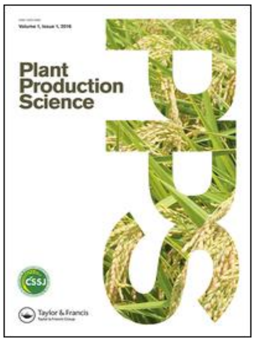

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Responses of Yielding Ability, Sink Size and Percentage of Filled Grains to the Cultivation Practices in a Chinese Large-Panicle-Type Rice Cultivar, Yangdao 4

Peter Aglua Gendua[1], **Yoshinori Yamamoto**[2], **Akira Miyazaki**[2], **Tetsushi Yoshida**[2] **and Yulong Wang**[3]

([1]United Post Graduate School of Ehime University, Matsuyama, Ehime 790-8566, Japan;
[2]Faculty of agriculture, Kochi University, Nankoku, Kochi 783-8502, Japan;
[3]Faculty of Agriculture, Yangzhou University, Yangzhou 225009, China)

Abstract : A Chinese high-yielding large-panicle indica cultivar Yangdao 4 (YD) was examined for the response of yielding ability, sink size and percentage of filled grains (PFG), to the cultivation practice in comparison with a Japanese cultivar Hinohikari (HH) that had almost the same growth duration in 2005 and 2006. Treatments included planting density and number of seedlings hill^{-1}, and supplement application of fertilizer to deep layer (SAFDL). Results revealed that the average sink size of YD was 17–28% larger than that of HH due to the larger number of spikelets panicle^{-1} and heavier grain weight. A significantly larger sink size was attained by the high density planting and SAFDL treatments in both cultivars, but not by changing the seedling number hill^{-1}. The sink size of YD responded more significantly to the cultivation practices than that of HH. The average PFG in YD was about 10% higher than that in HH in both years. The PFG in both cultivars decreased with increasing sink size, but the decreasing rate in YD was 1/3 of that in HH and its yearly fluctuation was also less in YD than in HH. Consequently, the yield of YD increased with increasing sink size in contrast to HH. The average brown-rice yield of YD (640–653 g m^{-2}) was 41–51% higher than that of HH (418–454 g m^{-2}). In comparison with HH, the stable PFG in YD at increased sink size could be attributed to the increase of carbohydrate accumulation in the panicle ($\Delta W+\Delta T$), larger amount of NSC in the LS+C and higher NSC/sink size.

Key words : Chinese high-yielding cultivar, Cultivation practice, Large panicle, Percentage of filled grains, Sink size, Rice, Yielding ability.

The high-yielding semidwarf indica and japonica-indica hybrid rice cultivars bred from 1960s to 1970s in IRRI, China, Korea, etc., which have larger number of spikelets and higher adaptability to heavy manuring, owing to their short culm, produce a higher yield compared with conventional Japanese rice cultivars (Komatsu et al., 1984; Takeda et al., 1984; Higashi, 1988; Saitoh et al., 1991, 1993; Yamamoto et al., 1991; Kusutani et al., 1993; Katsura et al. 2008). Moreover, the rice breeders in IRRI proposed the first-generation new plant type (NPT) that possess fewer panicles hill^{-1} and larger number of spikelets panicle^{-1} (Khush, 1995) and the second-generation NPT obtained by crossing the first-generation NPT lines with elite indica parents (Peng et al., 2004, 2008; Yang et al., 2007).

On the other hand, large-panicle rice cultivars including not only F_1 hybrids but also normal inbred cultivars with 150-200 spikelets panicle^{-1} have been bred in China in recent years and have contributed to yield increment (Song et al., 1990; Wan and Ikehashi, 1994a, 1994b; Wang et al., 1995, 1997; Amano et al., 1993, 1996; Katsura et al., 2007). The 1000-grain weight is also higher in these large-panicle-type cultivars than in the Japanese cultivars and tends to increase (Yamamoto et al., 2001).

Rice yield is composed of the number of panicles m^{-2} (NP-m^2), the number of spikelets panicle^{-1} (NS-P), the percentage of filled grains (PFG) and the winnowed 1000-grain (brown rice) weight (1000-GW). It can also be composed of sink size (sink size=number of spikelets m$^{-2}\times$1000-GW/1000) (Saitoh et al., 1991; Kusutani et al., 1993) and PFG. Of these components, the number of spikelets m^{-2} (NS-m^2) is determined by the NP-m^2 and the NS-P.

PFG determining yield with sink size is influenced by NP-m^2, NS-m^2 and NS-P (Matsushima, 1957; Wada, 1969). Therefore, NP-m^2 and NS-P are very important factors relating to sink size and PFG, which determine rice yield.

Using panicle weight-type high-yielding semidwarf

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Abbreviations: CGR, Crop growth rate; CV%, Coefficient of variation percentage; H density, High planting density; HH, Hinohikari; LAI, Leaf area index; L density, Low planting density; LS+C, Leaf sheath+culm; M density, Medium (standard) planting density; NAR, not assimilation rate; NP-m^2, Number of panicles m^{-2}; NSC, Nonstructural carbohydrates; NS-P, Number of spikelets panicle^{-1}; NS-m^2, Number of spikelets m^{-2}; PFG, Percentage of filled grains; SAFDL, Supplement application of fertilizer to deep layer; 1000-GW, winnowed 1000-grain (brown rice) weight; YD, Yangdao 4;

Table 1. Schedule and amount of fertilizer applied (g m^{-2}) in the cultivation of Yangdao 4 and Hinohikari in 2005 and 2006.

Treatment	Fertilizer	Fertilizer application stage (g m^{-2})						Total (g m^{-2})
		Basal	Tillering	Panicle formation			Heading	
				37/40 DBH	20 DBH	10 DBH		
CF-P	N	4	2		2	2	2	12
	P_2O_5	12						12
	K_2O	8			2	2		12
SAFDL-P	N	3		9				12
	P_2O_5	5		9				14
	K_2O	5		9				14

CF-P; Conventional fertilizer plot, surface application of nitrogen fertilizer. SAFDL-P; Supplement application of fertilizer to deep layer plot. One granular fertilizer (15 g) per 4 hills was placed 12 cm below soil surface at 37 and 40 days before heading for YD and HH, respectively.

and F_1 hybrid rice cultivars, many researchers in Japan have analyzed the factors relating to the high-yielding ability of these cultivars from the view points of yield components and/or dry matter production so far. However, most of these studies analyzed only the cultivar differences in yielding ability under limited cultivation conditions (Takeda et al., 1984; Song et al., 1990; Saitoh et al., 1991, 1993; Wang et al., 1991; Yamamoto et al., 1991; Amano et al., 1993, 1996; Kusutani et al., 1993; Miah et al., 1996; Shiotsu et al., 2006; Katsura et al., 2007), and few reports are available on the effects of a wide range of cultivation practices on the yielding ability (Weng et al., 1982; Komatsu et al., 1984; Kubota et al., 1988; Sumi et al., 1996). Analysis of the effects of cultivation practices on the yielding ability in relation to sink size and PFG might reveal practical information on high-yielding cultivation of these large-panicle-type cultivars.

Therefore, we carried out field experiments using a Chinese large-panicle-type cultivar, whose yielding ability was analyzed previously (Yao et al., 2000a, 2000b; Yamamoto et al., 2001; Ansari et al., 2003; Ju et al., 2006). The aim was to clarify the effects of cultivation practices, such as planting density, number of seedlings hill^{-1} and method of fertilizer application (supplement application of fertilizer to deep layer), on the NP-m^2 and NS-P, on the sink size and PFG, which determine the yielding ability.

