant density treatment; ND, normal plant density treatment; HD, high plant density treatment.

		YIELD ( $t\ ha^{-1}$ )	TDW ( $t\ ha^{-1}$ )	HI	PN ( $m^{-2}$ )	GN	SSR	TGW (g)
2013								
NF	Shennong265	6.94	12.15	.49	256.3	128.1	.85	21.4
	Nipponbare	5.69	12.57	.39	370.4	78.7	.73	23.2
	Takanari	9.72	16.17	.52	269.6	160.7	.89	23.1
LF	Shennong265	4.82	8.30	.50	153.3	144.0	.87	21.8
	Nipponbare	5.08	9.68	.45	262.2	76.2	.90	24.4
	Takanari	6.54	9.86	.57	189.6	150.7	.89	22.2
2014								
LD	Shennong265	6.41	11.06	.50	198.9	145.7	.85	22.4
	Nipponbare	6.51	15.44	.41	325.9	81.8	.88	23.9
	Takanari	9.76	13.75	.54	220.3	204.4	.82	22.9
ND	Shennong265	6.81	11.68	.50	227.4	145.9	.80	22.2
	Nipponbare	6.66	15.17	.41	345.2	78.2	.90	23.7
	Takanari	9.43	13.89	.53	266.7	166.6	.79	23.1
HD	Shennong265	7.30	12.98	.48	291.9	120.5	.80	22.5
	Nipponbare	6.41	16.58	.38	397.0	69.1	.86	23.2
	Takanari	10.16	14.44	.53	315.6	155.3	.77	23.3
ANOVA	Cultivar	**	**	**	**	**	*	**
	Treatment	**	**	**	**	**	**	ns
	C*T	**	*	ns	ns	**	**	*

Notes: Grain yield with a 14% moisture content. \*, \*\* represents the significance at .05, .01 probability levels, respectively. ns means non-significant at  $P = .05$  level.

**Figure 1.** Relationship between total dry weight (TDW) ( $g\ m^{-2}$ ) and grain yield ( $g\ m^{-2}$ ) of three cultivars at five treatments.

Notes: She, Shennong265; Nip, Nipponbare; Tak, Takanari; NF, normal-fertilizer treatment; LF, low fertilizer treatment; LD, low plant density treatment; ND, normal plant density treatment; HD, high plant density treatment.

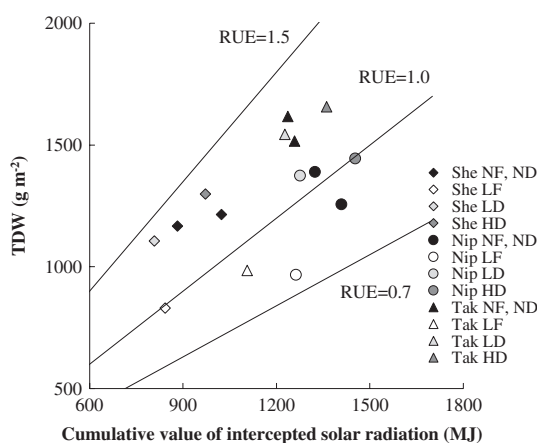
higher RUE and lower total radiation intercepted than Nipponbare and similar RUE and low cumulative value of intercepted solar radiation as compared to Takanari. Figure 3 shows the relationship between leaf nitrogen weight

(LNW) and LAI. LNW ranged from  $2.18\ g\ m^{-2}$  (with LF for Takanari) to  $7.97\ g\ m^{-2}$  (with HD for Shennong265), and LAI ranged from 1.88 (with LF for Shennong265) to 6.69 (with NF for Takanari). Shennong265 showed higher LNC and lower LAI except for with HD treatment. With HD treatment, Shennong265 showed higher LNC and higher LAI. In contrast, the LAI defoliation after heading observed in Shennong265 with HD treatment was significantly larger than that observed with ND treatment, while LAI defoliation observed in Nipponbare and Takanari was not significantly different between the HD and ND treatments (Figure 4). The LNC at heading observed in Shennong265 with HD treatment was significantly lower than that with ND treatment while LNC at heading in Nipponbare and Takanari was not significantly different between the HD and ND treatments (Figure 5).

