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REVIEW

Yield Potential of High-Yield Rice Varieties in the Tohoku Region of Japan

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Abstract

To achieve a super high brown rice yield exceeding 10 t ha^{-1} in the Tohoku region (relatively cold), a two-year field experiment was conducted. The yield components, morphological traits and dry matter production among the *Japonica* type high-yield variety "Fukuhibiki," *indica* type high-yield variety "Takanari," large grain type high-yield variety "Bekoaoba" and two conventional *Japonica* type varieties were compared. Although the traits relating to high yield varied greatly, the three high-yield varieties all showed a large sink size, heavy rice yield at 30 days after heading (30 DAH) and a high harvest index. The effects of nitrogen application and planting density on the morphological traits, dry matter production and yield in the large grain type variety Bekoaoba were investigated. Although high nitrogen application (HN) increased the brown rice yield from 8 to 9.5 t ha^{-1}, regulation of the timing of topdressing and/or planting density under HN could not increase the brown rice yield beyond 10 t ha^{-1}. Strategies to achieve a super high-yield rice in the Tohoku region were discussed.

Discipline: Crop production / Plant breeding

Additional key words: *Indica* type, *Japonica* type, large grain type, planting density, topdressing

Introduction

Super high-yield rice for multiple purposes is needed to improve food self-sufficiency and use paddy fields efficiently in Japan. Many kinds of high-yield rice varieties are grown in farm fields or used for research. Elucidation of the high-yield mechanism in varieties with differential yield related traits is important to attain a super high yield. In warm or temperate areas of Japan, *indica* type varieties, which often record high yields, have mainly been analyzed[7, 9, 10, 12]. In colder areas of Japan meanwhile, such as Tohoku, large grain type varieties often record high yields[5, 6]. However, the traits related to high yield and the cultivation techniques for high-yield varieties in the Tohoku region are not fully understood.

The peak brown rice yield in the Tohoku region is 9.2 t ha^{-1} (seven year average) of the large grain type variety Bekoaoba. However, this study targets a super high brown rice yield exceeding 10 t ha^{-1} by using high-yield varieties and regulating nitrogen application and planting density.

1. Varietal differences of yield components, morphological traits and dry matter production

Field experiments were conducted in a paddy field at the National Agricultural Research Center for Tohoku Region (Daisen city, Japan; 39°29'N, 140°29'E) in 2008 and 2009[3]. Fukuhibiki, a *Japonica* type high-yield variety in the Tohoku region; Takanari, an *indica* type high-yield variety for warmer areas in Japan; Bekoaoba, a large grain type high-yield variety in the Tohoku region and Akitakomachi and Hitomebore, conventional *Japonica* type varieties in the Tohoku region were used.

The formation of yield components was compared among the five varieties. Fukuhibiki had a relatively large number of spikelets per panicle and slightly large grains (Table 1). Takanari produced the largest number of spikelets per area because of the greater number of shoots per area and the most differentiated spikelets per panicle. These results indicate that a large potential sink size results in the largest sink size in Takanari (Fig. 1). Bekoaoba indicated the heaviest thousand grain weight exceeding 30 g. Accordingly, the three high-yield varieties indicated larger sink sizes, resulting in higher brown rice yields.

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Table 1. Differences in yield and yield components among five rice varieties

Year	Variety	Heading date	No. of panicles (m^{-2})	No. of spikelets per panicle	Thousand grain weight (g)	No. of spikelets (m^{-2})	Sink size (gm^{-2})	Brown rice yield ($g\ m^{-2}$)
2008	Akitakomachi	3 Aug.	414 c	76 a	23.0 b	31634 ab	726 a	690 a
	Hitomebore	8 Aug.	464 d	73 a	23.6 b	33990 ab	804 ab	738 ab
	Fukuhibiki	5 Aug.	333 b	107 b	25.4 c	35739 b	909 bc	804 bc
	Takanari	17 Aug.	293 a	146 c	21.9 a	42734 c	934 c	765 bc
	Bekoaoba	8 Aug.	301 ab	97 b	34.5 d	29219 a	1007 c	818 c
2009	Akitakomachi	6 Aug.	393 c	82 a	22.4 a	32186 a	721 a	679 a
	Hitomebore	9 Aug.	440 c	75 a	23.2 a	33004 a	764 a	710 a
	Fukuhibiki	6 Aug.	314 b	105 b	25.0 b	32957 a	822 ab	756 a
	Takanari	19 Aug.	251 ab	166 c	22.2 a	41572 b	922 b	756 a
	Bekoaoba	8 Aug.	278 a	98 b	34.6 c	27171 a	941 b	780 a
	Variety		**	**	**	**	**	**
	Year		**	*	NS	NS	*	*
	Interaction		NS	**	NS	NS	NS	NS