Materials and Methods

1. Cultivars, cultivation and treatments

The experiments were carried out at the Education and Research Centre for Subtropical Field Science (FSC) of the Faculty of Agriculture, Kochi University, Japan for two years (2005 and 2006). Two cultivars; a Chinese high-yielding indica cultivar with large panicle, Yangdao 4 (YD), and a Japanese intermediate type Hinohikari (HH) were used. YD was bred in Jiangsu Province in China and released in 1990, and recorded the maximum cultivation area of 179 thousand ha in China (Ju et al., 2006).

In mid-May in all experimental years, pre-treated seeds were sown in nursery boxes (30×60 cm^2) following the conventional method of the FSC, except that the seeding rate was 100g per box. Seedlings at 3-4 leaf stage were hand-transplanted on May 30 and 28 in 2005 and 2006, respectively. Eight treatments consisting of the combination of three planting densities [11.1 (30×30 cm^2), 22.2 (30×15 cm^2) and 44.4 (15×15 cm^2) hills m^{-2}, which are indicated as low (L density), medium (standard) (M density) and high (H density), respectively], and the two numbers of seedlings hill^{-1} (2- and 6-seedlings hill^{-1}) were set up, and the supplement application of fertilizer to deep layer (SAFDL) were assigned only to the M density in both the 2- and 6-seedlings hill^{-1} treatments. The experimental plots were arranged in a randomized complete spilt-split plot design with two replications. The cultivar was designated as the main plot, seedling number as subplot and planting density and SAFDL as sub-subplot. The size of the main plot was 15.3×4.3 m^2 (65.8 m^2) with two subplots of 7.65×4.3 m^2 (32.9 m^2) each. In addition, each sub-plot had four sub-subplots each, which were separated by corrugated plastic sheets from each other. Prior to transplanting, each partitioned plot was plowed, fertilized, puddled, leveled and then irrigated to keep a water depth of about 3 cm.

Table 1 shows the schedule of fertilization. For the SAFDL, the granular fertilizer (3×2 cm^2 size, ca. 15 g, Kumiai kokei hiryo No. 1, JA) was applied 12 cm below the soil surface at a rate of one granule per 4 hills at 30–40 days before heading.

The plots were flooded 4 days after transplanting and a floodwater depth of 3-5 cm was maintained until one week before physiological maturity when the fields were drained. Weed, diseases and pests were intensively controlled by spraying agricultural chemicals to avoid crop damage.

2. Measurements and samplings

(1) Growth parameters and dry weight

Measurements of plant and leaf length on the main stem and counting the number of tillers of five plants in each replicate (10 plants per treatment) were carried out at 10-day intervals from 3 days after transplanting until the full heading stage.

Leaf-color readings (SPAD values) were taken from the youngest expanded leaf blade on the main stem in the same five plants that were used for the growth measurements with a chlorophyll meter (SPAD–502, Minolta Co.) at 10-day intervals from 20 days after transplanting (DAT) until 10 days after heading in 2005 and 2006.

Leaf area and dry weight were measured at heading (80–90% headed) and maturity stages. Three hills with average stem number per replicate (totally six hills per treatment) were sampled for measurement of leaf area and dry weight at heading and maturity stages. The leaf area in one hill in each plot was measured with an automatic leaf area meter (AAM-7, Hayashi Denkoh Co. Ltd, Japan). The samples were oven dried, initially at 95°C for 2 hrs and then at 65°C for 48 hrs to determine their dry weights. The leaf area in the other two hills was calculated from the dry weights and specific leaf area of the leaf blade. Leaf area index was calculated as the product of the average leaf area hill^{-1} and the number of hills m^{-2} divided by 10000. The dry matter translocated (ΔT) to the panicle was calculated as decrement in leaf sheath and culm (LS+C) dry weight from heading to maturity. The positive ΔT means the movement of LS+C dry matter to the panicles and the negative ΔT stands for the increment of LS+C dry matter. The dry matter newly produced (ΔW) for the panicle was calculated as the increment of total dry weight from heading to maturity.

(2) Chemical analysis

Oven-dried samples of the LS+C at the heading stage were ground using the vibration mill (T1-100, CMT Co. Ltd., Japan). After extraction of sugars from the ground sample (0.2 g) by 80% hot ethanol, starch was extracted with $HClO_4$ (4.6*N*) following the methods of Murayama et al. (1955). The analysis of starch as glucose was performed by Anthrone method, and starch percentage was calculated by multiplying 0.9 to glucose percentage.

(3) Yield and yield components

For the measurements of yield and yield components, 15 hills from the L density treatment, and 20 hills each from all other treatments were harvested and air dried in the glasshouse keeping the panicles intact. After air-drying, the panicles of each hill was separated just below the neck node and weighed. From the 15 or 20 hills, three hills with the average number and weight of panicles from each replicate were selected for threshing. After hand threshing of each selected panicle, the total number of spikelets hill^{-1} was counted with an automatic grain counter (Motoyama Seisakusho, Japan). The number of filled grains was counted after screened with salt water at a specific gravity of 1.06. The 1000-GW was determined as brown rice with 15% water content and the yield was calculated from the yield components.

The sink size was calculated as the product of NS-m^{2} and 1000-GW divided by 1000 (Saitoh et al., 1991; Kusutani et al., 1993).

(4) Statistical analysis

All growth, yield, and yield component data were processed with an Excel spreadsheet (Microsoft. 2002) and the statistical analysis with JMP (SAS Institute, Inc., v5.1).

Results

The data in 2006 was mainly described because the data in 2005 and 2006 showed the same trend.

1. Heading and maturity date

The heading date of YD (Aug. 15–17) in 2006 was 1–4 d earlier than that in HH (Aug. 16–20). No significant differences were observed in the heading date between the treatments with the different seedling numbers in both cultivars. The heading date of L density and SAFDL treatments in YD was delayed 1–2 d later than that of M density treatment. HH headed in the order of H>M>L>SAFDL treatment with about 1 day difference between each treatment.

The harvesting (maturity) date of YD (Sept. 21–27) in 2006 was 2–6 d earlier than that of HH (Sept. 23–29). It was earlier in H and M density treatments compared with the L density and SAFDL treatments in both cultivars, and no significant differences were observed between the treatments with 2- and 6 seedlings hill^{-1}.

2. Growth characteristics

(1) Culm length

At maturity, the culm lengths of YD and HH in 2006 ranged from 90 to 103 cm and 81 to 96 cm, respectively, and the average culm length of YD (97 cm) was significantly greater than that of HH (86 cm). A significantly shorter culm length was observed in the treatments with 2 seedlings hill^{-1}compared with 6 seedlings hill^{-1}in both cultivars. The culm length in L density and SAFDL treatments tended to be greater than that in H and M density treatments.