## Discussion

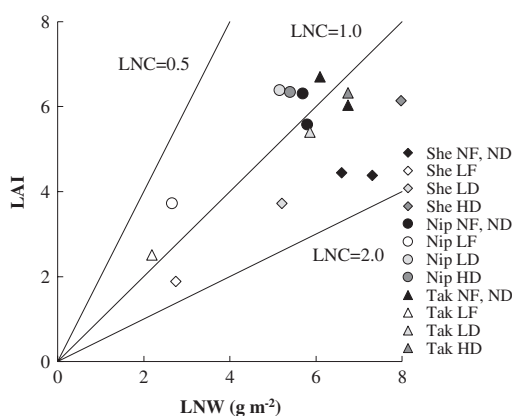
The average grain yield of Shennong265 under normal fertilizer and normal plant density growth conditions was approximately  $6.9\ t\ ha^{-1}$ . The yield levels observed in this study in Japan were much lower than those reported by Song et al. (2013) in China under similar treatment





**Figure 2.** Relationship between cumulative value of intercepted solar radiation (MJ) and total dry weight (TDW) ( $\text{g m}^{-2}$ ) of three cultivars at five treatments.

Notes: She, Shennong265; Nip, Nipponbare; Tak, Takanari; NF, normal-fertilizer treatment; LF, low fertilizer treatment; LD, low plant density treatment; ND, normal plant density treatment; HD, high plant density treatment.



**Figure 3.** Relationship between leaf area index (LAI) and leaf nitrogen weight (LNW) ( $\text{g m}^{-2}$ ) of three cultivars and five treatments.

Notes: She, Shennong265; Nip, Nipponbare; Tak, Takanari; NF, normal-fertilizer treatment; LF, low fertilizer treatment; LD, low plant density treatment; ND, normal plant density treatment; HD, high plant density treatment.

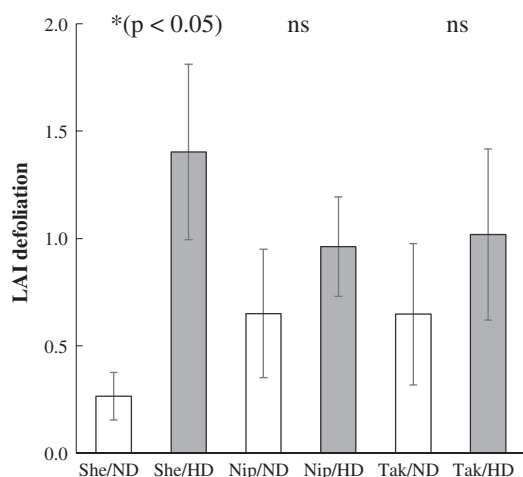
conditions (approximately  $9.0 \text{ t ha}^{-1}$ ) and slightly lower than those observed by Yamaguchi et al. (2009) and Fukushima et al. (2011) in Northeastern Japan under similar treatment conditions (approximately  $7.5 \text{ t ha}^{-1}$ ). Some researchers have suggested that higher solar radiation or lower night temperatures are important for high rice yields (Peng et al., 2004; Seshu & Cady, 1984). The longer insolation duration, lower daily average relative humidity, and higher diurnal temperature difference and solar radiation at the grain filling stage are the main ecological factors contributing to the high yield in Northeast China (Jin et al., 2013). This suggests that the meteorological conditions of Western Japan, with lower solar radiation and diurnal temperature difference, and relatively higher

night temperatures, were not suitable to achieve the maximum yield, especially for the erect panicle rice cultivar, Shennong265. While the yield of Shennong265 increased with increasing N application, it did not increase significantly with increasing plant density. These trends were similar to those observed by Yamaguchi et al. (2009) and Song et al. (2013).

The HI of Shennong265 was much higher than that of Nipponbare. This is because the GN of Shennong265 was considerably higher than that of Nipponbare. On the contrary, the PN in Shennong265 was significantly lower than that of Nipponbare and Takanari. Hirooka et al. (under submission) reported that the tillering rate and LAI growth rate of Shennong265 were lower than those of Nipponbare and Takanari. This leads to lower TDW in Shennong265 than Takanari and accounts for the lower yield of Shennong265 than Takanari despite the higher HI. The SSR, TGW, and TDW were significantly lower than the other japonica rice cultivar, Nipponbare, and these trends were in agreement with the result of Tang et al. (2017).