Sink size = one grain weight x No. of spikelets per area. Means followed by the same letters are not significantly different at the 0.05 level by Tukey's test (n=3). *: Significant at the 0.05 level, **: Significant at the 0.01 level, NS: Not significant by ANOVA.

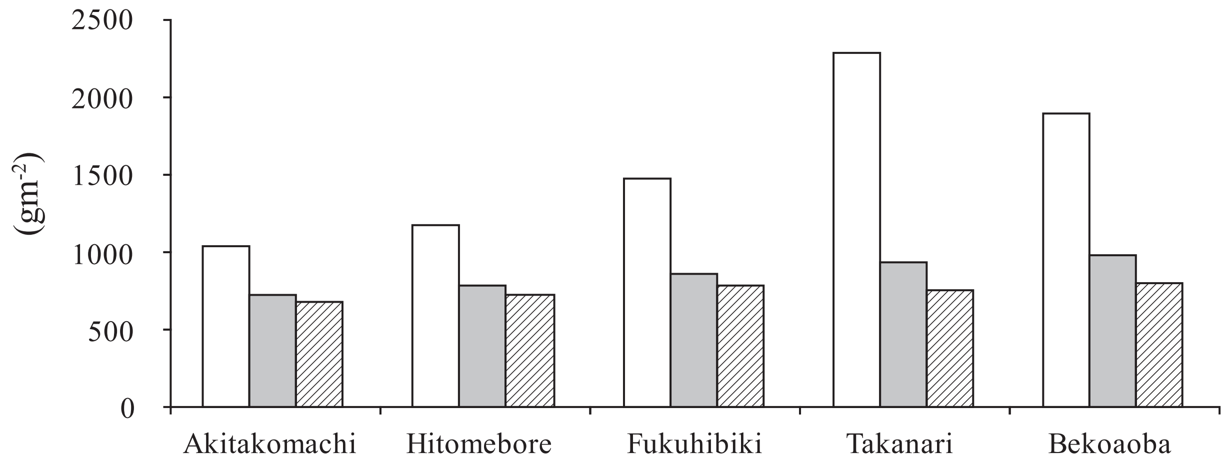

Fig. 1. Differences of yield formation among five rice varieties
Potential sink size = No. of differentiated spikelets x No. of maximum shoots x one grain weight, Sink size = No. of surviving spikelets x No. of panicles x one grain weight
☐ : Potential sink size, ▩ : Sink size, ▨ : Brown rice yield.

The morphological traits of panicles, leaves and stems in Takanari differed significantly from those of the other four varieties[3]. The number of large vascular bundles in the neck internode in particular exceeded twice as large in Takanari as in the other four varieties, indicating that the vascular system in the panicle of indica type Takanari differed significantly from that of the other four varieties (Fig. 2). The number of large vascular bundles in the neck node is equal to that of primary rachis branch in the *Japonica* type, including the large grain type. Conversely, the number of large vascular bundles is twice that of primary rachis branch in the high-yield *indica* type[1].