(2) Stem number

The maximum tiller and stem numbers were observed at 30–40 d after transplanting (DAT) in both cultivars and it was earlier in the treatments with a higher planting density and higher seedling number hill^{-1}. In SAFDL treatment, the maximum numbers were observed at almost the same day as those in the

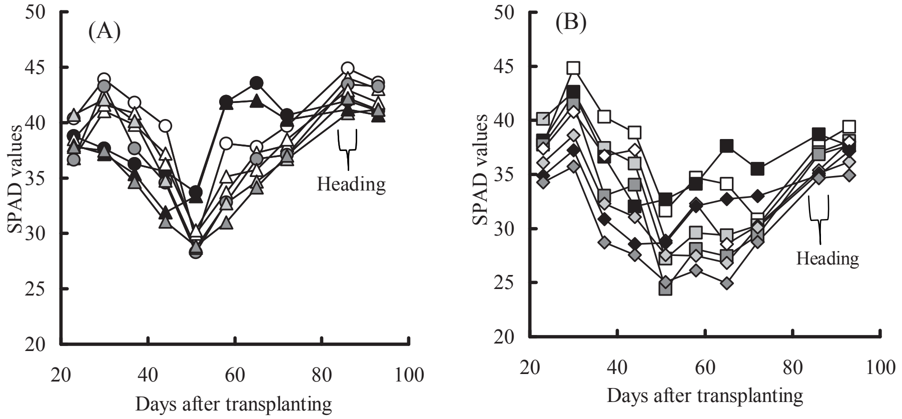

Fig. 1. Changes in the SPAD values from 20 days after transplanting to full heading in Yangdao 4 (A) and Hinohikari (B) under the different cultivation practices in 2006. ○, ◍, ◉, ● and △, ◬, ◭, ▲ ; 2 and 6 seedlings hill^{-1} in Yangdao 4 (YD), □, ▨, ▩, ■ and ◇, ◈, ⬖, ◆ ; 2 and 6 seedlings hill^{-1} in Hinohikari (HH). White, light gray, dark gray and black colors indicate low (11.1 hills m^{-2}), standard (22.2 hills m^{-2}) and high density (44.4 hills m^{-2}), and supplement application of fertilizer to deep layer (SAFDL, 22.2 hills m^{-2}), respectively.

M density treatment. The maximum stem number of YD and HH in 2006 ranged from 261 to 568 m^{-2} and 379 to 946 m^{-2}, respectively, and the average number of YD (400 m^{-2}) was significantly lower than that of HH (580 m^{-2}). The maximum stem number increased significantly with increasing planting density; and it was higher in 6 seedlings hill^{-1} treatment than in 2 seedlings hill^{-1} treatment. In SAFDL treatment, it was lower than that in M density treatment. The percentage of productive stems in 2006 ranged from 53.1–71.0% in YD and 57.7–84.2% in HH, and the average value of YD (59%) was lower than that in HH (70%). The percentage of productive stems was higher in the treatments with lower planting density and lower seedling number hill^{-1}, and a higher value was observed in SAFDL treatment compared with that in M density treatment.

(3) SPAD value

Fig. 1 shows the changes in SPAD values of the youngest expanded leaf blades from the productive tillering stage to the early grain filling stage in 2006. The SPAD values tended to increase until 30 DAT in a range of 35–45 in both cultivars, and then decreased to 30–35 in YD and 25–30 in HH at 50 DAT. Thereafter, the SPAD values in both cultivars increased in SAFDL or by top dressing at panicle formation stage, although the increment was greater in YD than in HH. Higher SPAD values during the panicle formation stage were observed in the treatments with lower planting density and seedling number, and the maximum SPAD reading was from the SAFDL treatments in both cultivars.

(4) Dry weight

Table 2 shows the shoot dry weight at heading and maturity stages in 2006. The average shoot dry weight of YD at heading and maturity stages was 131 g m^{-2} (12%) and 167 g m^{-2} (11%) higher than that of HH, respectively. The seedling number hill^{-1} did not significantly affect the dry weight at either stage in either cultivar except the shoot dry weight at maturity of HH. A significant difference in shoot dry weight at the heading stage was observed only between L density and SAFDL in 2 seedlings hill^{-1} treatment in HH, and in YD, shoot dry weight at maturity in M density was significantly lighter than that in H density in the 2 seedlings hill^{-1} treatment and H density and SAFDL treatments with 6 seedlings hill^{-1}. The average panicle dry weight of YD at the maturity stage was significantly heavier (219 g m^{-2}, 35%) than that of HH. The panicle dry weights in SAFDL and H density treatments tended to be heavier than those in the M density and L density treatments irrespective of the seedling number hill^{-1} in both cultivars except the 2 seedlings hill^{-1} in HH. The panicle dry weight was not significantly influenced by the seedling number hill^{-1} in either cultivar.

The leaf area index (LAI) at the heading stage in 2006 ranged from 5.1 to 7.6 in YD and 4.7 to 6.3 in HH and the average LAI in YD (6.1) was significantly higher than that in HH (5.7). The LAI was significantly correlated with the shoot dry weight at heading in both cultivars (YD: $r=0.928$, $p<0.001$; HH: $r=0.842$, $p<0.01$). The LAI at maturity ranged from 3.4 to 4.7 (average 3.8) in YD and 3.6 to 4.2 in HH (average 4.0), with negligible differences between cultivars and treatments.

The amount of nonstructural carbohydrates (NSC) in leaf sheath+culm (LS+C) at the heading stage, ΔW, ΔT and the sum of ΔW and ΔT ($\Delta W+\Delta T$) in 2006 are shown in Table 2. The average NSC in YD was 40 g m^{-2} (44%) higher than that in HH. Dry weight and

Table 2. Shoot and panicle dry weights and ΔW, ΔT *and* $\Delta W+\Delta T$ of Yangdao 4 and Hinohikari under the different cultivation practices in 2006.

Cultivars	Seedling number hill^{-1}	Planting Density m^{-2}	Shoot dry weight at Heading (g m^{-2})	Shoot dry weight at Maturity (g m^{-2})	Panicle dry Wt. at maturity (g m^{-2})	NSC[1] at heading (g m^{-2})	ΔW[2] (g m^{-2})	ΔT[3] (g m^{-2})	$\Delta W+\Delta T$ (g m^{-2})
Yangdao 4	2	11.1	1131	1642	759	136	511	109	620
	2	22.2	1212	1534	723	136	322	197	519
	2	22.2(D)	1214	1807	946	127	593	197	790
	2	44.4	1271	1863	868	118	592	102	694
	6	11.1	1142	1682	768	150	540	100	640
	6	22.2	1222	1622	763	139	400	192	592
	6	22.2(D)	1344	1879	983	132	525	261	786
	6	44.4	1204	1890	937	109	686	108	794
Hinohikari	2	11.1	940	1598	646	96	658	–14	644
	2	22.2	1149	1461	541	89	312	98	410
	2	22.2(D)	1234	1500	645	106	266	223	489
	2	44.4	1032	1539	603	85	507	–5	502
	6	11.1	1017	1534	610	87	517	14	531
	6	22.2	1127	1588	609	95	461	72	533
	6	22.2(D)	1190	1649	676	95	459	117	576
	6	44.4	1005	1706	663	76	700	–54	646
LSD (0.05)			*281*	*318*	*149*	*71*	*418*	*219*	*232*
Yangdao 4	Avg. of 2 seedling		1207a	1711a	824a	129a	504a	151a	656a
	Avg. of 6 seedling		1228a	1766a	863a	133a	538a	165a	703a
Hinohikari	Avg. of 2 seedling		1089a	1524b	609a	94b	436a	76a	511a
	Avg. of 6 seedling		1085a	1619a	640a	88b	534a	37a	571a
Yangdao 4	*Average*		*1218A*	*1739A*	*843A*	*131A*	*521A*	*158A*	*679A*
	CV(%)		*5.6*	*7.9*	*12.1*	*9.8*	*22.0*	*38.7*	*15.3*
Hinohikari	*Average*		*1087B*	*1572B*	*624B*	*91B*	*484A*	*56B*	*542B*
	CV(%)		*9.5*	*5.1*	*6.9*	*9.9*	*30.9*	*159.9*	*14.7*

[1] Nonstructural carbohydrate in leaf sheath+culm. [2] Increased shoot dry weight from heading to maturity. [3] Decreased dry weight in leaf sheath+culm from heading to maturity. Minus value means increase of the dry weight. (D)=Supplemental application of fertilizer to deep layer. The values followed by the same small letter in a column are not significantly different at 5% level by Tukey's test while the same small letter for the average values in 2- and 6-seedlings treatments in each cultivar in a column and capital letter for the average values of different cultivars in a column are not significantly at 5% level by *t* test.

percentage of NSC in LS+C significantly contributed to the differences. The amount of NSC in LS+C in the L and M density treatments in both cultivars was larger that those in the H density treatment, although not significantly. The amount of NSC in SAFDL treatments was marginally different from that in the M density treatment in both YD and HH.