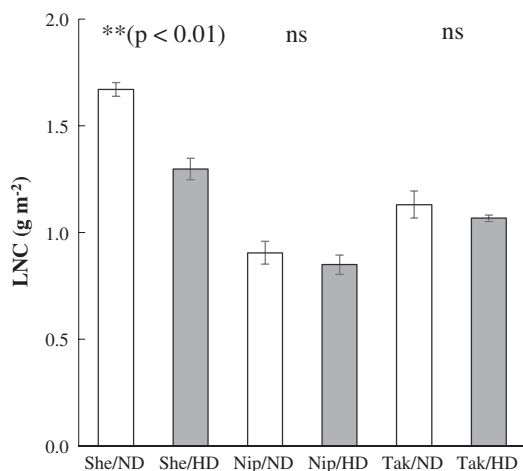
Intercepted solar radiation is closely related to dry matter productivity (Sivakumar & Virmani, 1984). Tang et al. (2017) reported that erect panicle rice is genetically exceptional for high yields as a result of improved photosynthetic capacity. Especially, Shennong265 is a cultivar suitable for high solar radiation conditions because it has erect leaves and panicles (Xue et al., 2014). In addition, the cultivar has remarkably higher photosynthetic capacity, and therefore, might be suitable for high nitrogen and/or solar radiation condition (Urairi et al., 2016). However, solar radiation in Western Japan was much lower than in Northeast China. Additionally, Shennong265 has a lower LAI growth rate and shorter growth periods (Hirooka et al., under submission). As a result, the intercepted solar radiation during the growing period of the Shennong265 cultivar was much lower than that of Nipponbare and Takanari. The RUE is the main factor accounting for the high grain yield of Takanari (Katsura et al., 2007); the RUE of Shennong265 was significantly higher than that of Nipponbare and was comparable to that of Takanari. The high yielding capacity of Takanari has been characterized by many researchers (Nagata et al., 2001; Takai et al., 2006). From these results, it is suggested that Shennong265 may also have high yielding potential and may enhance the dry matter productivity by intercepting more solar radiation through early transplanting and higher plant density.

The LNC of Shennong265 was considerably higher than that of Nipponbare and Takanari in this study, which is consistent with the results of Urairi et al. (2016). The LAI of Shennong265 under high plant density conditions was significantly higher than that under other treatments; the dry matter productivity did not increase as much as the LAI did under high plant density conditions. This may



**Figure 4.** The amount of LAI defoliation from heading to 2 weeks after heading of three cultivars at normal plant density (ND) and high plant density (HD) treatments.

Notes: \* indicates a significant difference between ND and HD by a student's *t*-test at the .05 probability level. ns means non-significant at  $P = .05$  level.



**Figure 5.** The leaf nitrogen content (LNC) at heading of three cultivars at normal plant density (ND) and high plant density (HD) treatments.

Notes: \*\* indicates a significant difference between ND and HD by a Student's *t*-test at the .01 probability level. ns means non-significant at  $P = .05$  level.

result in lower LNC and nitrogen uptake and a higher LAI defoliation after heading under high plant density conditions. Makino et al. (2016) reported that the dry matter productivity after heading was critical for erect panicle rice varieties. Nevertheless, in this study, nitrogen was insufficient for erect panicle rice cultivar after heading under high plant density condition. The shortage of nitrogen and solar radiation after heading may account for the reduction in dry matter in Shennong265 relative to that in Nipponbare and Takanari. Further study of the effects of additional fertilizer and climatic conditions is required to confirm this observation.

## Conclusion

The grain yield of Shennong265 was higher under high fertilizer and plant density conditions than of standard japonica cultivars, such as Nipponbare. The grain yield of Shennong265 observed in this study was, however, much lower than that observed in studies in Northern China. On the contrary, the RUE of Shennong265 was comparable to that of the high yielding cultivar such as Takanari and LNC of Shennong265 was much higher than Takanari and Nipponbare. These results indicate that Shennong265 has high yield potential but it does not attain its full yield potential in Western Japan under the conditions used in this study. The reduced performance of the cultivar may be caused by the climate of Western Japan, where solar radiation is low and night temperature is high. It may also be due to insufficient fertilizer after heading, and short growth periods. Therefore, additional fertilizer around the time of heading and earlier transplanting may be needed for Shennong265, when grown under the condition of high plant density level to obtain higher yields in Western Japan.

## Disclosure statement

No potential conflict of interest was reported by the authors.

## Funding

This study was supported by JSPS KAKENHI [grant number JP26292013]; JSPS Young Scientists Supports.

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