Plant type is closely related to canopy photosynthesis and dry matter production. Ensuring the low vertical positioning of panicles in the canopy is effective for increasing dry matter production during the ripening period[8]. We found that Takanari and Bekoaoba had panicles

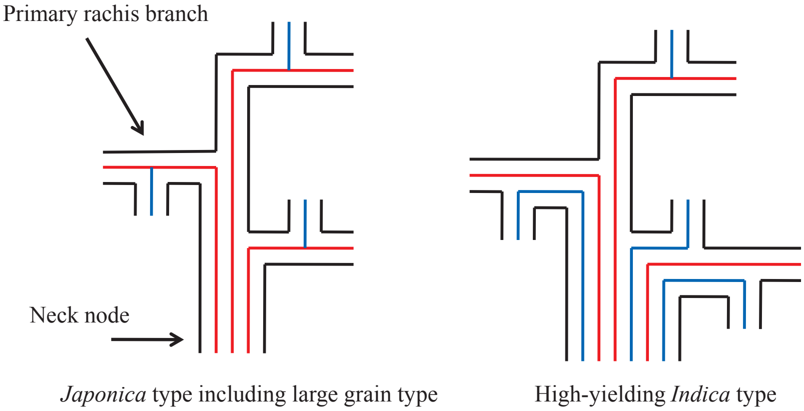

Fig. 2. Varietal differences of rice panicle vascular systems
: Large vascular bundles from primary rachis branch
: Large vascular bundles from secondary rachis branch

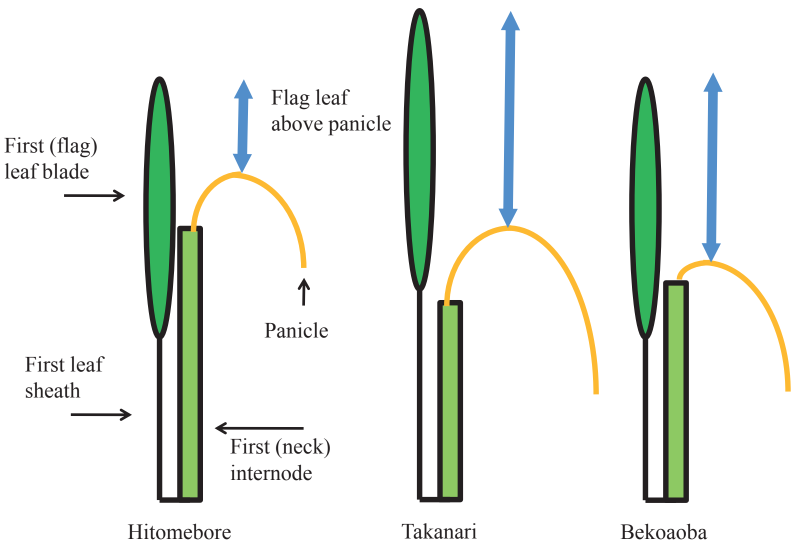

Fig. 3. Varietal differences in panicle position in the rice canopy

in the lower part of the canopy because the flag leaves were long and the first (neck) internode did not emerge beyond the lamina joint of the flag leaf in Takanari, while the panicles bent down lower in Bekoaoba (Fig. 3).

The dry matter production and ripening process were compared among the five rice varieties (Table 2). The three high-yield varieties produced heavy unhulled rice at 30 DAH and had a high harvest index in common, although ⊿W and the top dry weight at the full heading stage and maturity (TDWm) was not heavier. These results imply that a high yield is partly attributable to the remobilization of assimilate in the stem and leaf sheath during the early ripening period in addition to the large sink size.

2. Effects of Nitrogen Application and Planting Density on Yield Components Morphological Traits and Dry Matter Production of the Large Grain Type Rice Variety Bekoaoba

Two years of field experiments were conducted with a large grain type of the high-yield variety Bekoaoba[4]. The planting density and the pattern of nitrogen application were designed to obtain a super high-yield. Standard nitrogen application (SN) was eight gm^{-2} and high nitrogen application (HN) was 16 gm^{-2}. Early topdressing (ET) was conducted 30 days before heading (DBH), and standard topdressing (ST) was conducted at 20 DBH. The high planting density (HD) was three seedlings per hill at 44.4 hills m^{-2}, standard planting density (SD) was three seedlings per hill at 22.2 hills m^{-2} and low planting