The average ΔW in YD was 37 g m^{-2} (8%) larger than that in HH, yet not at a significant level. The ΔW was determined by the crop growth rate (CGR) during the grain filling period, and CGR was closely related with the net assimilation rate (NAR) (YD: $r=0.872$, $p<0.01$; HH: $r=0.979$, $p<0.001$), but not with the mean LAI. The ΔT was a positive value in all the treatments in YD, but negative values were observed in the L and H density treatments in HH. The average ΔT in YD (158 g m^{-2}) was significantly larger than that in HH (56 g m^{-2}). No significant differences were observed in the ΔT between 2 and 6 seedlings hill^{-1} treatments. The ΔT tended to be larger in SAFDL treatments irrespective of seedling number hill^{-1}. The $\Delta W+\Delta T$ was heavier in YD than in HH mainly due to the contribution of ΔT. The variation of ΔT as indicated by CV% was much higher than those of ΔW, shoot dry weight and panicle weight. Significant negative correlations were observed between the ΔW and the ΔT except in SAFDL treatments in YD in both years and in HH in 2006 (Fig. 2). The ΔT in SAFDL treatments was heavier than that in the conventional fertilization method at the same ΔW.

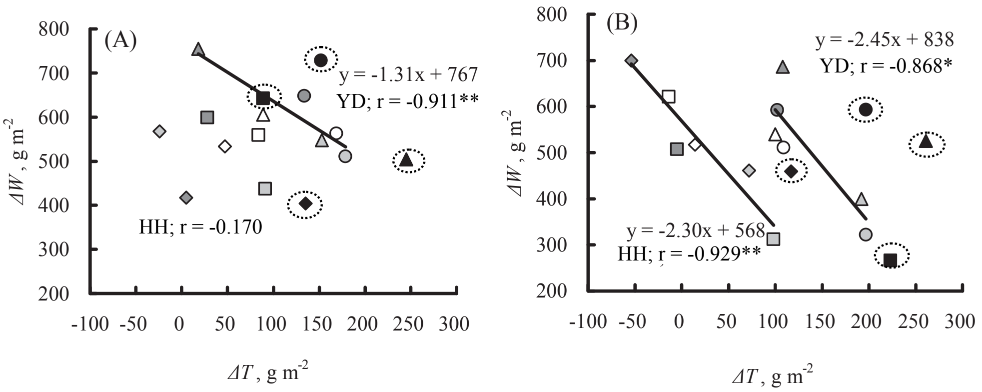

Fig. 2. Correlation between ΔW and ΔT in Yangdao 4 and Hinohikari in 2005 (A) and 2006 (B). Symbols are the same as those in Fig. 1. Correlation coefficients (rs) were calculated excluding the treatments of supplement application of fertilizer to deep layer (circled by the dotted lines) in each cultivar. * and **; significant at 5% and 1% level, respectively.

Table 3. Sink size, percentage of filled grains and yield of Yangdao 4 and Hinohikari under different cultivation practices in 2005 and 2006.

Cultivars	Seedling number hill^{-1}	Planting Density m^{-2}	Sink size		Percentage of filled grains		Grain yield	
			2005 (g m^{-2})	2006 (g m^{-2})	2005 (%)	2006 (%)	2005 (g m^{-2})	2006 (g m^{-2})
Yangdao 4	2	11.1	885	782	76.5	80.5	677	629
	2	22.2	847	799	75.7	77.6	643	620
	2	22.2(D)	959	1035	71.9	68.2	689	705
	2	44.4	1020	967	66.6	70.7	676	681
	6	11.1	765	805	74.7	78.3	571	630
	6	22.2	828	860	74.1	76.3	614	656
	6	22.2(D)	965	1094	67.7	65.3	652	712
	6	44.4	952	850	63.1	69.8	601	590
Hinohikari	2	11.1	758	621	56.0	76.6	423	476
	2	22.2	757	619	62.3	63.7	467	395
	2	22.2(D)	817	825	54.4	42.9	438	355
	2	44.4	768	727	61.4	56.4	470	408
	6	11.1	731	660	66.3	70.7	484	466
	6	22.2	767	644	62.3	66.7	477	429
	6	22.2(D)	787	767	52.5	53.1	413	407
	6	44.4	783	737	58.8	55.7	458	410
	LSD (0.05)		*119*	*128*	*13.4*	*14.3*	*100*	*142*
Yangdao 4	Avg. of 2 seedlings		928a	896a	72.7a	74.3a	671a	659a
	Avg. of 6 seedlings		878b	902a	72.4a	72.4a	610b	647a
Hinohikari	Avg. of 2 seedlings		775a	698a	58.5a	59.9a	450a	408a
	Avg. of 6 seedlings		767a	702a	60.0a	61.6a	458a	428a
Yangdao 4		*Average*	*903A*	*899A*	*71.3A*	*73.3A*	*640A*	*653A*
		CV(%)	*9.5*	*13.1*	*6.9*	*7.5*	*6.5*	*6.6*
Hinohikari		*Average*	*771B*	*700B*	*59.3B*	*60.7B*	*454B*	*418B*
		CV(%)	*3.3*	*10.8*	*7.9*	*17.8*	*5.7*	*9.3*

(D) = Supplemental application of fertilizer to deep layer. Grain yield was expressed by the brown rice yield with 15% water content. The values followed by the same small letter in a column are not significantly different at 5% level by Tukey's test while the same small letter for the average values in 2- and 6-seedlings treatments in each cultivar in a column and capital letter for the average values of different cultivars in a column are not significantly at 5% level by *t* test.

Table 4. Number of panicles and spikelets and1000-grain weight of Yangdao 4 and Hinohikari under the different cultivation practices in 2005 and 2006.

Cultivars	Seedling number hill^{-1}	Planting Density m^{-2}	Number of panicles, m^{-2}		Number of spikelets				1000-kernel weight, g	
					Panicle^{-1}		m^{-2}			
			2005	2006	2005	2006	2005	2006	2005	2006
Yangdao 4	2	11.1	192	178	165.0	152.8	31557	27080	28.04	28.89
	2	22.2	192	200	163.0	141.2	30991	28150	27.37	28.38
	2	22.2(D)	185	211	202.2	185.6	36719	38957	26.11	26.57
	2	44.4	289	274	130.6	125.0	37303	34158	27.36	28.33
	6	11.1	189	205	149.8	137.6	28179	28081	27.15	28.68
	6	22.2	255	259	120.4	118.5	30588	30636	27.10	28.07
	6	22.2(D)	244	274	149.6	148.2	36238	40508	26.63	26.99
	6	44.4	326	281	109.4	109.4	35113	30532	27.16	27.82
Hinohikari	2	11.1	344	292	98.8	90.3	33905	26374	22.34	23.56
	2	22.2	389	348	85.4	75.5	33104	26244	22.86	23.59
	2	22.2(D)	340	363	108.5	108.1	36822	39102	22.22	21.11
	2	44.4	481	414	70.3	75.3	33611	31169	22.85	23.34
	6	11.1	370	372	90.0	75.4	33202	27992	22.03	23.56
	6	22.2	481	433	71.2	64.8	34225	28028	22.41	22.98
	6	22.2(D)	433	414	79.3	85.4	34281	35257	22.91	21.79
	6	44.4	629	592	56.2	54.8	35180	32242	22.28	22.86
	LSD (0.05)		*63*	*92*	*28.7*	*17.9*	*4876*	*5425*	*1.21*	*1.71*
Yangdao 4	Avg. of 2 seedling		214b	216b	165.2a	151.0a	34143a	32086a	27.22a	28.04a
	Avg. of 6 seedling		253a	255a	132.3b	128.4b	32529b	32439a	27.01a	27.89a
Hinohikari	Avg. of 2 seedling		389b	354b	90.7a	87.3a	34361a	30722a	22.57a	22.90a
	Avg. of 6 seedling		478a	453a	74.1b	70.1b	34222a	30880a	22.41a	22.80a
Yangdao 4		*Average*	*234B*	*235B*	*148.7A*	*139.8A*	*33336A*	*32263A*	*27.12A*	*27.97A*
		CV(%)	*22.8*	*17.3*	*19.7*	*17.0*	*10.2*	*15.9*	*2.1*	*2.9*
Hinohikari		*Average*	*433A*	*404A*	*82.4B*	*78.7B*	*34291A*	*30801B*	*22.49B*	*22.85B*
		CV(%)	*22.3*	*21.9*	*20.4*	*20.6*	*3.6*	*14.9*	*1.5*	*4.0*

(D) = Supplemental application of fertilizer to deep layer. The values followed by the same small letter in a column are not significantly different at 5% level by Tukey's test while the same small letter for the average values in 2- and 6-seedlings treatments in each cultivar in a column and capital letter for the average values of different cultivars in a column are not significantly at 5% level by *t* test.

3. Sink size, PFG and yield

Table 3 shows the yield (brown rice) and yield components, sink size and PFG of both years. The average sink size in YD was significantly larger than that of HH in 2005 (132 g m^{-2}, 17%) and 2006 (199 g m^{-2}, 28%), respectively. Of the seedling numbers treatments, only sink size in YD in 2005 was significantly more in the 2 seedlings hill^{-1}treatment than in the 6 seedlings hill^{-1} treatment. Moreover, the sink size in H density and SAFDL treatments were larger than those in M and L density treatments and SAFDL treatments showed the maximum value except the 2-seedling hill^{-1} treatment in YD in 2005.

The average PFG in YD was significantly (10%) higher than that in HH in both 2005 and 2006. No significant effect of seedling number on the PFG was observed in either year. The treatments with a larger sink size (i.e., in SAFDL and H density treatments) showed lower PFG than those with a smaller sink size (i.e., L and M density treatments).

The average yield in YD was 186 g m^{-2} (41%) and 235 g m^{-2} (56%) higher than that in HH in 2005 and 2006, respectively and the difference was significant. A significant difference in yield between the 2 and 6 seedlings hill^{-1} treatments was only observed in YD in 2005 and the yield was higher in the 2 seedlings hill^{-1} treatment than in the 6 seedlings hill^{-1} treatment. The maximum yield was obtained in SAFDL treatment in YD but on the contrary, the yield in SAFDL treatment in HH was the lowest.

The response of sink size to cultivation practice was more significant in YD than in HH. However, the PFG varied more in HH than in YD. The yearly fluctuations of sink size and PFG were higher in HH than in YD,

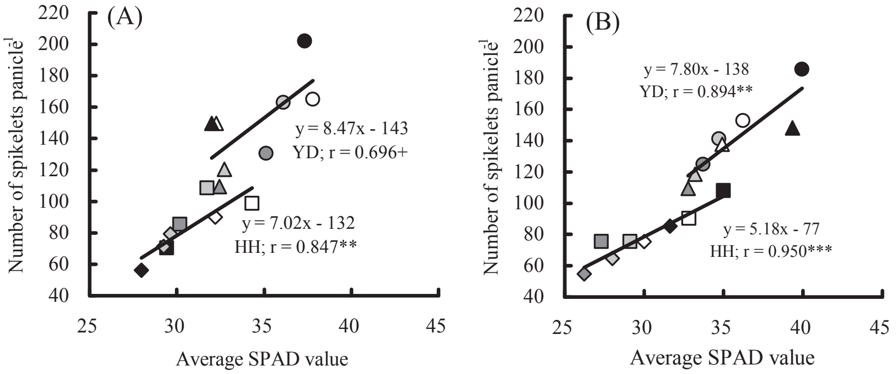

Fig. 3. Correlation between the average SPAD values of the youngest expanded leaf blade on the main stem and the number of spikelets panicle^{-1} during the panicle formation stage in Yangdao 4 and Hinohikari in 2005 (A) and 2006 (B). Symbols are the same as those in Fig. 1.+, ** and ***; Significant at 10%, 1% and 0.1% level, respectively.

Table 5. Correlation Coefficients (*rs*) between sink size or percentage of filled grains and yield components in Yangdao 4 and Hinohikari in 2005 and 2006.

Cultivar	Components	Sink size (g m^{-2})		Percentage of filled grains	
		2005	2006	2005	2006
Yandao 4	Number of panicles m^{-2}	0.518	0.495	−0.859 **	−0.690 +
	Number of spikelets panicle^{-1}	−0.006	0.394	0.505	−0.143
	Number of spikelets m^{-2}	0.979 ***	0.994 ***	−0.737 *	−0.908 **
	1000-kernel brown rice weight (g)	−0.267	−0.849 **	0.291	0.857 **
	Sink size panicle^{-1}	−0.046	0.250	0.565	0.022
Hinohikari	Number of panicles m^{-2}	0.118	0.337	0.102	−0.363
	Number of spikelets panicle^{-1}	0.120	0.398	−0.263	−0.310
	Number of spikelets m^{-2}	0.898 **	0.987 ***	−0.610	−0.922 **
	1000-kernel brown rice weight (g)	0.103	−0.877 **	−0.229	0.836 **
	Sink size panicle^{-1}	0.129	0.215	−0.285	−0.125

+,*,** and ***; Significant at 10%, 5%, 1% and 0.1% level, respectively.

especially in PFG.

Table 4 shows the NP-m^2, NS-P, NS-m^2 and 1000-GW in both years. The average NP-m^2 was significantly higher in HH than YD, whereas NS-P was significantly higher in YD than in HH. The NP-m^2 was significantly higher in the 6 seedlings hill^{-1} treatment than in the 2 seedlings hill^{-1} treatment, while NS-P was significantly higher in the 2 seedlings hill^{-1} treatment than in the 6 seedlings hill^{-1} treatment. The NP-m^2 was higher in H density treatment, while NS-P was higher in L density treatment. SAFDL had little effect on NP-m^2, but significantly increased the NS-P except in HH with 6 seedlings hill^{-1} treatment in 2005 and the maximum NS-P was obtained in the SAFDL treatment with 2 seedlings hill^{-1} in both cultivars. The NS-P was positively correlated with the average SPAD value during the panicle formation stage (Fig. 3).