Table 2. Differences in dry matter production in five rice varieties

Year	Variety	LAI	TDWh	TDWm (gm^{-2})	Harvest index	⊿W (gm^{-2})	RW30 (gm^{-2})	⊿$RW_{30\text{-}M}$ (gm^{-2})
2008	Akitakomachi	3.65 a	898 ab	1343 ab	0.47 a	445 ab	503 a	126 a
	Hitomebore	4.07 a	933 ab	1398 ab	0.47 a	465 ab	523 ab	136 a
	Fukuhibiki	3.88 a	863 ab	1369 ab	0.53 c	507 b	556 b	166 a
	Takanari	4.79 a	1063 b	1450 b	0.51 b	387 ab	624 c	114 a
	Bekoaoba	4.12 a	991 ab	1323 a	0.55 d	332 a	619 c	116 a
2009	Akitakomachi	4.48 a	835 a	1315 a	0.46 a	480 a	473 a	135 a
	Hitomebore	4.47 a	832 a	1358 a	0.48 ab	526 a	522 ab	124 a
	Fukuhibiki	4.79 a	832 a	1260 a	0.54 c	428 a	574 b	101 a
	Takanari	5.03 a	974 b	1351 a	0.50 b	377 a	544 ab	130 a
	Bekoaoba	4.30 a	858 ab	1251 a	0.56 c	393 a	556 ab	144 a
	Variety	*	**	NS	**	*	**	NS
	Year	**	**	*	NS	NS	**	NS
	Interaction	NS	NS	NS	NS	NS	*	NS

LAI: leaf area index at the full heading stage, TDWh: Top dry weight at the full heading stage, TDWm: TDW at maturity, ⊿W: TDWm -TDWh, Harvest index, brown rice yield / TDWm, RW30: Unhulled rice weight at 30 DAH, ⊿$RW_{30\text{-}M}$: Unhulled rice weight at maturity -RW30.

Table 3. Effects of nitrogen application and planting density on yield and yield component in the rice variety Bekoaoba

Year	Nitrogen application	Treatment	Heading date	No. of panicles (m^{-2})	No. of spikelets per panicle	Thousand grain weight (g)	No. of spikelets (m^{-2})	Sink size (gm^{-2})	Brown rice yield (gm^{-2})
2008	SN	ST-SD	8 Aug.	301	97	34.5	29219	1007	818
	HN	ST-SD	9 Aug.	361	101	35	36419	1275	974
		ST-HD	8 Aug.	418	82	35.5	34346	1219	936
		ET-SD	9 Aug.	366	101	34.6	36604	1266	964
		ET-HD	8 Aug.	424	82	35.2	34880	1226	957
	SN vs. HN (ST-SD)			**	NS	NS	*	**	**
	Timing of topdressing			NS	NS	NS	NS	NS	NS
	Planting density			**	**	NS	NS	NS	NS
	Interaction			NS	NS	NS	NS	NS	NS
2009	SN	ST-SD	8 Aug.	278	98	34.6	27171	941	780
	HN	ST-SD	6 Aug.	356	98	35	34826	1219	953
		ST-LD	8 Aug.	304	120	35	36324	1273	997
		ET-SD	8 Aug.	360	98	34	35120	1194	981
		ET-LD	9 Aug.	311	120	33.9	37310	1266	991
	SN vs. HN (ST-SD)			**	NS	NS	**	**	**
	Timing of topdressing			NS	NS	**	NS	NS	NS
	Planting density			**	**	NS	NS	NS	NS
	Interaction			NS	NS	NS	NS	NS	NS

SN: Standard nitrogen application, HN: High nitrogen application, ST: Standard topdressing, ET: Early topdressing, SD: Standard planting density, HD: High planting density, LD: Low planting density. Significant at the 0.05 level, **: Significant at the 0.01 level, NS: Not significant by t-test and ANOVA.

Table 4. Effects of nitrogen application and planting density on dry matter production in the rice variety Bekoaoba