The average NS-m^2 was significantly higher in YD than in HH in 2006, but not in 2005. The NS-m^2 responded significantly to the seedling number hill^{-1} treatments in YD in 2005 and tended to be higher in SAFDL and H density treatments than in M and L density treatments in both cultivars. The average 1000-GW in YD (27–28 g) was significantly higher than that in HH (22–23 g). No significant effect of the seedling number hill^{-1} on the 1000-GW was observed, while SAFDL treatment gave the least 1000-GW except in HH with 6 seedlings hill^{-1} treatment in 2005.

The NP-m^2 and NS-P were the yield components that gave the largest variations in the response to the cultivation practice; the CV% ranged from 17 to 23%, although the cultivar differences were small. The CV% of NS-m^2 in YD ranged from 10.2 to 15.9%, which was higher than that in HH (3.6 to 14.9%). The CV% of 1000-GW in both cultivars ranged from 1.5 to 4.0%, indicating a negligible response of 1000-GW.

Table 5 shows the correlation coefficients (*rs*) between sink size or PFG and the yield components in both years. Sink size in both cultivars was significantly and positively correlated with NS-m^2 in both years. On

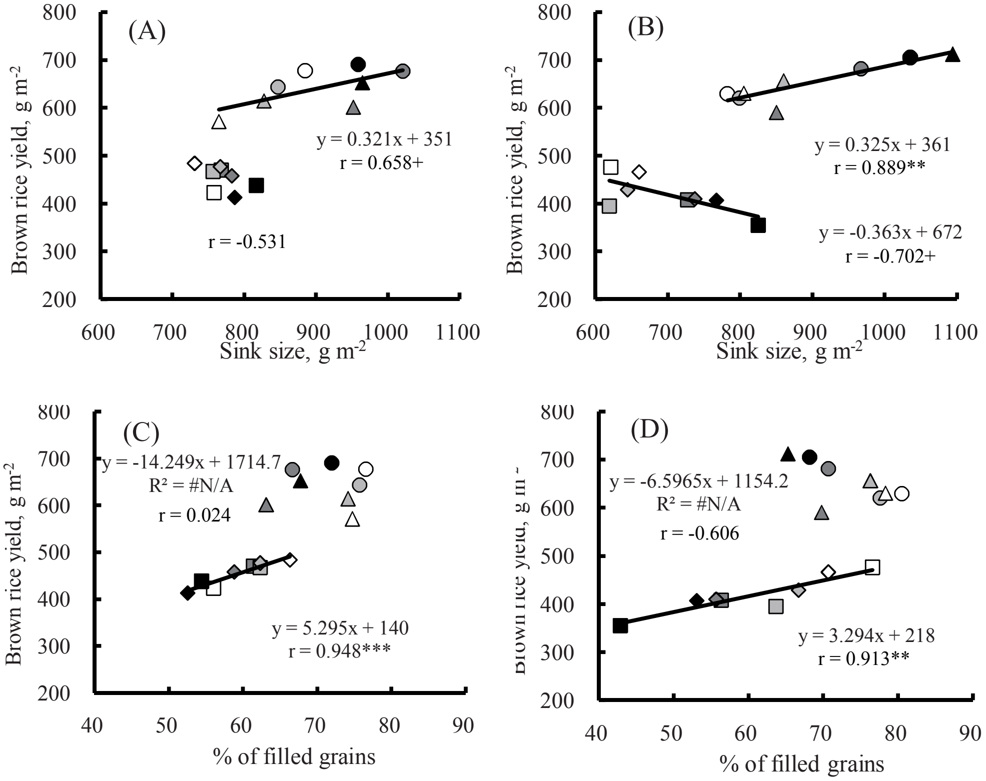

Fig. 4. Correlation of brown rice yield with sink size m^{-2} (upper) and percentage of filled grains (bottom) in Yangdao 4 and Hinohikari in 2005 (A, C) and 2006 (B, D). Symbols are the same as those in Fig. 1. +, ** and ***; Significant at 10, 1 and 0.1% level, respectively.

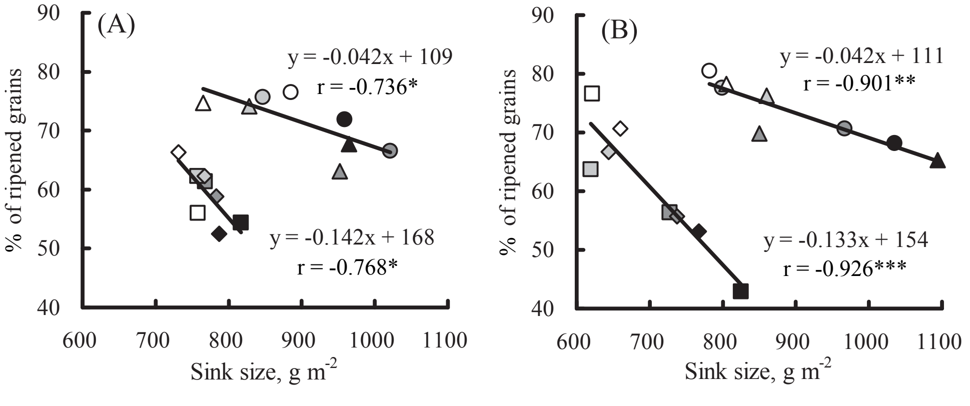

Fig. 5. Correlation between sink size m^{-2} and percentage of filled grains in Yangdao 4 and Hinohikari in 2005 (A) and 2006 (B). Symbols are the same as those in Fig. 1. *, ** and ***; Significant at 5, 1 and 0.1% level, respectively.

the other hand, PFG was significantly and negatively correlated with NS-m^2 except HH in 2005, although the *r* value in HH in 2005 was considerably high (r=−0.610). The Sink size and PFG in 2006 were significantly but negatively and positively correlated with the 1000-GW, respectively. Significant ($p<0.01$) and considerably high ($p<0.1$) negative correlations were observed between PFG and the NP-m^2 in YD in 2005 and 2006, respectively.

4. Correlation of sink size with PFG and yield

Fig. 4 shows the correlations of the sink size with the yield and PFG in both years. The yield of YD was positively correlated with the sink size in both years. However, the correlation was negative in HH. The yield positively correlated with PFG in HH in both years, but not in YD.

Sink size was negatively correlated with PFG in both cultivars and in both years, but the PFG decreased with

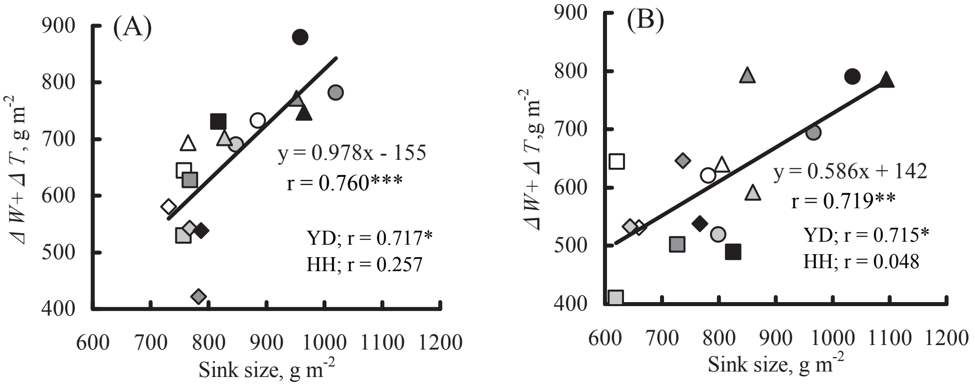

Fig. 6. Correlation between sink size and $\Delta W+\Delta T$ in Yangdao 4 and Hinohikari in 2005 (A) and 2006 (B). Symbols are the same as those in Fig. 1. *, ** and ***; Significant at 5%, 1% and 0.1% level, respectively.