Year	Nitrogen application	Treatment	Heading date	LAI	TDWh (gm^{-2})	TDWm (gm^{-2})	Harvest index	⊿W (gm^{-2})
2008	SN	ST-SD	8 Aug.	4.12	991	1323	0.55	332
	HN	ST-SD	9 Aug.	4.56	1019	1544	0.57	525
		ST-HD	8 Aug.	4.71	1097	1548	0.54	451
		ET-SD	9 Aug.	4.43	1011	1567	0.55	556
		ET-HD	8 Aug.	5.06	1150	1628	0.53	479
	SN vs. HN (ST-SD)			NS	NS	**	NS	NS
	Timing of topdressing			NS	NS	NS	*	NS
	Planting density			NS	*	NS	**	NS
	Interaction			NS	NS	NS	NS	NS
2009	SN	ST-SD	8 Aug.	4.3	858	1251	0.56	393
	HN	ST-SD	6 Aug.	5.65	969	1475	0.58	507
		ST-LD	8 Aug.	5.17	907	1509	0.6	601
		ET-SD	8 Aug.	5.34	956	1556	0.57	600
		ET-LD	9 Aug.	5.71	968	1514	0.6	546
	SN vs. HN (ST-SD)			*	NS	**	NS	*
	Timing of topdressing			NS	NS	*	NS	NS
	Planting density			NS	NS	NS	NS	NS
	Interaction			NS	NS	*	NS	*

density (LD) was one seedling per hill at 22.2 hills m^{-2}.

HN affected neither the number of spikelets per panicle nor the thousand grain weight, but increased the number of panicles per area, compared with SN (Table 3). Consequently, the sink size and brown rice yield in HN exceeded those in SN. In HN, ET increased the number of differentiated spikelets per panicle and the length of the upper leaves. These morphological responses to ET were almost coincident with those reported in a previous study in a warmer area of Japan[2]. However ET scarcely affected the number of surviving spikelets per panicle, the number of panicles and the brown rice yield. In HN, the higher the planting density, the larger the number of panicles per area, the fewer spikelets per panicle and the thinner the diameter of the internodes. However, planting densities did not significantly affect the sink size and brown rice yield. Timing of the topdressing and/or planting density affected some morphological traits, but it was difficult to evaluate how these changes affected the brown rice yield, since timing of topdressing and/or planting density did not significantly affect the sink size or brown rice yield.

The top dry weight at the full heading stage in HN was only 1.08 times that in SN (Table 4). In HN, however, the sink size was 1.27 times larger, LAI was 1.21 times larger, and ⊿W was 1.42 times larger respectively, which suggest that HN slightly increased the top dry weight at the full heading stage but that the sink size, LAI and ⊿W all increased significantly, resulting in a higher brown rice yield. In HN, the timing of the nitrogen application and planting density scarcely affected the top dry weight at the full heading stage and the ripening process.

3. Strategies for super high-yield rice in the Tohoku region

We elucidated that although HN produced brown rice yield exceeding 9.5 t ha^{-1} in the large grain-type rice variety Bekoaoba, it was difficult to generate a brown rice yield exceeding 10 t ha^{-1} by regulating the timing of topdressing and/or planting density. The top dry weight of Bekoaoba in HN, which was about 10t ha^{-1} at the full heading stage and 15.5 t ha^{-1} at maturity, seemed too light to achieve a brown rice yield of 10 t ha^{-1}. Nagata et al.[6] and Yoshinaga et al.[13] suggest that dry matter production is mainly dependent on growing duration in the Tohoku region. Late heading varieties might be effective in increasing dry matter production. The sink size of the large grain type variety Bekoaoba under HN, which exceeded 12 t ha^{-1}, seemed sufficient to achieve brown rice yield exceeding 10t ha^{-1}. However Takita[11] suggests that the extra-large spikelet size restricts grain filling. The optimal combination of spikelet size and spikelets per area has to be elucidated. Varieties with few vascular bundles in the neck internodes, such as Fukuhibiki and Bekoaoba, showed high yields in this study, suggesting that the conductivity of vascular systems in the panicles and neck internodes did not restrict rice yield at a yield level of 9 t ha^{-1}. To achieve super high yields exceeding 10 t ha^{-1}, however, it may be necessary to improve the vascular system in panicles (Fig. 2). Plant types, including the vertical position of the panicle, could be more easily regulated by the selection of varieties than by the method of nitrogen application[4]. Crossing of varieties with differential morphological traits might also improve the light intercept characteristics. Varietal differences in the brown rice yield were largely determined by the factors before 30 DAH in the Tohoku region. However, in order to obtain a super high yield, increasing the rice yield during the late ripening period might be important. To prove the feasibility and effectiveness of these strategies, we must compare and evaluate the yield ability of many varieties or lines with different traits or developmental patterns under various cultivation conditions in the Tohoku region.

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