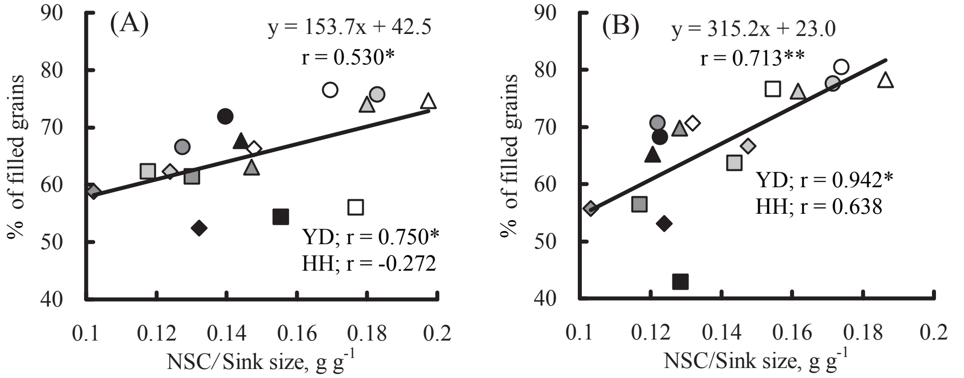

Fig. 7. Correlation between percentage of filled grains and nonstructural carbohydrate (NSC) per sink size in Yangdao 4 and Hinohikari in 2005 (A) and 2006 (B). Symbols are the same as those in Fig. 1. * and **; significant at 5% and 1% level, respectively.

increasing sink size at a 3 times higher rate in HH than in YD in both years (Fig. 5).

5. Relationships among dry matter production, sink size and PFG

Fig. 6 shows the relationship between sink size and $\Delta W+\Delta T$ (Table 2) in both years. The $\Delta W+\Delta T$ increased with increasing sink size and significant positive correlations were observed in YD and in the two cultivars as a whole in both years, but not in HH. The sink size was also significantly correlated with ΔT in the two cultivars as a whole (2005: $r=0.510$, $p<0.05$; 2006: $r=0.696$, $p<0.01$). Considering the differences of sink size, the coefficients of the correlation between PFG and ΔW, ΔT or $\Delta W+\Delta T$ per sink size were calculated, but none of the *r* values were significant ($r=0.052$-0.441). On the other hand, the NSC/sink size was significantly and positively correlated with PFG in YD in both years as well as in the two cultivars analyzed as a whole (Fig. 7).

Discussion

Rice yield is determined by the capacity of harvesting organ, i.e., sink size, and the amount of carbohydrates translocated to it (Murata and Matsushima, 1975; Kusutani et al., 1993). In this research, the sink size was indicated as the product of NS-m^2 and 1000-GW/1000 (Saitoh et al., 1991; Kusutani et al., 1993), and the response of yielding ability (sink size and PFG) of a Chinese high-yielding large panicle rice cultivar YD to the cultivation practices such as planting density, number of seedlings hill^{-1} and the SAFDL and their relationships were analyzed. We continue our discussion in the order of sink size, PFG and yielding ability.

1. Sink size

Sink size was mainly determined by NS-m^2 in both cultivars, and it was larger in H density and SAFDL treatments. However, the effect of seedling number hill^{-1} was small (Table 3). NS-m^2 was not significantly correlated with either NP-m^2 or NS-P ($r=0.073$–0.479)

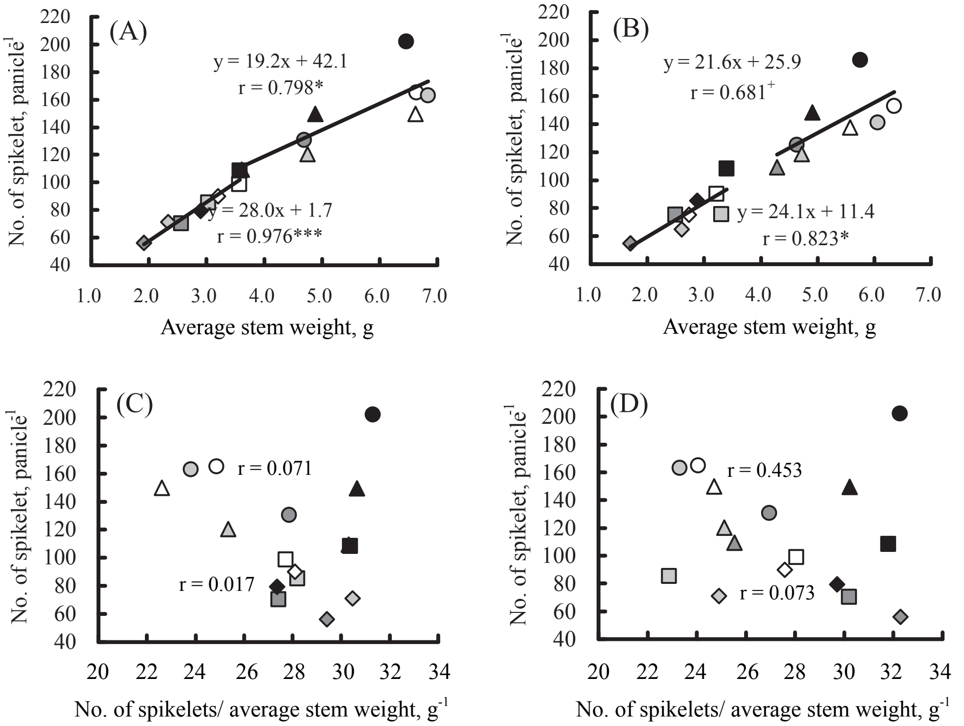

Fig. 8. Correlation of the number of spikelets per panicle with average dry weight per stem (A, B) and the number of spikelets per stem dry weight (C, D) in Yangdao 4 and Hinohikari at the heading stage in 2005 (left) and 2006 (right). Symbols are the same as those in Fig.1. +, * and *** Significant at 10%, 5% and 0.1% level, respectively.

probably due to the negative correlation between the two components (Matsushima, 1957). However, the response (CV%) of NP-m^2 and NS-P to the cultivation practice was comparatively high (Table 4). Due to the larger increasing rate of NP-m^2 relative to the decreasing rate of NS-P in response to an increase of planting density, the NS-m^2 was larger in H density treatment than in either L or M density treatment. Yamada et al. (1961) reported that the number of stems and panicles tended to increase and not to be constant with increasing planting density. NS-m^2 was larger in SAFDL treatment than in M density treatment due to the larger NS-P, although NP-m^2 was smaller. These findings are in agreement with the report by Tanaka (1979) that a smaller maximum tiller number, higher percentage of productive tillers and larger NS-P are associated with SAFDL practice.

The 1000-GW responded marginally to the cultivation practices in both cultivars (CV in YD=2.1-2.9%, HH=1.5–4.0%), but it decreased slightly in the SAFDL treatment due to the marked increase in NS-P though Tanaka (1979) reported an increase of 1000-GW by SAFDL practice. These results suggest that the effect of SAFDL on 1000-GW varies with the cultivar and/or cultivation practice.

The cultivar difference of sink size was mainly due to the difference in 1000-GW, not by NS-m^2. The average 1000-GW in YD was 4.63–5.12 g (21–22%) heavier than that in HH. Takita (1983) and Takeda et al. (1987) reported an achievement of high-yield through an increase of sink size by breeding larger grain cultivars, and Yamamoto et al. (2001) indicated that 1000-GW tended to increase in the newly bred Chinese high-yielding indica cultivars.

The cultivars and the cultivation practices associated with dry matter production were analyzed by separating NS-P into two components, i.e., the average dry weight stem^{-1} at the heading stage and the number of spikelets per average stem dry weight (spikelet production efficiency) (Yao et al., 2000a). Fig. 8 shows their correlations with NS-P. The spikelet production efficiency varied from 22 to −33 spikelets g^{-1} in both years, and the SAFDL treatment showed higher values in YD, although the spikelet production efficiency of YD was not higher than that of HH. Meanwhile, the average dry weight stem^{-1} at the heading stage was two-times heavier in YD than in HH, and the average stem dry weight was significantly correlated with NS-P in both cultivars except for YD in 2006 (significant at $p<0.1$). The larger NS-P in YD than in HH was also likely due to the higher SPAD values during the panicle formation stage (Fig. 3), since a higher nitrogen content in the leaf blades results in larger NS-P (Kumura, 1956). Yao et al. (2000a) reported that the larger NS-P in YD was achieved by the heavier stem dry weight at the heading stage, although the spikelet production efficiency was almost the same in YD at a lower NS-P.

2. Percentage of filled grains (PFG)

In YD, the average PFG was higher and its yearly fluctuations due to the cultivation practice were lower than in HH in both years, although the sink size and yearly fluctuation were larger (Table 3). This suggested that the PFG in YD was more stable and superior to that in the Japanese cultivar HH in spite of its larger sink size. PEG in Chinese F_1 hybrid rice cultivars with larger NS-P have been reported to decrease less with increasing NS-m^2 (Song et al., 1990; Amano et al., 1996).

The correlation analysis revealed that sink size and PFG were negatively and significantly correlated in both cultivars. PFG was lower in H density and SAFDL treatments, which had a larger sink size, than in M and L density treatments, which had a smaller sink size (Fig. 5). PFG was lower under a higher planting density (Takeda and Hirota, 1971) and SAFDL practice (Tanaka, 1979). The change of PFG in response to sink size differed with the cultivar; YD showed a decreasing rate in PFG 1/3 that of HH. PFG decreases with the increase of sink size when the carbohydrate (dry matter) production is relatively small, or when the carbohydrate is not translocated well to the sink (the panicle) (Wada, 1969; Murata and Matsushima, 1975; Kusutani et al., 1993). The carbohydrates accumulated in the panicle consist of the stored carbohydrates at heading (ΔT) and that synthesized after the heading stage (ΔW) (Murata and Matsushima, 1975). In the present experiments, YD had a larger amount of $\Delta W+\Delta T$ mainly due to the larger amount of ΔT than HH. Consequently, a high PFG was maintained in YD even with a large sink size. This was consistent with the high percentage of ΔT in panicle weight or yield in other large-sink cultivars (Song et al., 1990; Saitoh et al., 1991; Kusutani et al., 1993; Miah et al., 1996; Ueda et al., 2000b; Katsura et al., 2007). Moreover, the $\Delta W+\Delta T$ in YD increased with increasing sink size, which might also contribute to the smaller decrement of PFG. However, this was not the case in HH. On the other hand, the average amount of NSC in the LS+C in YD at the heading stage was significantly higher than that in HH (Table 2), and the ratio of the amount of NSC to sink size was closely related with the PFG (Fig. 7). Ueda et al. (2000a) and Shiotsu et al. (2006) reported a higher NSC content at the heading stage of high-yielding indica and japonica-indica hybrid cultivars compared with those of Japanese cultivars. A high PFG is associated with a large amount of stored carbohydrates (Weng et al., 1982; Sumi et al., 1996) or heavy dry weight of LS+C (Yamamoto et al., 1991) per sink size or number of spikelets at the heading stage.

However, the comparatively low PFG in both cultivars might be caused by the shorter sunshine hours during 20 days after heading, 68% in 2005 and 84% in 2006, compared with the average year, suggesting that the relationship between the sink size and the PFG is affected by the meteorological factors. Nagata et al. (2001) reported that the NSC reserve plays a role in compensating for the shortage of carbohydrate supply from assimilates after heading.

The higher PFG in YD was achieved mainly by a larger amount of $\Delta W+\Delta T$, the higher NSC content of LS+C and a larger amount of NSC/sink size compared with HH.

3. Yielding ability

The average yield in YD was 41% and 56% higher than that in HH in 2005 and 2006 respectively, and in YD the yearly variation (CV%) was smaller and yield was more stable than in HH (Table 3). The average highest yield in both years was 32% higher in YD (701 g m^{-2}) than in HH (480 g m^{-2}). The potential paddy yield of YD in Jiangsu Province where YD was bred was more than 1000 g m^{-2} (Yao et al., 2000c) and this equals to over 820 g m^{-2} of brown rice, assuming that the husking ratio is 82% (Gendua et al., unpublished data). The highest yield in YD obtained in this research was lower than the potential yield in Jiangsu Province, and the difference might be explained by the differences in soil fertility of paddy field, amount of fertilizer applied and the meteorological conditions. The yield of both cultivars responded differently to the sink size and PFG. The yield of YD increased with increasing sink size, whereas the yield of HH decreased with increasing sink size, and was more closely related with PFG (Fig. 4). This was because PFG in HH decreased with increasing sink size, at a 3 times higher rate than in YD. Consequently, the yield of SAFDL treatment, which gave the maximum sink size, was highest in YD but least in HH. Wada and Kudo (1966) and Wang et al. (1991) reported that the effect of SAFDL practice on the yield was strong in the cultivars with high adaptability to heavy manuring. In the present experiment, the lengths of the top three leaf blades on the main stem was 22–32% and 19–20% longer in SAFDL than in M density treatments in YD and HH, respectively, in 2006. Though the top three leaf blades extended less in HH than in YD, they bent more in HH than in YD, resulting in a poor light condition in the population of HH after the heading stage. Consequently, the dry matter production (ΔW) in SAFDL treatments was the lowest after the heading stage in HH and a higher translocation of the ΔT was necessary to make up for the smaller amount of ΔW. However, the PFG in SAFDL treatments in HH was still lower compared with that in the other treatments in HH and the treatments of YD even at the same amount of the NSC/sink size (Fig. 7), which awaits further experimentation. Wang et al. (1991) reported that the yield increase by the SAFDL practice was not observed in the cultivars with lower adaptability to heavy manuring due to the less dry matter production after the heading stage through the excess increase in leaf area by the higher NP-m^2 and longer leaf blades. This provides some clues to the cultivar differences between YD and HH in adaptability to the SAFDL.

In conclusion, the Chinese large-panicle-type high-yielding indica cultivar, YD, was significantly superior in sink size to the Japanese cultivar, HH, due to its larger NS-P and heavier 1000-GW, although NS-m^2 was almost the same due to the smaller NP-m^2. The effects of cultivation practice on the sink size might be larger in YD than in HH, because of the greater response of sink size to the cultivation practice in YD. The decreasing rate and yearly fluctuation of PFG with increasing sink size were much lower in YD than in HH, and the yield of YD increased with the increase of sink size. In comparison with HH, the stable PFG in YD at increased sink size could be attributed to the increase of carbohydrate accumulation in the panicle ($\Delta W+\Delta T$), larger amount of NSC in the LS+C and higher NSC/sink size.

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*In Japanese.

**In Japanese with English abstract.

***In Japanese with English summary.